Published in final edited form as:
Br J Sports Med. 2021 August ; 55(15): 851–856. doi:10.1136/bjsports-2020-103833.

Lower Step Rate is Associated with a Higher Risk of Bone Stress Injury: A Prospective Study of Collegiate Cross Country Runners

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Abstract

Objectives: To determine if running biomechanics and bone mineral density (BMD) were independently associated with bone stress injury (BSI) in a cohort of National Collegiate Athletic Association Division I cross country runners.

Methods: This was a prospective, observational study of 54 healthy collegiate cross country runners over 3 consecutive seasons. Whole body kinematics, ground reaction forces (GRF) and BMD measures were collected during the pre-season over 3 years via motion capture on an instrumented treadmill and total body densitometer scans. All medically diagnosed BSIs up to 12-months following pre-season data collection were recorded. Generalized Estimating Equations were used to identify independent risk factors of BSI.

Results: Univariably, step rate, center of mass vertical excursion, peak vertical GRF, and vertical GRF impulse were associated with BSI incidence. After adjusting for history of BSI and sex in a multivariable model, a higher step rate was independently associated with a decreased risk of BSI. BSI risk decreased by 5% (RR: 0.95; 95% CI: 0.91, 0.98) with each one step/min increase in step rate. BMD z-score was not a statistically significant risk predictor in the final multivariable model (RR: 0.93, 95% CI: 0.85, 1.03). No other biomechanical variables were found to be associated with BSI risk.

Conclusion: Low step rate is an important risk factor for BSI among collegiate cross country runners and should be considered when developing comprehensive programs to mitigate BSI risk in distance runners.

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Authorship Contributions: BCH, MRSJ, CMW and SAK designed the study, interpreted the results, and drafted the initial manuscript. MRSJ, JS and PZ collected the data and prepared it for analysis. SAK performed the statistical analyses. All authors provided critical reviews for the manuscript and all authors reviewed and approved the final draft of this manuscript prior to submission.

Competing Interests:
Authors have no conflicts of interest to declare

Data Sharing: Requests for data sharing from appropriate researchers and entities will be considered on a case-by-case basis. Interested parties should contact Dr. Heiderscheit (heiderscheit@ortho.wisc.edu).

Introduction

Bone stress injuries (BSI) are very common among collegiate cross country runners, occurring at a rate of 16 and 29 BSI per 100,000 athletic exposures for males and females, respectively.[1] The average recovery time following a BSI in this population is 13 weeks,[2] approximately the duration of a cross country season. A BSI can have devastating impacts on sports participation and negatively impact an athlete's mental health and well-being.[3,4] Therefore, identification of risk factors for BSI is vital for developing injury prevention programs, mitigating injury risk, and maintaining athlete health. Proposed risk factors for BSI include both biological and biomechanical risk factors[5]; although biological contributions are well established,[6–11] biomechanical contributions are less clear.

Running biomechanics are thought to influence BSI risk, however minimal consensus exists regarding which specific characteristics contribute to this risk. A recent meta-analysis observed a significant difference in vertical loading rate between those with and without prior BSI,[12] while others have found no relationship between any component of the ground reaction force (GRF) and BSI.[13] Spatiotemporal and kinematic metrics have also shown inconsistent associations with BSI. Reductions in stride length have been modeled to reduce tibial BSI risk,[14] while increased hip adduction[15] and tibial internal rotation[16] were observed in those with a history of tibial BSI compared to controls. However, these findings have not been corroborated prospectively.

Given the repetitive bone loads associated with distance running, bone mineral density (BMD) has also been studied in relation to BSI with varied results. Female runners with and without a history of tibial BSI showed no differences in BMD,[17] while lower leg BMD was retrospectively associated with BSI in National Collegiate Athletic Association (NCAA) Division I male endurance athletes.[18] Prospectively, lower BMD has been associated with BSI among female track athletes but not males.[19]

Varied study designs may contribute to the mixed relationships found between running biomechanics, BMD, and BSI. Limited prospective studies relating biomechanics and BMD to BSI are available; many studies assess these measures separately and following a BSI diagnosis or between those with and without a history of BSI.[13,15,20] Consequently, it is difficult to discern if differences in running mechanics and BMD between groups are a causal factor of BSIs or rather a compensation developed following a BSI. Additionally, multi-factorial assessment of these theorized risk factors may better clarify their relationships with BSI. Therefore, the purpose of this study was to determine if running biomechanics and BMD were prospectively associated with BSI occurrence in NCAA Division I cross country runners. We hypothesized biomechanical characteristics associated with greater loading (e.g. lower step rate) and lower BMD would be independently associated with BSI.

Methods

This study used three years of routinely collected health and performance data from NCAA Division 1 cross country runners in the University of Wisconsin-Madison Badger Athletic

Performance database. The study was approved by the University of Wisconsin-Madison Health Sciences Institutional Review Board. Athletes were not involved in the design or scientific conduct of this study; however, athletes and coaches received results of individual testing and were regularly informed of important scientific findings from the database. During annual pre-season assessments, running biomechanics and dual-x-ray absorptiometry (DXA) images are obtained on all cross country athletes. Data collected during the 2015-2016, 2016-2017, and 2017-2018 seasons were reviewed. An athlete's data for a given year were excluded if 1) the athlete was injured at time of testing, defined as musculoskeletal pain requiring medical attention which prevented participation in full, unrestricted training and competition; 2) the test session was not pre-season (e.g. at injury follow-up); 3) 1 year of injury follow-up was unavailable (e.g. athlete transferred after the season or left the team) or 9 months if the athlete was a graduating senior; or 4) pre-season DXA data were not available (Figure 1).

