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# Vertical Loading Rate Is not Associated with Running Injury, Regardless of Calculation Method

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## Abstract

**Introduction:** Loading rate (LR), the slope of the vertical ground reaction force (vGRF), is commonly used to assess running-related injury risk. However, the relationship between LR and running-related injuries, including bone stress injuries (BSI), is unclear. Inconsistent findings may result from the numerous LR calculation methods that exist and their application across different running speeds.

**Purpose:** Assess the influence of calculation method and running speed on LR values and determine the association of LR during healthy running with subsequent injury.

**Methods:** Healthy preseason running data and subsequent injury records from Division I cross country athletes (n = 79) over four seasons (2015–2019) at 2.68 m/s, preferred training pace, and 4.47 m/s were collected. LR at each speed was calculated four ways: 1) maximum and 2) average slope from 20–80% of vGRF magnitude at impact peak (IP), 3) average slope from initial contact to IP, and 4) average slope from 3–12% of stance time. Linear mixed effects models and generalized estimation equations were used to assess LR associations.

**Results:** LR values differed depending on speed and calculation method (p-value < 0.001). The maximum slope from 20–80% of the vGRF at 4.47 m/s produced the highest LR estimate and the average slope from initial contact to IP at 2.68 m/s produced the lowest. Sixty-four injuries (20 BSI) were observed. No significant association was found between LR and all injuries or BSI across any calculation method (p-values ≥ 0.13).

**Conclusions:** Calculation method and running speed result in significantly different LR values. Regardless of calculation method, no association between LR and subsequent injury was identified. Thus, healthy baseline LR may not be useful to prospectively assess running-related injury risk.

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Conflict of Interest:
All authors declare no conflicts of interest. The results of the present study do not constitute endorsements by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

**Keywords**

BONE STRESS INJURY; CROSS COUNTRY; GAIT; BIOMECHANICS

## INTRODUCTION

Loading rate (LR), calculated from the slope of the vertical ground reaction force (vGRF) over a specified period of time, is a common parameter used to evaluate running-related injury risk. The derived LR value represents the rate at which the acceleration of whole body center of mass changes immediately following initial contact (IC). Despite vGRF being only one of the many forces contributing to the complex internal loading patterns associated with injury, LR is often used as a simplified measure of this loading. However, the role of LR in running-related injuries is unclear, with some studies demonstrating an association between high LR and injury (1–3), particularly bone stress injuries (BSI) (4–6), and others finding no relationship (7–10). Inconsistent findings regarding the association of LR and injury may be related to the varying methods used to calculate LR, data collections occurring at different running speeds, and study design limitations.

Although all LR calculation methods report a rate of vGRF change during the loading portion of the gait cycle (initial contact to peak knee flexion), the specific region over which the rate is estimated differs. Typically, the LR calculation region is identified with respect to distinct features in the vGRF trace such as IC and impact peak (IP) (3, 4, 11), the local maximum in the vGRF prior to peak vGRF. However, a distinct IP is not always present and in these instances IP location is often estimated based on stance time (12), time to active peak (13), or the high frequency component of the vGRF (14). To avoid these estimations, some methods instead identify a specific portion of time between IC and toe-off in which to calculate LR (15–17). For the identified LR region, some studies will take the average vGRF slope over the entire region while others will only record the maximum, instantaneous slope.

Furthermore, running speed is known to influence LR (18, 19), thus the potential interaction between speed and calculation method must also be considered. The significance of the relationship between LR and speed, and how it holds across calculation methods is not well understood. It is not clear whether LR substantially differs between the varying calculation methods, or with speed, and whether the calculation method used ultimately influences the relationship between LR and injury.

Research linking high LR and injury has been largely based on retrospective studies (2, 4, 20), making it difficult to determine whether the observed running mechanics were the cause or result of injury. Interestingly, a majority of retrospective studies have found an association between LR and injury (2, 4, 20) whereas a majority of prospective studies have not (7–10). Amongst studies that found an association, conflicting conclusions have been drawn with some finding an association when all injury types are considered together (2), other studies only finding an association with BSI (5), specifically tibial stress fractures (4, 6), but clear trends were not apparent in other specific injuries such as tendinopathy, anterior knee pain, or iliotibial band syndrome (5). Inconsistent findings across studies may be due in part to each using a different LR calculation method.

Thus, despite the common practice of using LR to predict running-related injury risk, several uncertainties remain. Therefore, the first aim of this study was to assess the influence of LR calculation method and running speed on LR values. The second aim was to determine the association of LR during healthy baseline running with subsequent running-related injury, and if any particular method of LR calculation was more associated with prospective injury. Study findings will indicate which, if any, LR calculation method is best suited for prospectively evaluating running injury risk. We hypothesized LR calculation method and running speed would influence LR values, with LR increasing with running speed, and that the calculation method would influence the association of LR and injury.

# METHODS

## Participants

This study analyzed routinely collected preseason running gait data from healthy NCAA Division I cross country athletes in the University of Wisconsin-Madison Badger Athletic Performance database from 2015 to 2019. The records review was approved by the University's Health Sciences Institutional Review Board. During annual preseason assessments, running biomechanics were obtained on all cross country athletes. Data collected during the 2015–2016, 2016–2017, 2017–2018, and 2018–2019 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 or competition; (2) the test session was not preseason (e.g. 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) the in-season injury sustained was a low back injury.

