Case Study

The use of motion analysis system to determine gait deviation in a person with multiple stress reactions

Nickole Heckman[1], Megan Lasceski[1], Allison Summers[1], Ksenia Ustinova[1*]

[1]The Herbert H. and Grace A. Dow College of Health Professions, Central Michigan University, Mount Pleasant, MI 48489, United States
*Corresponding Author: ustin1k@cmich.edu

Health Research and Education Innovation 2026;1(1):12-20

Background and Purpose: Tibial stress reactions and stress fractures are common among runners and often occur when bone remodeling cannot keep pace with repetitive mechanical loading. Although existing research has primarily focused on running biomechanics, limited attention has been given to gait mechanics during everyday walking. Additionally, the extent to which different types of athletic footwear influence walking gait patterns remains unclear. The purpose of this single-subject design study was to use instrumented motion analysis to examine gait alterations in an individual with a history of recurrent tibial shaft stress injuries while walking barefoot and while wearing different types of corrective athletic footwear.

Methods: The participant walked approximately 8,000–10,000 steps per day, had a history of repetitive tibial stress reactions, previously participated on a sports team, and had undergone diagnostic MRI confirming a stress reaction of the right tibial shaft. A standard deviation band method was used to evaluate the significance of differences in movement patterns between the affected and non-affected limbs across four footwear conditions (walking barefoot, wearing Addidas, New Balance and walking boot). Kinematic gait parameters that exceeded two standard deviations from the mean were interpreted as meaningful differences.

Results: The findings indicated a complex pattern of gait deviations that may contribute to increased mechanical stress on the tibial shaft. Angular displacements of the right tibia, foot, ankle, knee, and hip across the frontal, sagittal, and transverse planes differed from those of the left limb, with variation depending on footwear condition. Differences in lower-limb kinematics between the barefoot condition and the New Balance and Adidas footwear conditions remained within two standard deviations, suggesting no meaningful effect of these shoes on leg kinematics. The only significant correction of right-leg kinematics was observed while walking in the walking boot.

Conclusion: These findings may help inform footwear selection and gait modification strategies aimed at reducing tibial loading during walking and minimizing the risk of future lower-leg stress injuries.

Keywords: walking, stress fracture, gait analysis

Introduction

Stress-related bone injuries are among the most common overuse injuries experienced by athletes.[1–4] In runners, repetitive mechanical loading through the tibial shaft can exceed the bone capacity for remodeling, resulting in tibial stress reactions and stress fractures.[1–4] Bone remodeling is a gradual process, typically requiring approximately 3–4 months for damaged bone to be resorbed and replaced.

However, many runners do not allow sufficient time for skeletal adaptation to the mechanical demands of training, which may contribute to progressive bone damage and impaired healing.[3,5] Previous studies have shown that once an individual sustains a stress reaction, the risk of experiencing a future stress injury in the same extremity increases fivefold.[6] Although substantial research has examined gait mechanics and running biomechanics, these findings are not consistently translated into clinical practice, which may contribute to persistent symptoms and increased reinjury rates.[7]

Improper lower-extremity biomechanics are a major contributor to abnormal gait patterns and may increase the risk of tibial stress reactions and other lower-extremity injuries.[8] Several gait-related factors have been associated with an elevated risk of tibial stress fractures. For example, excessive rearfoot eversion has been linked to an increased risk of tibial injury in runners.[8,9] Contralateral pelvic drop has also been identified as a potential risk factor for stress-related injuries.[10] Increased pelvic drop may contribute to greater hip adduction, thereby increasing mechanical stress along the medial tibia. Over time, these biomechanical deviations may compound, contributing to the development or recurrence of clinically significant stress injuries.

Previous research suggests that running gait analysis may be useful for identifying risk factors associated with stress fractures, including peak tibial acceleration and vertical ground reaction force.[11] However, important gaps remain in the literature regarding diagnostic approaches for identifying why tibial stress reactions continue to occur in runners. Magnetic resonance imaging (MRI) is considered the gold standard for diagnosing stress injuries, particularly when radiographs are negative, and can help prevent progression to more severe bone injury.[12,13] Computed tomography is also commonly used and can provide reliable visualization of stress-related bone changes. However, these imaging modalities provide static assessments and do not capture the dynamic movement patterns that may contribute to repetitive tibial loading. Therefore, it remains unclear how gait patterns during activities of daily living, particularly walking, contribute to tibial stress accumulation. Additionally, limited evidence exists regarding how different types of footwear alter walking mechanics and whether these changes influence tibial loading.