Running Mechanics Acquisition and Processing

Running assessments followed a standardized testing protocol, previously described.[21] Athletes were instructed to wear the shoes they use for the majority of their training mileage for testing. Briefly, athletes walked for at least two minutes to acclimate to the treadmill, then ran at their preferred speed, which was determined by adjusting speed until identifying a speed that the athlete indicated was representative of a typical moderate-intensity run. Data were recorded for 15 seconds after the athlete had acclimated to the speed for at least 30 seconds. Whole body kinematics were collected using 42 reflective markers placed on the body segments, 23 were located on anatomical landmarks. Markers were placed by the same researcher [MRSJ] for all data collections. A static standing position was also recorded to establish joint centers and model scaling.

Kinematic data from the running trials were recorded at 200 Hz using an 8-camera passive marker system (Motion Analysis Corporation, Santa Rosa, CA). Three-dimensional GRF was synchronously recorded at 2000 Hz using an instrumented treadmill (Bertec Corporation, Columbus, OH). Kinematic data were low-pass filtered using a bi-directional, 4th-order Butterworth filter with a cutoff frequency of 12 Hz. GRFs were low-pass filtered using a bi-directional, 3rd-order Butterworth filter with a cutoff frequency of 50 Hz. Foot contact and toe-off times were identified when the vertical GRF (VGRF) went above and fell below 50 N, respectively. The body was modeled as a 14-segment, 31 degrees-of-freedom articulated linkage. Anthropometric properties of body segments were scaled to each athlete using the individual's height, mass, and segment lengths.[22,23] For each stride, joint angles were computed using a global optimization routine, minimizing the weighted sum of squared differences between measured and modeled marker positions. Fifteen strides were analyzed on both limbs from each athlete. All processing was done using custom MATLAB processing code (MathWorks Inc., Natick, MA).

Bone Health Measures Acquisition and Processing

A GE Healthcare (Madison, WI) Lunar iDXA densitometer was used for all examinations. Total body scans were performed and analyzed by International Society for Clinical Densitometry-trained technologists, following standard clinical operating procedures based on published recommendations.[22,23] Athletes were scanned in their usual hydration state; no fasting or other limitations on their usual activities were implemented. All scans were acquired using enCORE software version 14.1 and analyzed using the auto-analysis feature. When necessary, manual correction of identification markers of the trunk, arms, and legs was completed. No estimations of tissues were acquired using the hemi-scan software feature. One physician with extensive total body DXA experience reviewed all scans to verify acquisition and analysis. Precision (% coefficient of variation) of total body DXA metrics from our center are excellent, ranging between 0.07-1.46%.[24] Body mass index (BMI) was calculated from height (stadiometer) and weight (digital scale) obtained at the time of the DXA scan.

Biomechanical Variables

Spatiotemporal biomechanical variables of interest included preferred running speed (m/s) and step rate (steps/min). Kinematic variables included foot inclination angle (FIA) with respect to the ground at initial contact, normalized to standing posture (°); horizontal distance from center of mass (COM) to heel marker (cm); COM vertical excursion over a gait cycle (cm); peak hip adduction during stance (°); and base of gait (BOG) at midstance (cm). GRF variables included peak VGRF (N/kg); impact peak (N/kg); VGRF impulse (Ns/kg); average vertical loading rate (N/kg/s); and braking impulse (Ns/kg). These variables are commonly used to assess an injured runner's mechanics and are targets of gait retraining.[25–27] Average vertical loading rate was calculated as the slope of the VGRF between 20-80% of the impact peak magnitude. The magnitude of the force at 30.79% of the time to active peak was used when the impact peak was not present.[21] Braking impulse was calculated by numerically integrating the posterior GRF.

DXA Variables

Extracted variables from DXA images included lean mass (g), total leg BMD, total body bone mineral content (BMC) and BMD, and total Z-score BMD. All BMD measurements refer to DXA-derived BMD, which is an areal calculation (aBMD). Z-scores were calculated by the enCORE software using the USA combined NHANES/Lunar population based on age-matched values adjusted for ethnicity and weight.

Outcome Variables

The primary outcome was BSI occurrence during the 12-month calendar year beginning on July 15th, coinciding with the end of NCAA National Track and Field competitions and thus the beginning of the cross country season. A BSI was defined as a stress fracture or reaction confirmed via magnetic resonance imaging by the presence of periosteal, marrow and/or cortical edema. All injuries requiring medical attention were evaluated by team physicians and prospectively monitored by team athletic trainers and reported weekly throughout the calendar year. Location of BSI, involved lower extremity (left or right side), and date of diagnosis were recorded for each BSI. History of BSI occurring prior to enrollment at our institution (e.g. BSI sustained in high school or from a different institution) was recorded based on athlete self-report and prior imaging (when available).

Statistical Analysis

Standard descriptive statistics, means (standard deviations), and frequencies (percentages) were used to describe continuous and categorical variables, respectively. Generalized Estimating Equations (GEE) for a binomial outcome with a log link were used to provide unadjusted associations between demographics, running mechanics, and DXA variables and sustaining a BSI. The modeled correlation structure accounted for both limbs and up to three years of data per athlete. The multivariable model was built by including all primary predictors of interest (z-score BMD and biomechanics variables) and using a combination of Akaike Information Criteria and backwards selection criteria, after adjusting for well-known confounders of BSI (i.e. sex and history of BSI) to determine a best-fitting model. Pairwise interactions with sex were considered for all variables. Results are reported as relative risks (RR) and 95% confidence intervals (CI). SAS v9.4 (SAS Institutes, Cary, NC) was used for all analyses.