## Data Acquisition

Ground reaction forces at running speeds of 2.68m/s, preferred training pace, and 4.47m/s were recorded using an instrumented treadmill (Bertec Corporation, Columbus, OH) at 2000 Hz. To acclimate to the treadmill and test setup, athletes walked on the treadmill for a minimum of 2 minutes. Treadmill speed was then increased to the different target speeds (2.68 m/s, preferred speed, 4.47 m/s) at which the athlete ran for at least 30 seconds before a 15 second recording was taken. Preferred training pace varied by athlete and was defined as the running speed the athlete indicated represented the moderate-intensity training pace at which they performed most of their training. Ground reaction forces were low-pass filtered using a bi-directional, third-order Butterworth filter with a cutoff frequency of 50Hz. Foot contact and toe-off times were identified as the instant when the vGRF went above and below 50N, respectively (21).

## Injury Monitoring

Athletes were followed for injury over the duration of the ensuing cross country season. The season was defined as two weeks before and after the first and last competitive meet, respectively. All injuries requiring medical attention were prospectively monitored by team athletic trainers and reported weekly. For this study, an injury was defined as reduced training for ≥7 days due to pelvis or lower extremity pain (22). A BSI was defined as a stress fracture or reaction confirmed via MRI by the presence of periosteal, marrow, and/or cortical edema. Although several athletes had multiple injuries or BSI within the season, only injury characteristics from the first injury and/or first BSI were reported.

## Loading Rate Calculation Methods

Vertical LR at each speed was calculated four ways: 1) the maximum (instantaneous) slope from 20–80% of the vGRF magnitude at IP and 2) average slope from 20–80% of the vGRF magnitude at IP (23), 3) the average slope from IC to IP (11), and 4) the average slope from 3–12% of stance time (17) (Figure 1A). When a stride did not contain an IP, IP location was estimated based on the average of all IP locations identified for the athlete's left limb for that particular speed. When an athlete had no identified IPs during a collection, IP location was estimated to occur at 30.79% of stance time to active peak (AP) (13) (Figure 1B) for each stride in the collection (See Table, Supplemental Digital Content 1, SDC 1, for a linear mixed effects model comparison of different IP location estimation methods). Methods 1, 2, and 3 required identification of an IP.

For all athletes LR was calculated using data from the left limb within the 15 second period of data collection (approximately 20 strides) at each speed. LR values were then averaged across strides within each condition. All LR calculations were done using custom processing code (MATLAB 2018a, MathWorks, Natick, Massachusetts, USA).

## Statistical Analysis

Standard descriptive statistics were used to describe the study sample. Means (standard deviations) and frequencies (percentages) were used to describe continuous and categorical variables, respectively. Linear mixed effects (LME) models were used to determine if LR calculation method, speed at which an athlete ran, or the interaction between LR calculation method and speed demonstrated a significant association with the calculated LR value. To account for repeated years of athlete data, athlete was included as a random effect. Meaningful pairwise comparisons of LR methods at each speed were conducted using Tukey's adjustment for multiple comparisons and results were reported as least square means and 95% confidence intervals (CI).

Generalized estimating equations (GEE) for a binomial outcome with a logit link were used to assess associations between LR during healthy baseline running at preferred speed with subsequent lower extremity injury or BSI for each LR calculation method. Separate GEE models were created to assess the influence of each LR calculation method on all running-related lower extremity and pelvis injuries. In this analysis, runners who sustained an in-season injury were compared to those who remained healthy. Similarly, as BSI have shown a potential relationship with LR, separate GEE models compared athletes who sustained a BSI during the season to those who did not. In all models, self-selected preferred training pace was controlled for. Results are reported as odds ratios (OR) and 95% CIs. An OR > 1.0 indicates an increase in the odds of sustaining an in-season injury and an OR < 1.0 indicates a decrease in the odds of sustaining an injury (24). Models were compared using Quasi-Information Criterion (QIC) values (25), with lower QICs by at least 2 points indicating a better fitting model. An exchangeable correlation structure accounted for up to 4 years of data per athlete. SAS V.9.4 (SAS Institutes, Cary, North Carolina) was used for all statistical analyses.

## RESULTS

One-hundred and thirty-nine cross country athlete records (79 unique athletes) met the eligibility criteria and were included in the final dataset (Figure 2). Women comprised 57% (n = 45) of the sample (Table 1). A total of 64 lower extremity injuries and 20 BSI were recorded. Lower extremity running-related injuries were most prevalent in the pelvis and hip (n=16; 25.0%), while BSIs were most prevalent in the femur (n=6; 30.0%). Muscle injuries (n = 19; 28.1%) were the most common initial in-season injury sustained (Table 2). Unadjusted means and standard deviations of LR values calculated across all athletes using each method at preferred speed are reported in a supplementary table (Table, Supplemental Digital Content 2, SDC 2, Descriptive characteristics of loading rates). Gait collections with no IPs present at 2.68m/s, preferred speed, and 4.47m/s comprised 36.0%, 28.1%, and 22.4% (n = 50, 39, 30) of the sample, respectively (Table, Supplemental Digital Content 3, SDC 3, Descriptive characteristics of impact peak incidence for the left limb during gait collection).