Daily walking exposure may be especially important when considering cumulative tibial stress. One study reported that 42% of individuals walked for approximately 1.5 hours or more per day, and 87.5% walked at a fast pace for at least 30 minutes per day. In contrast, 44% of individuals ran for more than 10 seconds per day, and only 13.2% ran for more than 20 minutes per day.[14] These findings suggest that individuals generally spend substantially more time walking than running. As a result, biomechanical analysis of walking gait may be necessary to better understand cumulative loading patterns that contribute to tibial stress injuries. While much of the existing literature focuses on running biomechanics, stress accumulation may occur during both running and walking. Given the greater amount of time spent walking during daily activities, further investigation of walking gait mechanics is warranted.

To address these gaps in the literature, the purpose of this study was to conduct a biomechanical analysis of walking gait in an individual with a history of recurrent tibial stress reactions who did not respond successfully to conservative treatment. Specifically, this study aimed to identify gait alteration patterns across different footwear conditions. The findings may provide clinically relevant information for developing recommendations to improve walking mechanics and reduce tibial loading, thereby potentially decreasing the risk of recurrent stress injury.

Methods

Participant

The participant was a 23-year-old female who is active and walks 8,000-10,000 steps per day and has a history of multiple tibial stress reactions of the right tibial shaft that causes mild to moderate pain. The participant was on a sports team and underwent physical therapy treatment after having had an MRI. The participant was not involved in any co-interventions at the time of biomechanical gait analysis.

Subject Design

The study used a single-subject design. During a single experimental session, the participant walked a 12-meter distance under four conditions: barefoot at a self-selected comfortable speed (Barefoot); wearing Adidas Solar Boost 4 shoes at a self-selected comfortable speed (Adidas); wearing New Balance Women's Fresh Foam X 880v13 running shoes at a self-selected comfortable speed (New Balance); and wearing a walking boot (Boot) on the involved (right) leg and an Adidas Solar Boost 4 shoe on the uninvolved (left) leg at a self-selected comfortable speed. All footwear conditions are illustrated in Figure 1.

During each trial, the participant was instructed to walk as normally as possible. The participant completed a total of 12 walking trials, with three trials performed under each condition. Rest periods were provided between trials as needed.

Figure 1. Footwear conditions (A) Barefoot, (B) Adidas solar boost 4 shoes, (C) New Balance fresh shoes, and (D) walking Boot on the involved leg.

Data Collection and Analysis

During walking trials, the participant's body motion was recorded using a 12-camera Vicon T160 motion capture system[15] at 100 Hz. A total of 39 reflective markers were placed according to the Plug-in Gait Full Body Model. Spatiotemporal gait parameters were calculated from the raw motion capture data, including cadence, walking speed, step time, step length, step width, gait deviation index (GDI), single-limb support time, double-limb support time, and limp index. In addition, lower-extremity kinematic parameters were analyzed, including angular displacement of the ankle, knee, and hip joints.

Gait velocity was calculated by dividing the 12-m walking distance by the time required to complete each trial. Velocity values from the three trials within each condition were then averaged. Step length was calculated as the longitudinal distance between the right and left feet, and three consecutive step lengths were averaged for each trial. Step width was calculated as the mediolateral distance between the right and left feet and was averaged across the three trials for each condition. Double-limb support time was calculated as the total duration during which both limbs were in contact with the ground. For each condition, double-limb support values from the three trials were averaged.

Hip angular displacement was calculated as the maximum, or peak, angle between two vectors: one defined by markers on the pelvis and the other defined by markers on the thigh. Knee angular displacement was calculated using two vectors, one aligned with the thigh and the other aligned with the shank. Ankle angular displacement was calculated as the angle between vectors aligned with the shank and foot. Angular displacements were analyzed in the sagittal, frontal, and transverse planes for both the right and left lower extremities.