Results

Forty-six student-athletes were listed on the cross country roster for the 2015-2016 season, 33 during the 2016-2017 season, and 40 during the 2017-2018 season. After applying exclusion criteria, 34 (74%), 26 (79%), and 31 (78%) athletes per season were included, respectively (Figure 1), resulting in 91 student-athlete years and 54 unique runners participating over the 2015-2018 school years. Females (n=33) comprised 61% of the sample (Table 1). Thirty-two BSIs were recorded on 24 unique athletes (44.4%) over the study period (Table 2). The number of athletes sustaining a BSI per year ranged from 30%-32%. Of all observed BSIs, 25% were in the sacrum, 22% each in the metatarsals and femur, and the remaining in the innominate, tibia, fibula, and navicular bones.

Univariable associations with BSI risk

When considering athlete demographics, no univariable associations between age, sex, or BMI and BSI risk were detected (Table 3). However, the risk of BSI was 2.22 times (95% CI: 1.14, 4.33) greater in athletes with a prior BSI versus those without (p=0.02). BSI risk decreased by 4% (RR 0.96, 95% CI: 0.92, 0.99) with each step/min increase in step rate. Among kinematic variables, only COM vertical excursion was associated with BSI. The risk of BSI increased by 17% (RR=1.17, 95% CI: 1.04, 1.31) for each 0.5 cm increase in COM vertical excursion (p=0.01). No GRF variables were univariably associated with BSI; however, the 95% CIs for peak VGRF (RR=1.12, 95% CI: 0.99, 1.27) and VGRF impulse (RR=1.19, 95% CI: 1.00, 1.43) suggest potential associations exist. No DXA-derived variables (e.g. BMD, BMC, lean mass) were univariably associated with BSI risk.

Multivariable associations with BSI risk

Low step rate was identified as a predictor of BSI in a multivariable model after adjusting for known BSI risk factors (history of BSI and sex). No significant interactions with sex were detected. Step rate was the only variable significantly associated with BSI risk (p=0.008). A 1 step/min increase in step rate was associated with a 5% decreased risk of BSI (RR: 0.95; 95% CI: 0.91, 0.98). Although not statistically significant, BMD z-score was an important covariate in the best-fitting model; the 95% CI suggests that larger BMD z-scores may be indicative of decreased BSI risk (RR: 0.93, 95% CI: 0.85, 1.03, unit=0.5).

Discussion

We sought to determine if running mechanics and BMD were prospectively associated with BSI incidence among collegiate cross country runners. Low step rate was identified as an independent risk factor after adjusting for sex and history of BSI, while BMD z-score was also determined to potentially influence BSI risk. Importantly, step rate was the strongest predictor of BSI risk and can be modified directly via gait training to help mitigate BSI risk. Although indirect modification of BMD is possible, it is more challenging due to multiple biological factors contributing to BMD levels (e.g. nutrition, applied loads, genetics).

Step rate

Low step rate during running at a self-selected moderate intensity speed was identified as a primary risk factor for BSI in collegiate distance runners. In this sample, runners with a higher step rate had a reduced risk of BSI during the subsequent year. A similar relationship with shin pain has also been shown among high school cross country runners.[26]

The association of step rate with other biomechanical variables may explain its inclusion in the final model over other possible predictors. Although direct measures of bone-loading were not measured, step rate may indirectly influence tissue-level loads, resulting in the observed association between step rate and BSI. The influence of step rate on measures of loading, including GRFs, may also explain why these measures fell out of the final model despite observed univariable associations. Although peak VGRF, VGRF impulse, and COM vertical excursion each demonstrated univariable associations, these variables are strongly associated with each other and step rate.[28,29] Inclusion of step rate in the final model indicates it is the stronger risk factor for BSI and likely captures changes associated with other biomechanical measures and BSI risk. This may explain the lack of significance identified among GRF variables.

Bone Mineral Density

Despite not reaching statistical significance, AIC values suggested BMD z-score as an important covariate in the final, best-fitting model. The 95% CI suggests higher BMD z-scores may reduce BSI risk (RR: 0.93, 95% CI: 0.85, 1.03); however, thorough assessment of this association may have been underpowered given the relative homogeneity of the study sample. Our conclusion is consistent with prior work that found female track and field athletes who developed stress fractures had reduced total body BMD.[19] This relationship appears to be greatest for trabecular-rich sites (i.e. calcaneus, femoral neck, sacrum, and innominate)-particularly for BMD measured in the lumbar spine,[32,33] which accounted for over 30% of the BSIs in our study. A larger, more diverse sample and inclusion of site-specific scans of the hip and lumbar spine may strengthen our findings.

Loading Rate and Foot Inclination Angle

Importantly, an association between average vertical loading rate and FIA with BSI was not detected, despite these often being suggested as primary markers of running injury risk. A meta-analysis of cross-sectional and retrospective studies concluded loading rate is higher in individuals with a history of tibial BSI.[12] However, prospective, causal associations cannot be determined with the included study designs. A subsequent prospective study of female recreational runners found loading rate to be significantly greater in those who self-reported injuries compared to those with no injury history.[34] However, this study was not specific to BSI and lacked injury confirmation through medical record review. Additionally, mechanical models of fatigue on cortical bone samples suggest impact-related loading rates during running have little influence on mechanical fatigue.[35] Thus, the relationship between impact peak, average vertical loading rate, and BSI should be reassessed.

Although foot-strike modification is often suggested to reduce BSI risk, we did not identify FIA as an independent risk factor for BSI. FIA is a continuous measure of foot-strike that more accurately captures the underlying non-linear relationship with loading rate than does categorical foot-strike (i.e. forefoot, midfoot, heel).[21] While loading rate can differ with foot-strike, our findings indicate that neither are primary BSI risk factors.

