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Orthosis and Foot Structure Affect the Fifth Metatarsal Principal Strains During Simulated Level Walking

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Background: Fractures of the proximal fifth metatarsal bone are common injuries in elite athletes and are associated with high rates of delayed union and nonunion. Structural features of the foot may increase fracture risk in some individuals, emphasizing the need for intervention strategies to prevent fracture. Although orthotic devices have shown promise in reducing fractures of the fifth metatarsal bone, the effect of orthosis on fifth metatarsal strains is not well understood.

Purpose: To quantify the effects of different foot orthotic constructs on principal tensile strains in the proximal fifth metatarsal bone during cadaveric simulations of level walking. An additional purpose was to investigate the relationships between structural features of the foot and corresponding strains on the fifth metatarsal bone during level walking.

Study Design: Controlled laboratory study.

Methods: A total of 10 midtibial cadaveric specimens were attached to a 6 degrees of freedom robotic gait simulator. Strain gauges were placed at the metaphyseal-diaphyseal junction (zone II) and the proximal diaphysis (zone III) during level walking simulations using 11 different foot orthotic configurations. Images of each specimen were used to measure structural features of the foot in an axially loaded position. The peak tensile strains were measured and reported relative to the sneaker-only condition for each orthotic condition and orthotic-specific association between structural features and principal strains of both zones.

Results: In total, 2 of the 11 orthotic conditions significantly reduced strain relative to the sneaker-only condition in zone II. Further, 6 orthotic conditions significantly reduced strain relative to the sneaker-only condition in zone III. Increased zone II principal strain incurred during level walking in the sneaker-only condition showed a significant association with increases in the Meary's angle. Changes in zone III principal strain relative to the sneaker-only condition were significantly associated with increases in the Meary's angle and fourth-fifth intermetatarsal angle.

Conclusion: The use of orthotic devices reduced principal strain relative to the condition of a sneaker without any orthosis in zone II and zone III. The ability to reduce strain relative to the sneaker-only condition in zone III was indicated by increasing values of the Meary's angle and levels of the fourth-fifth intermetatarsal angle.

Clinical Relevance: Clinicians can use characteristics of foot structure to determine the proper foot orthosis to potentially reduce stress fracture risk in high-risk individuals.

Keywords: fifth metatarsal fracture; proximal fifth metatarsal; bone morphology; orthosis; dynamic gait simulation

Fractures of the fifth metatarsal bone account for up to 70% of metatarsal fractures, with a large portion occurring in the proximal regions of the bone.[14,21] Surgical treatment of these fractures is often preferred over nonoperative treatment, especially in young adults and athletes, because evidence has suggested that nonoperative treatment may delay return to activity and increase the risk of delayed union or nonunion.[20,23,28] However, despite efforts to protect the fracture site, postoperative complications such as refracture or nonunion are still common, even when radiographic evidence of healing is present.[15,18,19,24,25]

Morphological features of the foot seem to play a significant role in the predisposition of individuals to develop a fifth metatarsal fracture. Structural features of the foot, such as forefoot adductus and hindfoot varus, were previously correlated with an increased risk of fractures.[7,10,15,19] Intuitively, these structural features naturally place the foot in a position to incur a higher bending moment within the bone during active movements.[13] However, few biomechanical studies have attempted to quantify the relationship of foot morphological features with fracture risk. Understanding this relationship would help inform preventive treatment strategies for high-risk individuals.