Results were compared between the right and left lower extremities and across all four experimental conditions. All parameters were calculated for each gait stride and then averaged across three consecutive strides for each extremity. Data were then averaged across the three trials within each condition for both the left and right limbs. Mean values were compared between limbs using the two-standard-deviation band method. Differences exceeding ±2 standard deviation (SD) from the mean were interpreted as meaningful gait deviations.

Results

The participant walked at their self-selected gait speed and cadence across all four conditions, as shown in Table 1. The self-selected gait speed was within normative values for an individual of this age. The participant maintained typical gait mechanics across all conditions, with no pain or gait deviations observed or reported. No visible asymmetry was detected between the right and left lower extremities, and no meaningful differences were identified between conditions, as all data remained within the ±2 SD range.

Table 1. Spatiotemporal gait parameters across different footwear conditions (Barefoot, Adidas, New Balance, and Boot) for the right (involved) and left (uninvolved) lower extremities.

Gait Parameters	**Barefoot**		**Adidas**		**New Balance**		**Boot**	
	Right	Left	Right	Left	Right	Left	Right	Left
Cadence (steps/min)	122.0	117.1	122.0	119.3	118.3	119.6	76.8	79.5
Walking Speed (m/s)	1.36	1.34	1.58	1.57	1.57	1.57	1.40	1.43
Step Time (s)	0.44	0.54	0.49	0.49	0.53	0.48	0.57	0.52
Step Length (m)	0.63	0.71	0.78	0.77	0.84	0.77	0.78	0.77
GDI	65.7	62.15	63.8	62.1	67.9	62.7	47.6	60.9
Single Support Time (s)	0.44	0.40	0.40	0.47	0.41	0.38	0.38	0.42
Limp Index	1.10	0.95	0.86	1.17	1.04	0.96	0.93	1.05

Tibial Angular Displacement

Across most footwear conditions, angular displacement of the involved right tibia differed meaningfully from that of the uninvolved limb, exceeding the ±2 SD threshold. Tibial angular displacement across all three planes is presented in Figure 1.

During the Barefoot trials, the right tibia demonstrated greater frontal-plane displacement than the left tibia (56.72° vs. 19.07°). In contrast, right tibial displacement was lower than left tibial displacement in both the sagittal plane (50.20° vs. 105.79°) and transverse plane (13.27° vs. 21.89°). Wearing the Adidas and New Balance shoes did not meaningfully alter angular displacement of the right tibia compared with the Barefoot condition. Differences between the right and left tibiae were minimal across all three planes during these footwear conditions. During the Boot trials, right tibial frontal-plane displacement decreased compared with Barefoot walking (12.80° vs. 56.72°) and was lower than left tibial displacement in the same condition (12.80° vs. 27.88°). However, right tibial displacement increased meaningfully in both the sagittal and transverse planes, approaching the values observed for the left tibia during the Boot condition.

Ankle Angular Displacement

Angular displacement of the right and left ankles across the frontal, sagittal, and transverse planes is presented in Figure 2.

During the Barefoot condition, the right ankle demonstrated greater angular displacement than the left ankle in both the frontal plane (14.13° vs. 10.04°) and sagittal plane (31.69° vs. 25.94°). Wearing the Adidas and New Balance shoes did not result in meaningful changes in ankle angular displacement in any of the three planes. No meaningful differences were observed between the right and left ankles under these footwear conditions. The only meaningful differences were observed during the Boot condition. Wearing the Boot resulted in an increase in frontal-plane angular displacement of the right ankle compared with the Barefoot condition (22.8° vs. 14.1°). Frontal-plane displacement was also greater in the right ankle than in the left ankle during the Boot condition (22.8° vs. 13.6°). In contrast, wearing the Boot reduced sagittal-plane displacement at the right ankle compared with the Barefoot condition (18.8° vs. 31.6°). No other meaningful differences were observed across conditions. Overall, ankle angular displacement varied between the right and left limbs and appeared to be influenced by footwear type, particularly during the Boot condition.