Application of findings to clinical care

Step rate is a clinically modifiable risk factor and our findings suggest small changes in step rate can have substantial effects on BSI risk. Indeed, an increase of only 1 step/min was associated with a 5% decrease in risk. Runners have successfully increased step rate up to 18 steps/min following a few weeks of training sessions involving cueing and feedback. [30,36,37] However, this magnitude of change may not be necessary to reduce injury risk. Runners may experience meaningful reductions in BSI risk with subtle, attainable increases in step rate. Given the relatively high incidence of BSI in this cohort (30%-32% per year), adjustments in step rate should be considered as one potential means to reduce BSI risk within our athletic program.

Given the majority of collegiate athletes are still in the accrual period for BMD,[38] careful attention to indirect BMD modifiers is warranted, including diet, nutrition,[10,38] and mechanical loading (i.e. mode, duration, and intensity of exercise).[39,40] Proper monitoring accompanied by corrective intervention, especially in athletes presenting with oligomenorrhea/amenorrhea or disordered eating, may also result in reduced BSI risk in collegiate runners.

Limitations

To our knowledge, this is the first study to prospectively describe the relationship of running biomechanics, BMD, and risk of BSI; however, there are some limitations. BMD was not measured in the lumbar spine, which may partially explain the lack of significant association identified with BSI risk. Running mechanics in racing flats or spikes worn for competition may differ from the mechanics measured in training shoes. Some variation in running mechanics may exist between treadmill and overground running, although a recent meta-analysis found spatiotemporal running mechanics to be comparable.[41] Unfortunately, we were unable to account for additional factors known to influence BSI risk, such as oligomenorrhea/amenorrhea or disordered eating[8,42] as we only began collecting these data at our institution recently. Training characteristics were also not captured in this study; however, there is limited evidence that running mileage, duration, frequency, or pace affect BSI risk.[43] Due to the limited sample size and number of observed BSIs, we were unable to assess associations by BSI location. Of note, the athletes were all from the same cross country program with the same coaches throughout the study period. Given the high-level of athletes in our study, our findings may not be generalizable to distance runners outside of the collegiate setting.

Conclusion

Low step rate was identified as an independent risk factor for BSI after adjusting for sex and history of BSI, and BMD z-score may also influence risk. These risk factors are clinically meaningful as small increases in step rate are attainable and may significantly influence BSI risk. Thus, monitoring step rate, along with BMD and its related factors, may be worthwhile as part of a comprehensive program to treat and prevent BSIs in collegiate runners.

Acknowledgements:

The authors would like to acknowledge the Sports Medicine staff in the University of Wisconsin-Madison Division of Athletics for their commitment to the welfare of the student athletes and contributions to the Badger Athletic Performance program.

References

1. Rizzone KH, Ackerman KE, Roos KG, et al. The Epidemiology of Stress Fractures in Collegiate Student-Athletes, 2004-2005 Through 2013-2014 Academic Years. Journal of athletic training 2017;52(10):966–75. doi: 10.4085/1062-6050-52.8.01 [published Online First: 2017/09/25] [PubMed: 28937802]
2. Miller TL, Jamieson M, Everson S, et al. Expected Time to Return to Athletic Participation After Stress Fracture in Division I Collegiate Athletes. Sports health 2018;10(4):340–44. doi: 10.1177/1941738117747868 [published Online First: 2017/12/15] [PubMed: 29240544]
3. Houston MN, Hoch JM, Van Lunen BL, et al. The Impact of Injury on Health-Related Quality of Life in College Athletes. Journal of sport rehabilitation 2017;26(5):365–75. doi: 10.1123/jsr.2016-0011 [published Online First: 2016/09/17] [PubMed: 27632873]
4. Valovich McLeod TC, Bay RC, Parsons JT, et al. Recent injury and health-related quality of life in adolescent athletes. Journal of athletic training 2009;44(6):603–10. doi: 10.4085/1062-6050-44.6.603 [published Online First: 2009/11/17] [PubMed: 19911086]
5. Tenforde AS, Kraus E, Fredericson M. Bone Stress Injuries in Runners. Physical medicine and rehabilitation clinics of North America 2016;27(1):139–49. doi: 10.1016/j.pmr.2015.08.008 [published Online First: 2015/12/01] [PubMed: 26616181]
6. Barrack MT, Gibbs JC, De Souza MJ, et al. Higher incidence of bone stress injuries with increasing female athlete triad-related risk factors: a prospective multisite study of exercising girls and women. The American journal of sports medicine 2014;42(4):949–58. doi: 10.1177/0363546513520295 [published Online First: 2014/02/26] [PubMed: 24567250]
7. Kelsey JL, Bachrach LK, Procter-Gray E, et al. Risk factors for stress fracture among young female cross-country runners. Medicine and science in sports and exercise 2007;39(9): 1457–63. doi: 10.1249/mss.0b013e318074e54b [published Online First: 2007/09/07] [PubMed: 17805074]
8. Kraus E, Tenforde AS, Nattiv A, et al. Bone stress injuries in male distance runners: higher modified Female Athlete Triad Cumulative Risk Assessment scores predict increased rates of injury. British

journal of sports medicine 2019;53(4):237–42. doi: 10.1136/bjsports-2018-099861 [published Online First: 2018/12/24] [PubMed: 30580252]