### Effect of Calculation Method and Running Speed on Loading Rate Values

A significant interaction between calculation method and speed was identified ($p<0.001$). LR values were highest (1210.1 N/kg/s; 95% CI: 1160.3, 1259.9) when calculated as the maximum slope between 20–80% of the vGRF magnitude at IP while running at the fastest speed (4.47 m/s). The lowest LR values (398.4 N/kg/s; 95% CI: 348.9, 448.0) occurred using the average slope from IC to IP of the vGRF trace at the slowest speed (2.68 m/s) (Table 3). All meaningful pairwise comparisons identified significant differences in LR values between all combinations of calculation method within the same speed, except for comparing LR values calculated using the average slope from IC to IP to the average slope from 3–12% of stance ($p = 1.00$) (Table 4).

### Effect of Loading Rate on Running-Related Injury

No significant association was found between LR and subsequent injury across any of the methods used to calculate LR (max slope 20–80% vGRF at IP OR=0.99 (95% CI: 0.88, 1.12), p=0.92; average slope 20–80% vGRF at IP OR=0.99 (95% CI: 0.88–1.12), p=0.89; average slope IC to IP OR=0.99 (95% CI: 0.79, 1.24), p=0.92; average slope 3–12% of stance OR=1.13 (95% CI: 0.91, 1.39), p=0.26). QIC values demonstrated no meaningful difference across models (range = 197.7–198.7) (Table 5). Similarly, no significant association was found between LR and subsequent BSI across any of the methods used to calculate LR (max slope 20–80% vGRF at IP OR 1.01 (95% CI: 0.88, 1.15), p=0.86; average slope 20–80% vGRF at IP OR=1.01 (95% CI: 0.89, 1.17), p=0.78; average slope IC to IP OR=1.02 (95% CI: 0.81, 1.29), p=0.84; average slope 3–12% of stance OR=1.22 (95% CI: 0.94, 1.59), p=0.13). QIC values demonstrated no meaningful difference across models (range = 117.2–118.9).

## DISCUSSION

The purpose of this study was two-fold: (1) to assess the influence of LR calculation method and running speed on LR values and (2) to determine the association of LR during healthy baseline running with subsequent injury. Our findings indicate that the LR calculation method and the running speed assessed result in significantly different LR values, supporting the first part of our hypothesis. However, as no association between LR and subsequent injury (all injuries or BSI alone) was found, regardless of calculation method, we rejected the latter part of our hypothesis, which postulated an association between LR calculation method and injury.

### Effect of Calculation Method and Speed on Loading Rate Values

A significant interaction existed between the LR calculation method and the speed at which data were collected, implying that LR values must be interpreted within the context of both the calculation method and running speed used. Of the different LR calculation methods, maximum slope from 20–80% of the vGRF magnitude at IP at 4.47 m/s produced the largest LR values (1210.1 N/kg/s; 95% CI: 1160.3, 1259.9). IC to IP and 3–12% stance were the only LR methods that showed no significant difference in pairwise comparisons ($p \geq 0.99$). At 2.68 m/s, IC to IP and 3–12% stance produced the smallest LR values (398.4 N/kg/s; 95% CI: 348.9, 448.0 and 412.2 N/kg/s; 95% CI: 362.7, 461.7, respectively). As the IC to IP and 3–12% stance methods average the slope of the vGRF over a greater period of the stance phase, these methods produced consistently lower LR values than the other methods. Not surprisingly, maximum slope from 20–80% of the vGRF magnitude at IP method consistently produced the highest LR values as this was an instantaneous value, not one averaged over time (Table 3).

It is worth noting for the average slope from 20–80% of the vGRF magnitude at IP method that methodological discrepancies exist with some studies calculating LR using the region between 20–80% of the *vGRF magnitude at* IP (8, 26, 27) and others using the region between 20–80% of the *time to* IP (4, 7, 10). These methods are not interchangeable and due to unclear verbiage it is at times difficult to determine which calculation method was used. If the intent is to calculate LR over the most linear portion of the vGRF, the 20–80% region of the vGRF magnitude at IP should be used as the region between 20–80% of time to IP would likely include non-linear portions of the loading phase, potentially biasing the calculated LR values.

Previous research has demonstrated both average and instantaneous LR values increase with running speed (18, 19). Consistent with these findings, our study found an increase in LR values across all four methods as running speed increased. In general, the increase in LR with increasing speeds can be attributed to an increase in peak vGRF and simultaneous decrease in stance time (3, 19, 28). The significant interaction of calculation method and speed indicates that the incremental change in LR values with a unit increase in speed varies uniquely across the calculation methods used. Therefore, careful consideration must be given before making comparisons of LR values derived from various running speeds, across studies using different LR calculation methods. This may partially explain why previous work with varying LR calculation methods and collection speeds have led to conflicting conclusions regarding the relationship between LR and injury risk.