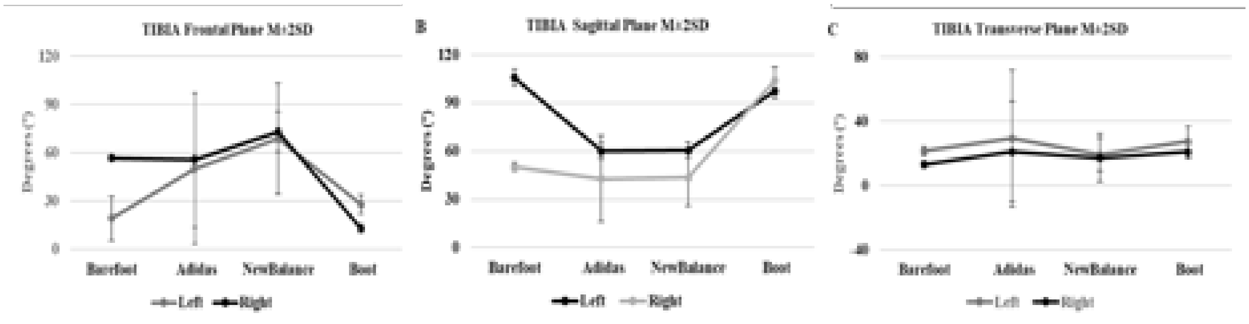

Figure 2: Tibial angular displacement across different footwear conditions, Barefoot, Adidas, NewBalance, and Boot, in the frontal (A), sagittal (B), and transverse (C) planes.

Knee Angular Displacement

Angular displacement of the right and left knees across the frontal, sagittal, and transverse planes is presented in Figure 3. Differences exceeding the ±2 SD threshold between the right and left knees were observed in several conditions.

During the Barefoot condition, the right knee demonstrated lower angular displacement than the left knee in both the frontal plane (9.30° vs. 24.14°) and sagittal plane (52.03° vs. 58.47°).

Wearing the Adidas or New Balance shoes did not produce meaningful changes in knee angular displacement compared with the Barefoot condition. In addition, no meaningful differences between the right and left knees were observed under these footwear conditions in any of the three planes. In contrast, the Boot condition altered knee angular displacement in the right leg. Specifically, wearing the Boot increased frontal displacement of the right knee compared with Barefoot walking (37.9° vs. 9.3°) and decreased sagittal displacement (31.7° vs. 52.0°). Transverse-plane angular displacement also increased during the Boot condition compared with the Barefoot condition (29.4° vs. 11.8°). During the Boot condition, meaningful differences between the right and left knees were observed across all three planes. Overall, knee angular displacement varied between limbs and was influenced primarily by wearing the Boot.

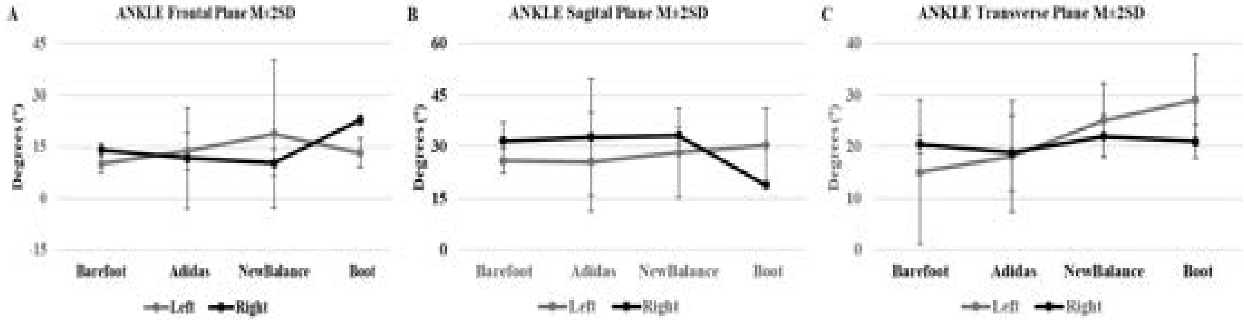

Figure 3: Ankle angular displacement across different footwear conditions, Barefoot, Adidas, NewBalance, and Boot, in the frontal (A), sagittal (B), and transverse (C) planes.