9. Nattiv A, Loucks AB, Manore MM, et al. American College of Sports Medicine position stand. The female athlete triad. Medicine and science in sports and exercise 2007;39(10): 1867–82. doi: 10.1249/mss.0b013e318149f111 [published Online First: 2007/10/03] [PubMed: 17909417]
10. Nieves JW, Melsop K, Curtis M, et al. Nutritional factors that influence change in bone density and stress fracture risk among young female cross-country runners. PM & R : the journal of injury, function, and rehabilitation 2010;2(8):740–50; quiz 94. doi: 10.1016/j.pmrj.2010.04.020 [published Online First: 2010/08/17]
11. Tenforde AS, Carlson JL, Sainani KL, et al. Sport and Triad Risk Factors Influence Bone Mineral Density in Collegiate Athletes. Medicine and science in sports and exercise 2018;50(12):2536–43. doi: 10.1249/mss.0000000000001711 [published Online First: 2018/07/06] [PubMed: 29975299]
12. van der Worp H, Vrielink JW, Bredeweg SW. Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis. British journal of sports medicine 2016;50(8):450–7. doi: 10.1136/bjsports-2015-094924 [published Online First: 2016/01/06] [PubMed: 26729857]
13. Bennell K, Crossley K, Jayarajan J, et al. Ground reaction forces and bone parameters in females with tibial stress fracture. Medicine and science in sports and exercise 2004;36(3):397–404. doi: 10.1249/01.mss.0000117116.90297.e1 [published Online First: 2004/04/13] [PubMed: 15076780]
14. Edwards WB, Taylor D, Rudolphi TJ, et al. Effects of stride length and running mileage on a probabilistic stress fracture model. Medicine and science in sports and exercise 2009;41(12):2177–84. doi: 10.1249/MSS.0b013e3181a984c4 [published Online First: 2009/11/17] [PubMed: 19915501]
15. Pohl MB, Mullineaux DR, Milner CE, et al. Biomechanical predictors of retrospective tibial stress fractures in runners. Journal of biomechanics 2008;41(6):1160–5. doi: 10.1016/j.jbiomech.2008.02.001 [published Online First: 2008/04/02] [PubMed: 18377913]
16. Nunns M, House C, Rice H, et al. Four biomechanical and anthropometric measures predict tibial stress fracture: a prospective study of 1065 Royal Marines. British journal of sports medicine 2016;50(19):1206–10. doi: 10.1136/bjsports-2015-095394 [published Online First: 2016/01/10] [PubMed: 26746906]
17. Popp KL, McDermott W, Hughes JM, et al. Bone strength estimates relative to vertical ground reaction force discriminates women runners with stress fracture history. Bone 2017;94:22–28. doi: 10.1016/j.bone.2016.10.006 [published Online First: 2016/11/03] [PubMed: 27729292]
18. Carbuhn AF, Sanchez Z, Fry AC, et al. A Simplified Prediction Model for Lower Extremity Long Bone Stress Injuries in Male Endurance Running Athletes. Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine 2020;30(5):e124–e26. doi: 10.1097/jsm.0000000000000661 [published Online First: 2018/09/01] [PubMed: 30169347]
19. Bennell KL, Malcolm SA, Thomas SA, et al. Risk factors for stress fractures in track and field athletes. A twelve-month prospective study. The American journal of sports medicine 1996;24(6):810–8. doi: 10.1177/036354659602400617 [published Online First: 1996/11/01] [PubMed: 8947404]
20. Meardon SA, Willson JD, Gries SR, et al. Bone stress in runners with tibial stress fracture. Clinical biomechanics (Bristol, Avon) 2015;30(9):895–902. doi: 10.1016/j.clinbiomech.2015.07.012 [published Online First: 2015/08/19]
21. Stiffler-Joachim MR, Wille CM, Kliethermes SA, et al. Foot Angle and Loading Rate during Running Demonstrate a Nonlinear Relationship. Medicine and science in sports and exercise 2019;51(10):2067–72. doi: 10.1249/mss.0000000000002023 [published Online First: 2019/09/17] [PubMed: 31525170]
22. Libber J, Binkley N, Krueger D. Clinical observations in total body DXA: technical aspects of positioning and analysis. Journal of clinical densitometry : the official journal of the International Society for Clinical Densitometry 2012;15(3):282–9. doi: 10.1016/j.jocd.2011.12.003 [published Online First: 2012/02/11] [PubMed: 22321660]
23. Petak S, Barbu CG, Yu EW, et al. The Official Positions of the International Society for Clinical Densitometry: body composition analysis reporting. Journal of clinical densitometry : the official

journal of the International Society for Clinical Densitometry 2013;16(4):508–19. doi: 10.1016/j.jocd.2013.08.018 [published Online First: 2013/11/05] [PubMed: 24183640]