### Effect of Loading Rate on Running-Related Injury

No association between LR during healthy, baseline running and subsequent running-related injury was observed in this sample, neither for all injuries nor BSI specifically. The present study is the first to prospectively assess the relationships between various LR calculation methods and subsequent injury. Our findings indicate that LR, regardless of calculation method, may not be useful for identifying subsequent injury risk. A meta-analysis of mainly retrospective studies also failed to find an association between LR and all running injuries, but concluded LR is higher in individuals with a history of BSI (5). However, the lack of adequate prospective studies included in this review prevents the determination of LR as a risk factor for BSI. Indeed, our recent prospective study involving a similar 3-yr dataset of collegiate cross country runners failed to identify LR as a predictor of subsequent BSI (8). Additionally, the ground reaction forces from which LR is derived do not reflect the internal loading of muscles, bones, and joints during running (16, 29–31). Mechanical models of fatigue on cortical bone samples suggest LR associated with the impact phase of running has little influence on mechanical fatigue (32). As LR represents a force measure applied at a single point on the foot, it is unlikely to predict the internal loading of all the different locations and tissues that can experience a running-related injury (Table 2). Thus, LR should not be considered a primary risk factor for running-related injuries, BSI or otherwise.

### Clinical Relevance

Clinical running analysis programs often assess injury risk based on previously reported LR injury thresholds (1, 2, 33), and use running gait retraining approaches to decrease LR values (17, 34–36). As LR values are generally dependent on calculation method and running speed, the previously reported LR injury thresholds are only applicable to running analyses and retraining programs using the same LR calculation method and speed as the study that defined the threshold. Furthermore, the use of LR injury thresholds to inform injury risk and retraining are questionable as LR at healthy baseline failed to demonstrate a significant association with subsequent running-related injury. Relying on LR injury thresholds to inform the plan of care could lead to inappropriate decision-making and unnecessary treatment. Therefore, continued efforts should explore alternative gait parameters (8, 37) to assess injury risk and monitor running gait retraining progress.

### Limitations

While the four LR calculation methods included in this study are the most commonly used in running analyses, other calculation methods exist. Differing vGRF data processing methods (e.g. selected filter cutoff frequency and IC threshold) may also contribute to inconsistent LR-injury findings. LR was calculated for the left limb only; we chose not to take bilateral differences into account as between-limb vGRF asymmetries have been found to be negligible across speeds (37). Although all baseline gait collections occurred within 2 months of the start of the cross country season, changes in running mechanics after evaluation, but prior to injury may have occurred. The study findings may be specific to runners of a similar skill, training, and competition level; therefore, given our study population of elite cross country runners, results may not be generalizable to all recreational distance runners. In addition, no *a priori* power analysis was conducted, therefore, the BSI analysis may have been underpowered to detect difference if differences existed. Due to the limited number of BSI, we were unable to assess LR and BSI association by BSI location.

## CONCLUSIONS

LR calculation method and running speed were found to influence LR values, such that LR values should be interpreted within the context of the calculation method and running speed used. Regardless of calculation method, no association between LR and subsequent running-related injury, BSI or otherwise, was identified. Thus, LR may not be an informative metric to prospectively assess running-related injury risk.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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### Conflict of Interest and Funding Statement:

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## REFERENCES

1. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. Br J Sports Med. 2016;50(14):887–92. [PubMed: 26644428]
2. Johnson CD, Tenforde AS, Outerleys J, Reilly J, Davis IS. Impact-Related Ground Reaction Forces Are More Strongly Associated With Some Running Injuries Than Others. Am J Sports Med. 2020;48(12):3072–80. [PubMed: 32915664]
3. Bredeweg SW, Kluitenberg B, Bessem B, Buist I. Differences in kinetic variables between injured and noninjured novice runners: a prospective cohort study. J Sci Med Sport. 2013;16(3):205–10. [PubMed: 22921763]
4. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. Med Sci Sports Exerc. 2006;38(2):323–8. [PubMed: 16531902]
5. 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. Br J Sports Med. 2016;50(8):450–7. [PubMed: 26729857]
6. Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review. Clin Biomech (Bristol, Avon). 2011;26(1):23–8.
7. Dudley RI, Pamukoff DN, Lynn SK, Kersey RD, Noffal GJ. A prospective comparison of lower extremity kinematics and kinetics between injured and non-injured collegiate cross country runners. Hum Mov Sci. 2017;52:197–202. [PubMed: 28237655]