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A promising alternative to the reactive approach of treating fifth metatarsal fractures may be the prescription of an orthotic device to redistribute loads and prevent an initial fracture from occurring. Postoperative clinical studies demonstrated that orthotic devices with a lateral wedge effectively prevented reinjury or refracture of the proximal fifth metatarsal bone.[6,22,30] These studies used a full-length design with a lateral wedge to redistribute load toward the medial portion of the foot. Orthotic devices designed to mitigate the load on the fifth metatarsal bone after surgery may also be effective as a preventive strategy. Other studies reported encouraging results at preventing fifth metatarsal fractures using different configurations of orthotic designs; however, these studies together do not provide definitive information about the most effective strategy to decrease fracture incidence.[9,11,26]

Although the cause of fifth metatarsal fractures may be attributed to many factors, such as bone morphological features and quality, the stress response of the bone during activity is an important factor that an orthosis can address. Oblique loading on the lateral portion of the fifth metatarsal bone creates a levering effect that increases the tensile strain at the proximal base of the bone.[1,2,8,12] Repetitive loads that induce high magnitudes of this tensile strain result in microdamage that may increase the risk of a stress fracture.[8,30] Structural features of the foot can exacerbate the load at the metatarsal base by affecting the obliquity of the force that is transmitted to the bone.[13] Orthotic devices that consistently decrease the proximal fifth metatarsal strain are expected to be effective at reducing fractures. Different configurations of cuts in carbon fiber plates and foam wedges have been used to account for the structural features of the foot and to redistribute loads away from the fifth metatarsal bone; however, which configuration is most effective at reducing strain and how each configuration interacts with the structure of the foot during activity remain unknown.

Therefore, we asked the following questions: How does foot structure affect principal strain in the proximal fifth metatarsal bone, and what is the effect of different orthotic configurations on principal strain in the bone? To address these questions, we first quantified the effects of different orthotic constructs on strain in the proximal fifth metatarsal bone during simulations of level walking in cadaveric specimens. We then investigated the relationships between structural features and the strains measured on the fifth metatarsal bone during level walking. We hypothesized that all the orthotic constructs would reduce strain in the proximal fifth metatarsal bone relative to a sneaker-only condition with no orthosis, whereas orthotic types with a full-length lateral wedge would reduce strain the most compared with the control condition. We also hypothesized that structural features of the foot such as forefoot adductus and hindfoot varus would be associated with increased tensile principal strain during level walking and a reduction in principal strain using orthotic devices.

METHODS

Specimen Preparation

A total of 10 midtibial foot and ankle cadaveric specimens (6 right and 4 left) from 6 male and 4 female donors ranging in age from 50 to 78 years at the time of death were used in this study with approval from our hospital's institutional review board (IRB #2016-0071). Specimens were excluded if the donor patients had a history of injury or surgery to the foot or ankle, diabetes, or gout. Soft tissue approximately 15 cm superior to the ankle joint was removed, and the tibia was potted with poly-methyl methacrylate in a cylindrical fixture. Muscle tissue was removed from tendons of the triceps surae (Achilles), flexor hallucis longus, flexor digitorum longus, extensor hallucis longus, extensor digitorum longus, posterior tibialis, anterior tibialis, peroneal longus, and peroneal brevis. The Achilles tendon was fixed to a linear actuator via an aluminum clamp, and the other tendons were fixed to actuators via nylon ropes. A generic basketball sneaker was placed on the foot of the specimen to simulate level walking with a sneaker.

Robotic Gait Simulator

The process for performing a step using our robotic gait simulator has been previously described.[4] Briefly, the potted tibia was fixed to a static mounting frame of the robotic gait simulator with a 6 degrees of freedom platform that moved a force plate underneath the foot. Ground-reaction forces and tibial kinematic inputs from a previous in vivo study were used to replicate the stance phase of level walking in the cadaveric simulations.[16] The stance phase was simulated by moving the force plate relative to the