24. Buehring B, Krueger D, Libber J, et al. Dual-energy X-ray absorptiometry measured regional body composition least significant change: effect of region of interest and gender in athletes. Journal of clinical densitometry : the official journal of the International Society for Clinical Densitometry 2014;17(1):121–8. doi: 10.1016/j.jocd.2013.02.012 [published Online First: 2013/05/07] [PubMed: 23643968]
25. Johnson CD, Tenforde AS, Outerleys J, et al. Impact-Related Ground Reaction Forces Are More Strongly Associated With Some Running Injuries Than Others. The American journal of sports medicine 2020;48(12):3072–80. doi: 10.1177/0363546520950731 [published Online First: 2020/09/12] [PubMed: 32915664]
26. Luedke LE, Heiderscheit BC, Williams DS, et al. Influence of Step Rate on Shin Injury and Anterior Knee Pain in High School Runners. Medicine and science in sports and exercise 2016;48(7): 1244–50. doi: 10.1249/mss.0000000000000890 [published Online First: 2016/01/29] [PubMed: 26818150]
27. Napier C, MacLean CL, Maurer J, et al. Kinetic risk factors of running-related injuries in female recreational runners. Scandinavian journal of medicine & science in sports 2018;28(10):2164–72. doi: 10.1111/sms.13228 [published Online First: 2018/05/31] [PubMed: 29846979]
28. Heiderscheit BC, Chumanov ES, Michalski MP, et al. Effects of step rate manipulation on joint mechanics during running. Medicine and science in sports and exercise 2011;43(2):296–302. doi: 10.1249/MSS.0b013e3181ebedf4 [published Online First: 2010/06/29] [PubMed: 20581720]
29. Wille CM, Lenhart RL, Wang S, et al. Ability of sagittal kinematic variables to estimate ground reaction forces and joint kinetics in running. The Journal of orthopaedic and sports physical therapy 2014;44(10):825–30. doi: 10.2519/jospt.2014.5367 [published Online First: 2014/08/27] [PubMed: 25156183]
30. Willy RW, Buchenic L, Rogacki K, et al. In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. Scandinavian journal of medicine & science in sports 2016;26(2):197–205. doi: 10.1111/sms.12413 [published Online First: 2015/02/06] [PubMed: 25652871]
31. Yong JR, Silder A, Montgomery KL, et al. Acute changes in foot strike pattern and cadence affect running parameters associated with tibial stress fractures. Journal of biomechanics 2018;76:1–7. doi: 10.1016/j.jbiomech.2018.05.017 [published Online First: 2018/06/06] [PubMed: 29866518]
32. Nattiv A, Kennedy G, Barrack MT, et al. Correlation of MRI grading of bone stress injuries with clinical risk factors and return to play: a 5-year prospective study in collegiate track and field athletes. The American journal of sports medicine 2013;41(8):1930–41. doi: 10.1177/0363546513490645 [published Online First: 2013/07/05] [PubMed: 23825184]
33. Tenforde AS, Parziale AL, Popp KL, et al. Low Bone Mineral Density in Male Athletes Is Associated With Bone Stress Injuries at Anatomic Sites With Greater Trabecular Composition. The American journal of sports medicine 2018;46(1):30–36. doi: 10.1177/0363546517730584 [published Online First: 2017/10/07] [PubMed: 28985103]
34. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. British journal of sports medicine 2016;50(14):887–92. doi: 10.1136/bjsports-2015-094579 [published Online First: 2015/12/09] [PubMed: 26644428]
35. Loundagin LL, Schmidt TA, Edwards WB. Mechanical Fatigue of Bovine Cortical Bone Using Ground Reaction Force Waveforms in Running. Journal of biomechanical engineering 2018;140(3):0310031–5. doi: 10.1115/1.4038288 [published Online First: 2017/10/29]
36. Hafer JF, Brown AM, deMille P, et al. The effect of a cadence retraining protocol on running biomechanics and efficiency: a pilot study. Journal of sports sciences 2015;33(7):724–31. doi: 10.1080/02640414.2014.962573 [published Online First: 2014/11/05] [PubMed: 25369525]
37. Wille C, Chumanov E, Steingraver K, et al. STEP-RATE-MODIFICATION TRAINING WHILE RUNNING: OPO3226 [Abstract]. Journal of Orthopaedic & Sports Physical 2013;43(1)
38. Sale C, Elliott-Sale KJ. Nutrition and Athlete Bone Health. Sports medicine (Auckland, NZ) 2019;49(Suppl 2):139–51. doi: 10.1007/s40279-019-01161-2 [published Online First: 2019/11/07]

39. Kelley GA, Kelley KS, Kohrt WM. Exercise and bone mineral density in premenopausal women: a meta-analysis of randomized controlled trials. International journal of endocrinology 2013;2013:741639. doi: 10.1155/2013/741639 [published Online First: 2013/02/13] [PubMed: 23401684]

40. Skerry TM. The response of bone to mechanical loading and disuse: fundamental principles and influences on osteoblast/osteocyte homeostasis. Archives of biochemistry and biophysics 2008;473(2):117–23. doi: 10.1016/j.abb.2008.02.028 [published Online First: 2008/03/13] [PubMed: 18334226]

41. Van Hooren B, Fuller JT, Buckley JD, et al. Is Motorized Treadmill Running Biomechanically Comparable to Overground Running? A Systematic Review and Meta-Analysis of Cross-Over Studies. Sports medicine (Auckland, NZ) 2020;50(4):785–813. doi: 10.1007/s40279-019-01237-z [published Online First: 2019/12/06]

42. Tenforde AS, Carlson JL, Chang A, et al. Association of the Female Athlete Triad Risk Assessment Stratification to the Development of Bone Stress Injuries in Collegiate Athletes. The American journal of sports medicine 2017;45(2):302–10. doi: 10.1177/0363546516676262 [published Online First: 2016/12/31] [PubMed: 28038316]

43. Hulme A, Nielsen RO, Timpka T, et al. Risk and Protective Factors for Middle- and Long-Distance Running-Related Injury. Sports medicine (Auckland, NZ) 2017;47(5):869–86. doi: 10.1007/s40279-016-0636-4 [published Online First: 2016/10/28]

What are the new Findings?

- Step rate was prospectively determined to be the strongest biomechanics predictor of bone stress injury (BSI) among common measures of running mechanics.
- Although peak vertical ground reaction force and impulse have been associated with BSI risk, step rate (which is highly associated with these ground reaction force metrics) may effectively capture their influence on BSI risk.
- A low bone minderal density (BMD) in combination with a low step rate were most influential in prediction of BSI risk.
- Average vertical loading rate and foot inclination angle were not associated with BSI risk.