8. Kliethermes SA, Stiffler-Joachim MR, Wille CM, Sanfilippo JL, Zavala P, Heiderscheit BC. Lower step rate is associated with a higher risk of bone stress injury: a prospective study of collegiate cross country runners. Br J Sports Med. 2021;55(15):851–6. [PubMed: 33990294]
9. Kuhman DJ, Paquette MR, Peel SA, Melcher DA. Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. Hum Mov Sci. 2016;47:9–15. [PubMed: 26827155]
10. Napier C, MacLean CL, Maurer J, Taunton JE, Hunt MA. Kinetic risk factors of running-related injuries in female recreational runners. Scand J Med Sci Sports. 2018;28(10):2164–72. [PubMed: 29846979]
11. Gottschall JS, Kram R. Ground reaction forces during downhill and uphill running. J Biomech. 2005;38(3):445–52. [PubMed: 15652542]
12. Willy R, Pohl MB, Davis IS. Calculation of vertical load rates in the absence of vertical impact peaks. The North American Congress Of Biomechanics; 2008; Ann Arbor, MI, USA.
13. Wille CM, Heiderscheit BC. Methods of calculating loading rate during running in the absence of an impact peak. 7th World Congress of Biomechanics; 2014; Boston, MA.
14. Blackmore T, Willy RW, Creaby MW. The high frequency component of the vertical ground reaction force is a valid surrogate measure of the impact peak. J Biomech. 2016;49(3):479–83. [PubMed: 26783094]
15. Giandolini M, Arnal PJ, Millet GY, Peyrot N, Samozino P, Dubois B, et al. Impact reduction during running: efficiency of simple acute interventions in recreational runners. Eur J Appl Physiol. 2013;113(3):599–609. [PubMed: 22875194]
16. Matijevich ES, Branscombe LM, Scott LR, Zelik KE. Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. PLoS One. 2019;14(1):e0210000. [PubMed: 30653510]
17. Miller EM, Crowell MS, Morris JB, Mason JS, Zifchock R, Goss DL. Gait Retraining Improves Running Impact Loading and Function in Previously Injured U.S. Military Cadets: A Pilot Study. Mil Med. 2021;186(11–12):e1077–e1087. [PubMed: 33215669]
18. Stiffler-Joachim MR, Wille CM, Kliethermes SA, Johnston W, Heiderscheit BC. Foot Angle and Loading Rate during Running Demonstrate a Nonlinear Relationship. Med Sci Sports Exerc. 2019;51(10):2067–72. [PubMed: 31525170]
19. Ueda T, Hobara H, Kobayashi Y, Heldoorn TA, Mochimaru M, Mizoguchi H. Comparison of 3 Methods for Computing Loading Rate during Running. Int J Sports Med. 2016;37(13):1087–90. [PubMed: 27676146]
20. Pohl MB, Mullineaux DR, Milner CE, Hamill J, Davis IS. Biomechanical predictors of retrospective tibial stress fractures in runners. J Biomech. 2008;41(6):1160–5. [PubMed: 18377913]
21. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc. 2011;43(2):296–302. [PubMed: 20581720]
22. Yamato TP, Saragiotto BT, Lopes AD. A Consensus Definition of Running-Related Injury in Recreational Runners: A Modified Delphi Approach. J Orthop Sports Phys Ther. 2015;45(5):375–80. [PubMed: 25808527]
23. Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. Clin Biomech (Bristol, Avon). 2011;26(1):78–83.
24. Ranganathan P, Aggarwal R, Pramesh CS. Common pitfalls in statistical analysis: Odds versus risk. Perspect Clin Res. 2015;6(4):222–4. [PubMed: 26623395]
25. Pan W Akaike’s information criterion in generalized estimating equations. Biometrics. 2001;57(1):120–5. [PubMed: 11252586]
26. Crowell HP, Milner CE, Hamill J, Davis IS. Reducing impact loading during running with the use of real-time visual feedback. J Orthop Sports Phys Ther. 2010;40(4):206–13. [PubMed: 20357417]
27. Tate JJ, Milner CE. Sound-Intensity Feedback During Running Reduces Loading Rates and Impact Peak. J Orthop Sports Phys Ther. 2017;47(8):565–9. [PubMed: 28683231]
28. Grabowski AM, Kram R. Effects of velocity and weight support on ground reaction forces and metabolic power during running. J Appl Biomech. 2008;24(3):288–97. [PubMed: 18843159]

29. Scott SH, Winter DA. Internal forces of chronic running injury sites. Med Sci Sports Exerc. 1990;22(3):357–69. [PubMed: 2381304]
30. Sharkey NA, Hamel AJ. A dynamic cadaver model of the stance phase of gait: performance characteristics and kinetic validation. Clin Biomech (Bristol, Avon). 1998;13(6):420–33.
31. Sasimontonkul S, Bay BK, Pavol MJ. Bone contact forces on the distal tibia during the stance phase of running. J Biomech. 2007;40(15):3503–9. [PubMed: 17662295]
32. Loundagin LL, Schmidt TA, Edwards WB. Mechanical Fatigue of Bovine Cortical Bone Using Ground Reaction Force Waveforms in Running. J Biomech Eng. 2018;140(3):0310031–5.
33. Pohl MB, Hamill J, Davis IS. Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. Clin J Sport Med. 2009;19(5):372–6. [PubMed: 19741308]
34. Goss DL, Watson DJ, Miller EM, Weart AN, Szymanek EB, Freisinger GM. Wearable Technology May Assist in Retraining Foot Strike Patterns in Previously Injured Military Service Members: A Prospective Case Series. Front Sports Act Living. 2021;3:630937. [PubMed: 33718868]
35. Chan ZYS, Zhang JH, Au IPH, An WW, Shum GLK, Ng GYF, et al. Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial. Am J Sports Med. 2018;46(2):388–95. [PubMed: 29065279]
36. Yong JR, Silder A, Montgomery KL, Fredericson M, Delp SL. Acute changes in foot strike pattern and cadence affect running parameters associated with tibial stress fractures. J Biomech. 2018;76:1–7. [PubMed: 29866518]
37. Stiffler-Joachim MR, Lukes DH, Kliethermes SA, Heiderscheit BC. Lower Extremity Kinematic and Kinetic Asymmetries during Running. Med Sci Sports Exerc. 2021;53(5):945–50. [PubMed: 33148971]