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specimen while the tendons were actuated to replicate the muscle forces during in vivo level walking.[3,29] The stance phase was simulated at one-fourth of the average body weight and one-sixth of typical walking speed to mitigate the risk of damaging the specimens during testing. The simulator has been previously validated to reproduce kinematic parameters with these values similar to full body weight testing.[4] For each specimen, an iterative learning control algorithm was used to optimize the motion of the force plate to minimize error in ground-reaction forces as well as to minimize error in the Achilles and tibialis anterior tendon forces to reproduce in vivo ground-reaction forces. The optimization process led to a trajectory of the force plate that inverted the step, where the specimen tibia remained fixed with the force plate moving to replicate the step. After optimization, the force plate trajectory and muscle forces produced a replication of in vivo healthy level walking for each specimen. Vertical displacement of the plate during the stance phase was adjusted between conditions to account for the thickness of the orthotic device and the sneaker. The final step trajectory of the force plate was then used to simulate the stance phase of level walking and measure the subsequent strain on the fifth metatarsal bone.

Strain Measurements

The maximum principal tensile strains were measured at the metaphyseal-diaphyseal junction (zone II) and the proximal diaphysis (zone III) during simulations of level walking (Figure 1). The fifth metatarsal bone was prepared by removing the surrounding periosteum and locally preparing the bone using sandpaper to ensure proper fixation of rectangular rosette strain gauges (125LW strain gauge; L2A Measurements) to the bone. Tendon and ligamentous attachments were preserved. The gauges were placed perpendicular to the longitudinal axis of the fifth metatarsal bone on the plantar side in each zone. Raw strain data for both zones were transmitted directly into a data acquisition bridge (NI CompactDAQ; National Instruments) at 10 Hz, and the principal strains were calculated at each zone. A total of 3 simulations of stance were performed for each orthotic condition, and the principal strains were measured for each. The maximum principal strains were identified from each simulation of level walking. The maximum principal tensile strains from each of the 3 simulations were then averaged to determine the strain value for each condition.

Orthosis

Different configurations of orthotic devices were created to reduce the load transmitted to the proximal fifth metatarsal bone. Orthotic conditions were created via combinations of different carbon fiber plates (a full-length plate, a full-length lateral plate, and a full-length lateral cut plate with a cutout at the base of the fifth metatarsal bone) and full-length foam wedges (no wedge, a full-length lateral wedge, and a full-length lateral cut wedge with

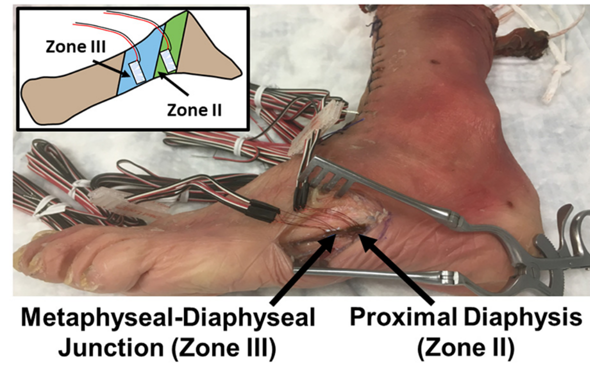

Figure 1. Strain gauges were placed on the fifth metatarsal bone to measure principal strains during simulations of level walking. Rectangular rosette strain gauges were placed on the plantar surface at the metaphyseal-diaphyseal junction (zone II) and the proximal diaphysis (zone III).

a cutout at the base of the fifth metatarsal bone) (Figure 2). Overall, 11 orthotic conditions were constructed to be used during level walking simulations (Table 1). The plate and wedge conditions were inserted inferior to a commercial orthotic device (Lynco Orthotic; Aetrex Orthotics) that was used for each orthotic condition and then placed inside the sneaker before testing. The orthotic conditions were tested in a randomized order that was not repeated for any specimen in order to minimize information bias.