How might it impact on clinical practice in the near future

- Low step rate is an important predictor of bone stress injury (BSI) in collegiate cross country runners; each one step/min increase in step rate is associated with a 5% decrease in BSI risk.
- While not directly tested in this study, step rate can be modified with gait retraining and may reduce BSI risk.
- Foot strike modification may not be an effective approach for reducing BSI risk in distance runners.

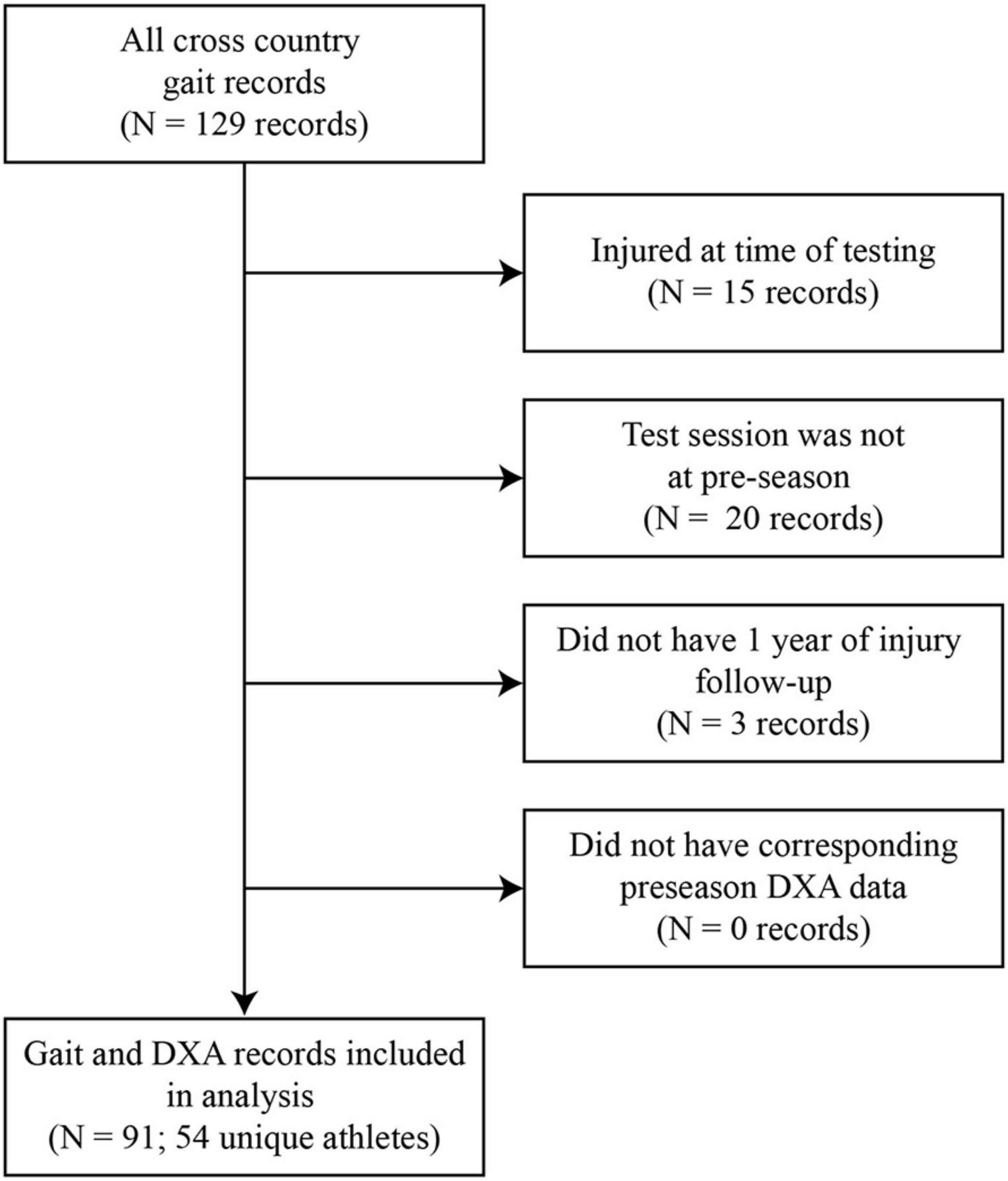

Figure 1.

Flowchart showing process used to select records included in this study. DXA: Dual x-ray absorptiometry.

Table 1:

Participant Characteristics, Running Mechanics and BMD at baseline[a]