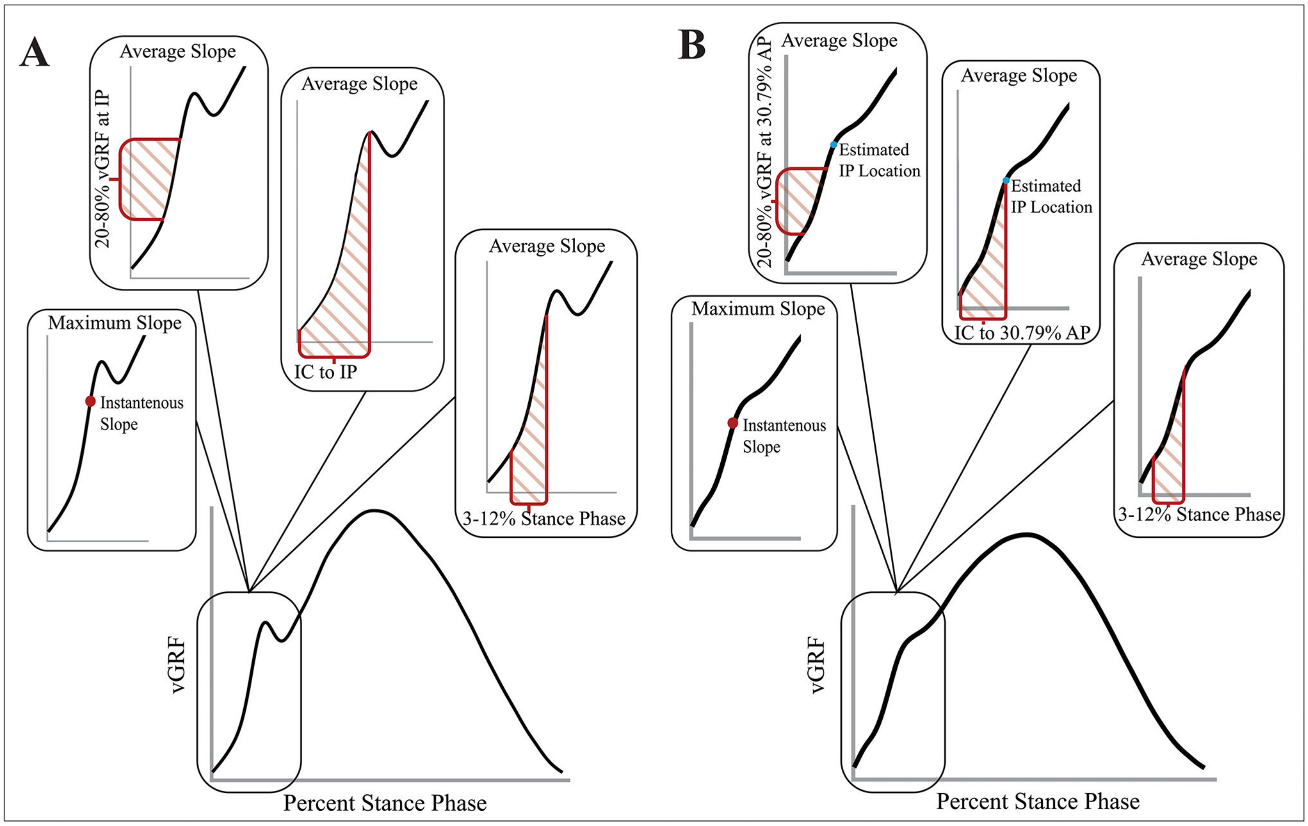


**Figure 1.**

Loading rate (LR) was calculated for each individual running stride as the maximum (instantaneous) slope from 20–80% of the vertical ground reaction force (vGRF) magnitude at impact peak (IP), the average slope from 20–80% of vGRF magnitude at IP, the average slope from initial contact (IC) to IP, and the average slope from 3–12% of stance time in the presence of IP (**A**). In the absence of IP, IP was estimated to occur at 30.79% time to active peak (AP) (**B**).