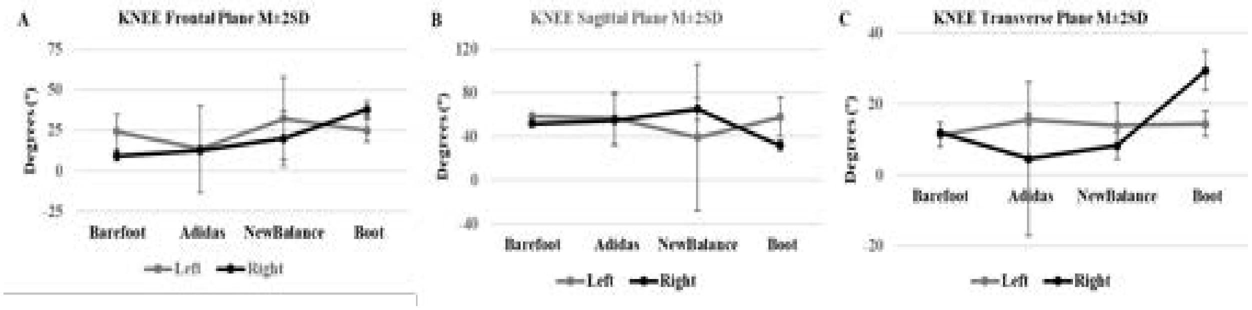

Figure 3: Knee angular displacement across different footwear conditions, Barefoot, Adidas, NewBalance, and Boot, in the frontal (A), sagittal (B), and transverse (C) planes.

Discussion

The purpose of this biomechanical analysis was to compare three-dimensional angular displacement of the right tibia, including segmental tibial displacement and angular displacement at the ankle and knee joints, with that of the uninvolved left leg across barefoot walking and three different footwear conditions. The right tibia had previously been prone to tibial stress fracture. The participant walked at a self-selected speed without visible gait deviations or pain, and spatiotemporal characteristics were within normative ranges.

Several leg-specific differences in tibial motion that may contribute to tibial stress loading were revealed through kinematic analysis. These findings suggest that visual gait analysis may not fully reflect underlying segmental movement differences in an individual with a history of, or predisposition to, tibial stress fracture. Instrumented gait analysis can detect subtle movement differences that may not be apparent through visual observation alone.[21]

The most meaningful finding was the presence of measurable asymmetry in tibial angular displacement between the involved and uninvolved legs mostly during the barefoot condition. During barefoot walking, the involved right tibia demonstrated greater frontal plane displacement than the left tibia, while sagittal and transverse plane displacement were lower. Increased frontal plane tibial motion may be clinically relevant because repetitive mediolateral tibial motion or bending has been associated with increased mechanical demand on the tibial shaft. In individuals prone to tibial stress injuries, excessive or poorly controlled frontal-plane motion may contribute to abnormal tibial loading over repeated gait cycles. Previous studies have identified altered lower-extremity biomechanics, including differences in rearfoot, knee, and tibial motion, in runners with a history of tibial stress fracture.[22,23] Additionally, elevated loading variables and repeated mechanical strain have been associated with lower-extremity bone stress injuries.[24,25] Conversely, the reduced sagittal-plane displacement of the involved tibia may reflect a stiffer limb strategy or altered forward progression of the tibia during stance. Such a strategy could represent a compensatory mechanism to reduce discomfort or loading, even in the absence of reported pain.

Conventional athletic footwear, represented by the Adidas and New Balance conditions, did not change meaningfully tibial angular displacement compared with barefoot walking. This suggests that standard footwear alone may not be sufficient to modify the underlying segmental movement pattern of the involved limb. Although athletic shoes may provide cushioning or support, these features did not appear to meaningfully change tibial motion in this participant. Footwear can influence lower extremity mechanics, but individual responses are variable and may depend on each person’s preferred movement pattern, neuromuscular control, and limb alignment.[26] From a clinical perspective, this finding indicates that footwear changes alone may not adequately address biomechanical factors potentially related to tibial stress fracture risk.

The boot condition produced a different kinematic response. Wearing boots reduced frontal angular displacement of the involved tibia compared with the barefoot condition and brought sagittal- and transverse displacement closer to the values observed in the uninvolved limb. This may indicate that the boot provided greater external constraint to the tibia or altered lower-limb mechanics in a way that reduced excessive frontal-plane tibial motion. More rigid footwear, such as boots, can alter ankle and lower-limb mechanics by restricting motion and changing joint demands during walking.[27] However, this apparent normalization at the tibia should be interpreted cautiously because the boot condition also produced meaningful changes at the ankle and knee.