Baseline Characteristics	**Male (n=21)**	**Female (n=33)**	**Overall (n=54)**
Demographic			
Age (yr)	19.7 (1.2)	19.4 (1.4)	19.5 (1.3)
Body Mass Index (kg/m^2)	20.7 (1.3)	20.1 (1.9)	20.3 (1.7)
History of BSI (n)	6 (29%)	12 (36%)	18 (33%)
Spatiotemporal Variables			
Preferred Speed (m/s)	4.12 (0.20)	3.70 (0.18)	3.87 (0.28)
Step Rate (steps/min)	170.4 (6.6)	175.8 (9.0)	173.7 (8.5)
Kinematic Variables			
Foot Inclination Angle (°)	−0.2 (6.8)	4.6 (7.5)	2.7 (7.5)
Horizontal Distance from COM to Heel (cm)	11.2 (2.9)	12.9 (2.5)	12.2 (2.7)
COM Vertical Excursion (cm)	10.2 (1.0)	9.0 (1.3)	9.5 (1.3)
Peak Hip Adduction during Stance (°)	12.2 (2.0)	13.2 (3.4)	12.8 (3.0)
Base of Gait at Midstance (cm)	−0.7 (1.4)	1.1 (1.6)	0.4 (1.7)
GRF Variables			
Peak Vertical GRF (N/kg)	27.8 (1.7)	24.7 (2.4)	25.9 (2.6)
Impact Peak (N/kg)	18.9 (4.3)	16.3 (2.5)	17.2 (3.3)
Average Vertical Loading Rate (N/kg/s)	970.6 (356.6)	846.1 (239.1)	894.5 (293.7)
Vertical GRF Impulse (Ns/kg)	3.44 (0.14)	3.32 (0.18)	3.36 (0.17)
Braking Impulse (Ns/kg)	−0.22 (0.02)	−0.22 (0.02)	−0.22 (0.02)
DXA Variables			
Total Leg BMD (g/cm^2)	1.423 (0.143)	1.282 (0.099)	1.337 (0.136)
Total Body BMD (g/cm^2)	1.223 (0.105)	1.163 (0.085)	1.186 (0.097)
BMD Z-Score	0.36 (0.91)	0.88 (0.98)	0.67 (0.98)
Total Body BMC (g)	3055.23 (369.19)	2444.04 (254.04)	2681.73 (425.27)
Whole Body Lean Mass (g)	56469.19 (5044.60)	42467.85 (3605.19)	47912.81 (8057.21)

BMC, bone mineral content; BMD, bone mineral density; BSI, bone stress injury; COM, center of mass; GRF, ground reaction force

[a] Baseline values represent first year of available data for each athlete

Table 2:

Bone Stress Injury (BSI) Incidence and Location, n(%)

Injury Characteristics	**Male**	**Female**	**Overall**
Number of Injured Athletes	11 (46%)	13 (54%)	24
Number of BSI	15	17	32
BSI Location			
Sacrum	2 (13%)	6 (35%)	8 (25%)
Innominate	1 (7%)	1 (6%)	2 (6%)
Femur	3 (20%)	4 (24%)	7 (22%)
Tibia	1 (7%)	1 (6%)	2 (6%)
Fibula	3 (20%)	0	3 (9%)
Navicular	1 (7%)	2 (12%)	3 (9%)
Sesamoid	0	0	0
Metatarsal	4 (27%)	3 (18%)	7 (22%)

Table 3:

Univariable Generalized Estimating Equations for Potential Risk Factors of BSI[a, b]

Variable[c]	**RR (95% CI)**	**p-value**
Demographic Characteristics		
Age (yr)	0.83 (0.65, 1.08)	0.17
Sex (Female vs Male)	0.97 (0.50, 1.88)	0.93
Body Mass Index (kg/m^2)	0.97 (0.78, 1.21)	0.81
History of BSI	2.22 (1.14, 4.33)	0.02
Spatiotemporal Variables		
Preferred Speed (m/s) (unit=0.5)	1.29 (0.63, 2.64)	0.48
Step Rate (steps/min)	0.96 (0.92, 0.99)	0.03
Kinematic Variables		
Foot Inclination Angle at initial contact(°)	1.00 (0.96, 1.04)	0.92
Horizontal Distance from COM to Heel Marker (cm)	1.02 (0.91, 1.13)	0.77
COM Vertical Excursion (cm) (unit=0.5)	1.17 (1.04, 1.31)	0.01
Peak Hip Adduction during Stance (°)	0.95 (0.85, 1.06)	0.37
Base of Gait at Midstance (cm)(unit=0.5)	0.93 (0.85, 1.01)	0.10
GRF Variables		
Peak Vertical GRF (N/kg)	1.12 (0.99, 1.27)	0.08
Impact Peak (N/kg)	1.03 (0.93, 1.15)	0.54
Average Vertical Loading Rate (N/kg/s) (unit=100)	1.00 (0.89, 1.11)	0.95
Vertical GRF Impulse (Ns/kg) (unit=0.1)	1.19 (1.00, 1.43)	0.06
Braking Impulse (Ns/kg) (unit=0.05)	0.52 (0.11, 2.48)	0.41
DXA Variables		
Total Leg BMD (g/cm^2) (unit=0.1)	0.87 (0.68, 1.12)	0.27
Total Body BMD (g/cm^2) (unit=0.1)	0.79 (0.57, 1.10)	0.16
BMD Z-score (unit=0.5)	0.91 (0.77, 1.08)	0.29
Total Body BMC(g) (unit=100)	0.98 (0.91, 1.05)	0.50
Whole Body Lean Mass (g) (unit=1000)	0.99 (0.96, 1.03)	0.76

BMC, bone mineral content; BMD, bone mineral density; BSI, bone stress injury; CI, confidence interval; COM, center of mass; GRF, ground reaction force; RR, relative risk

[a] Models were performed separately for each variable of interest.

[b] Models accounted for repeated measures with subject. Females were the reference group for sex.

[c] Unit represents the unit increase used for interpretation of relative risk and 95% CI. Unit=1 if not otherwise specified.

Table 4:

Multivariable Marginal Generalized Estimating Equation model for potential risk factors of BSI[a]

Variable[b]	**Relative Risk (95% CI)**	**p-value**
Step Rate (steps/min)	0.95 (0.91, 0.98)	0.008
BMD Z-Score (unit= 0.5)	0.93 (0.85, 1.03)	0.16

BMD, bone mineral density; BSI, bone stress injury; CI, confidence interval

[a] Model adjusted for history of BSI (p=0.07) and sex (p=0.23). Additionally, the model covariance structure accounted for repeated measures among individuals. The final model was selected using a combination of backward selection and Akaike information criterion.

[b] Unit represents the unit increase used for interpretation of relative risk and 95% CI. Unit=1 if not otherwise specified.