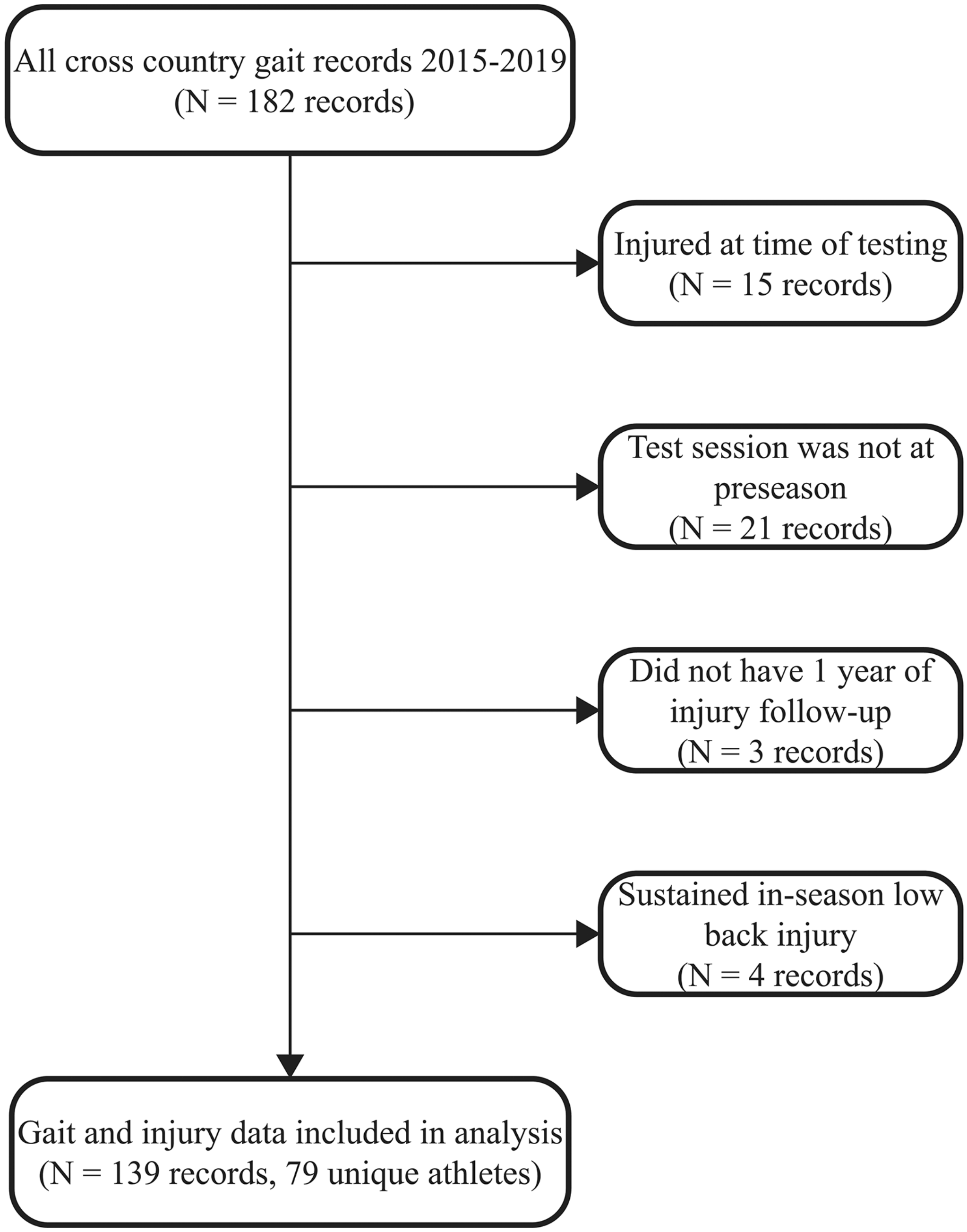


**Figure 2.**

Flowchart demonstrating process for the final selection of 139 gait collections (79 unique athletes) included in this study.

**Table 1.**

Athlete characteristics reported from each athlete's first year in the study, mean (standard deviation).

| | Overall | Females | Males |
|---|---|---|---|
| **Unique Subjects** | 79 | 45 | 34 |
| **Age (years)** | 19.4 (1.2) | 19.3 (1.3) | 19.6 (1.1) |
| **Height (m)** | 1.72 (0.09) | 1.66 (0.06) | 1.79 (0.06) |
| **Mass (kg)** | 61.1 (7.6) | 56.3 (5.3) | 67.4 (5.3) |
| **Preferred Speed (m/s)** | 3.9 (0.3) | 3.70 (0.2) | 4.1 (0.2) |

**Table 2.**

Incidence of first in-season injury by location and tissue type for all injury types and incidence of bone stress injuries by location, n (% injuries by location and tissue type relative to all injuries and bone stress injuries).

| | **Overall** | **Females** | **Males** |
|---|---|---|---|
| **Total Athlete Records** | **139** | **76** | **63** |
| **All Injuries (By Location)** | **64** | **37** | **27** |
| Pelvis and hip | 16 (25.0%) | 11 (29.7%) | 5 (18.5%) |
| Thigh | 14 (21.9%) | 8 (21.6%) | 4 (14.8%) |
| Knee | 5 (7.8%) | 2 (5.4%) | 2 (7.4%) |
| Lower leg | 12 (18.8%) | 6 (16.2%) | 5 (18.5%) |
| Ankle | 10 (15.6%) | 5 (13.5%) | 4 (14.8%) |
| Foot | 12 (18.8%) | 5 (13.5%) | 7 (25.9%) |
| **All Injuries (By Tissue Type)** | **64** | **37** | **27** |
| Bone | 18 (28.1%) | 10 (27.0%) | 8 (28.6%) |
| Fascia | 5 (7.8%) | 2 (5.4%) | 3 (11.1%) |
| Joint (non-bone) | 10 (15.6%) | 5 (13.5%) | 5 (18.5%) |
| Ligament | 2 (3.1%) | 2 (5.4%) | 0 |
| Muscle | 19 (29.7%) | 13 (35.1%) | 6 (22.2%) |
| Tendon | 10 (15.6%) | 5 (13.5%) | 5 (18.5%) |
| **Bone Stress Injuries** | **20** | **12** | **8** |
| Sacral | 5 (25.0%) | 4 (33.3%) | 1 (12.5%) |
| Femur | 6 (30.0%) | 4 (33.3%) | 2 (25.0%) |
| Tibia | 3 (15.0%) | 1 (8.3%) | 2 (25.0%) |
| Fibula | 1 (5.0%) | 0 | 1 (12.5%) |
| Metatarsal | 4 (20.0%) | 2 (16.7%) | 2 (25.0%) |
| Navicular | 1 (5.0%) | 1 (8.3%) | 0 |