At the ankle, the boot condition increased frontal-plane angular displacement of the involved limb while reducing sagittal-plane displacement. This pattern is consistent with the mechanical effects of more rigid footwear. Boots may restrict normal dorsiflexion and plantarflexion during stance and push-off, resulting in reduced sagittal-plane ankle motion. To compensate, motion may increase in the frontal plane. Increased frontal-plane ankle motion could reflect greater inversion-eversion movement or altered foot control, which may influence tibial rotation and loading patterns. Previous research has emphasized that distal foot and ankle mechanics can influence proximal lower-extremity movement and loading patterns through the kinetic chain.[28] Therefore, while the boot reduced frontal tibial displacement, it may have shifted motion demands distally to the ankle.

A similar compensatory pattern was observed at the knee. During the boot condition, the involved right knee demonstrated increased frontal- and transverse-plane displacement and decreased sagittal-plane displacement compared with barefoot walking. The reduction in sagittal-plane knee motion may reflect a stiffer gait pattern, while the increase in frontal- and transverse-plane motion suggests greater non-sagittal-plane movement at the knee. These changes may be important because excessive frontal- and transverse-plane knee motion can increase rotational and shear demands throughout the lower extremity. In the context of tibial stress fracture risk, increased transverse-plane knee motion may be particularly relevant because tibial torsion and rotational loading have been proposed as contributors to tibial strain and stress injury development.[22,23,25]

Taken together, the boot condition appeared to reduce or normalize some aspects of tibial angular displacement but introduced compensatory changes at adjacent joints. This highlights the importance of evaluating the entire lower-extremity kinetic chain rather than focusing only on the tibia. A footwear condition that appears beneficial at one segment may increase movement demands at another segment. Therefore, although boots may reduce frontal tibial motion, they may also alter ankle and knee mechanics in ways that could influence overall limb loading. This supports the concept that lower-extremity injury risk is multifactorial and may involve both proximal and distal biomechanical contributors.[28,29]

Clinically, the findings suggest that the involved right limb may use a different movement strategy than the uninvolved limb, particularly at the tibia. The persistence of tibial asymmetry across barefoot condition may indicate residual biomechanical adaptation, neuromuscular control differences, or limb-specific loading patterns. Interventions should therefore not rely solely on footwear modification. Rehabilitation strategies aimed at improving lower-limb control, especially frontal- and transverse-plane control of the tibia, ankle, and knee, may be beneficial. Strengthening of the hip abductors, external rotators, ankle stabilizers, and calf musculature, along with gait retraining, may help reduce excessive segmental motion and improve limb symmetry. Similar multifactorial approaches have been recommended for the management and prevention of bone stress injuries in runners and other physically active populations.[29]

Several limitations should be considered. First, these findings are based on a single participant, which limits generalizability. Second, angular displacement describes movement but does not directly quantify tibial loading, ground reaction forces, muscle forces, or bone strain. Therefore, conclusions about stress fracture risk must be made cautiously. Prior work has shown that stress fracture risk is related to cumulative loading and bone strain, which cannot be fully inferred from kinematic data alone.[24,25] Third, the ±2 SD threshold identifies meaningful differences within this dataset but should not be interpreted as definitive evidence of pathological movement. Finally, walking was performed at a self-selected speed, and results may differ during running, loaded walking, fatigue, or higher-impact activities, which are more commonly associated with tibial stress fracture development.[22,29]

In conclusion, the involved right limb demonstrated meaningful differences in angular displacement compared with the uninvolved left limb, particularly at the tibia. Conventional athletic footwear did not substantially modify these asymmetries, whereas boots reduced frontal-plane tibial displacement but produced compensatory changes at the ankle and knee. These findings suggest that footwear can influence lower-extremity kinematics, but changes at one segment may be accompanied by altered motion elsewhere in the kinetic chain. For individuals prone to tibial stress fracture, assessment of three-dimensional lower-extremity mechanics may be useful for identifying subtle asymmetries and guiding targeted intervention strategies.

Data Availability Statement: Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study.

Conflict of Interest Statement: The authors declare no conflicts of interest.

Statement on the Use of Artificial Intelligence in Manuscript Preparation: The ChatGPT 4.1 AI tool was used for editorial purposes during the preparation of the manuscript. The authors reviewed and revised all AI-assisted output and assume full responsibility for the final content.

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