**Table 3.**

Least square means estimates of loading rate values at different running speeds across all loading rate calculation methods.

| **Loading Rate Method** | **Least Squares Means Estimate N/kg/s (95% CI)** | | |
|---|---|---|---|
| | **2.68 m/s** | **Preferred Speed** | **4.47 m/s** |
| Maximum Slope | | | |
| 20–80% vGRF at IP | 667.4 (617.8, 716.9) | 1036.0 (986.5, 1085.6) | 1210.1 (1160.3, 1259.9) |
| Average Slope | | | |
| 20–80% vGRF at IP | 535.5 (485.9, 585.0) | 882.1 (832.6, 931.7) | 1043.4 (993.6, 1093.2) |
| IC to IP | 398.4 (348.9, 448.0) | 603.5 (553.9, 653.0) | 706.9 (657.1, 756.7) |
| 3–12% Stance | 412.2 (362.7, 461.7) | 635.3 (585.8, 684.9) | 739.2 (689.4, 789.0) |

CI, confidence interval; vGRF, vertical ground reaction force; IP, impact peak; IC, initial contact

**Table 4.**

Differences of least square means for selected pairwise comparisons from the linear mixed effects model comparing loading rate values at different running speeds across all loading rate calculation methods.

| Loading Rate Methods Compared | | Running Speed | Least Square Means Differences (95% CI; N/kg/s) | Adjusted p-Value* |
|---|---|---|---|---|
| 3–12% Stance | IC to IP | 2.68 m/s | 13.8 (−56.3, 83.8) | 1.00 |
| | | Preferred | 31.8 (−38.2, 101.9) | 0.999 |
| | | 4.47 m/s | 32.3 (−38.1, 102.8) | 0.999 |
| 3–12% Stance | Max 20–80% vGRF at IP | 2.68 m/s | −255.2 (−325.3, −185.1) | <0.001 |
| | | Preferred | −400.7 (−470.8, −330.6) | <0.001 |
| | | 4.47 m/s | −470.8 (−541.3, −400.4) | <0.001 |
| 3–12% Stance | Average 20–80% vGRF at IP | 2.68 m/s | −123.3 (−193.4, −53.2) | 0.03 |
| | | Preferred | −304.2 (−374.6, −233.7) | <0.001 |
| | | 4.47 m/s | −304.2 (−374.6, −233.7) | <0.001 |
| IC to IP | Average 20–80% vGRF at IP | 2.68 m/s | −137.1 (−207.1, −67.0) | 0.007 |
| | | Preferred | −278.7 (−348.7, −208.6) | <0.001 |
| | | 4.47 m/s | −336.5 (−407.0, −266.1) | <0.001 |
| IC to IP | Max 20–80% vGRF at IP | 2.68 m/s | −269.0 (−339.0, −198.9) | <0.001 |
| | | Preferred | −432.5 (−502.6, −362.5) | <0.001 |
| | | 4.47 m/s | −503.2 (−573.6, −432.7) | <0.001 |
| Max 20–80% vGRF at IP | Average 20–80% vGRF at IP | 2.68 m/s | 131.9 (61.8, 202.0) | 0.01 |
| | | Preferred | 153.9 (83.8, 224.0) | 0.001 |
| | | 4.47 m/s | 166.7 (96.2, 237.1) | <0.001 |

*Tukey's adjustment for multiple comparisons was applied.

CI, confidence interval; IC, initial contact; IP, impact peak; vGRF, vertical ground reaction force

**Table 5.**

Odds ratios and 95% confidence intervals (CI) from generalized estimating equations assessing the association between loading rate method and injury status for all injuries and bone stress injuries[§].

| Loading Rate Method | All Injuries | | | Bone Stress Injuries | | |
|---|---|---|---|---|---|---|
| | Odds Ratio (95% CI) | p-Value | QIC[*] | Odds Ratio (95% CI) | p-Value | QIC[*] |
| Maximum Slope | | | | | | |
| 20–80% vGRF at IP | 0.99 (0.88, 1.12) | 0.92 | 198.7 | 1.01 (0.88, 1.15) | 0.86 | 118.9 |
| Average Slope | | | | | | |
| 20–80% vGRF at IP | 0.99 (0.88, 1.12) | 0.89 | 198.6 | 1.01 (0.89, 1.17) | 0.78 | 118.9 |
| IC to First Peak | 0.99 (0.79, 1.24) | 0.92 | 197.8 | 1.02 (0.81, 1.29) | 0.84 | 118.8 |
| 3–12% Stance | 1.13 (0.91, 1.39) | 0.26 | 197.7 | 1.22 (0.94, 1.59) | 0.13 | 117.2 |

[§]Models control for athletes' preferred speed

[*]QIC = Quasi-Information Criterion and is used to assess model-fit in GEE models. A lower QIC by at least 2 points is considered a better model than the comparator.

vGRF, vertical ground reaction force; IC, initial contact; IP, impact peak