Measurement of Intrinsic Risk Factors

Images of specimens were taken using cone-beam computed tomography (CT) (PedCAT; Curvebeam) after tests were conducted on the robotic gait simulator to analyze the relationship between structural features of the foot and the principal strain measured during the experiment (Figure 3). Before testing, threaded pins were used to rigidly affix clusters of reflective markers to 7 bones of the foot: the tibia, talus, calcaneus, navicular, first metatarsal, fourth metatarsal, and fifth metatarsal bones. An 8-camera motion capture setup was used to capture the orientation of the structure of the foot during a static, axially loaded position on the robotic gait simulator, with a 100-N axial compressive force and 100-N force through the Achilles tendon. After testing, each specimen was scanned with a 0.3-mm slice thickness and 0.3×0.3 mm^2 in-plane pixel dimensions (settings, 120 kV and 120 mA). Scans of all specimens were performed with the marker clusters in place. Foot and ankle geometric features were segmented from the CT images using a commercial image processing software (Mimics Research 22.0; Materialise) and exported as STL files to a commercial reverse engineering software (Geomagic Design X; 3D Systems). The static, axially loaded position representing the standing position of each specimen was reconstructed by transforming the bones from CT scans to the motion capture coordinate system based on the marker clusters using the reverse

TABLE 1
The 11 Orthotic Conditions Tested for Each Specimen in a Generic Basketball Sneaker[a]

Abbreviation	Components
Commercial orthotic device	A commercial orthotic device with no carbon fiber plate or foam wedge
FP	Full-length carbon fiber plate with no wedge
FPLW	Full-length carbon fiber plate with a lateral foam wedge
FPLCW	Full-length carbon fiber plate with a lateral cut foam wedge
LP	Lateral carbon fiber plate with no foam wedge
LPLW	Lateral carbon fiber plate with a lateral foam wedge
LPLCW	Lateral carbon fiber plate with a lateral cut foam wedge
LCP	Lateral cut carbon fiber plate with no wedge
LCPLW	Lateral cut carbon fiber plate with a lateral foam wedge
LCPLCW	Lateral cut carbon fiber plate with a lateral cut foam wedge
Sneaker-only (control)	Basketball sneaker with no orthotic device, carbon fiber plates, or wedges

[a]Each condition was tested in a randomized order for each specimen that was not repeated.

Figure 2. Orthotic components were combined to form 11 conditions, which were tested in a randomized order for each specimen. Images of components used in orthotic conditions include combinations of (A) a commercial orthotic device, (B) a full-length carbon fiber plate, (C) a full-length lateral carbon fiber plate, (D) a full-length lateral cut carbon fiber plate, (E) a full-length lateral foam wedge, and (F) a full-length lateral cut foam wedge.

engineering software. The origin of the foot and ankle was then found by defining the ankle joint center according to International Society of Biomechanics standard.[31] Cylindrical fit tools within the software were used to describe the longitudinal axes of each bone of interest. A total of 6 structural features that have previously been correlated with fifth metatarsal fractures were then measured: metatarsus adductus angle, calcaneal pitch, Meary's angle, fifth metatarsal lateral deviation angle, the fourth-fifth intermetatarsal angle, and talocalcaneal angle.[15]

Statistical Analysis

Statistical analyses were performed to compare the effects of various orthotic conditions to the sneaker-alone condition. Separate linear mixed-effects models were constructed for zone II and zone III principal strains with a random intercept specified for the specimen. Effect estimates were calculated for the mean principal strain for each orthotic type and contrasted with the estimated mean principal strain of the sneaker alone. All comparisons with the sneaker condition are presented as 95% CIs and *P* values, which are adjusted for multiple comparisons using the Dunnett method. A post hoc power analysis was performed using G*Power 3.1.9.7 to calculate the minimum detectable difference in principal strains between the orthotic conditions and the sneaker-only condition (Heinrich Heine Universität, Düsseldorf, Germany). To achieve a power of 0.80 at a significance level of 0.05 with 10 specimens tested the minimum detectable difference between the orthotic conditions and the sneaker-only condition was 200 $\mu\varepsilon$.

The association between structural features of the foot and fifth metatarsal principal strain was evaluated using linear mixed-effects models. When the association of structural factors and fifth metatarsal strain was evaluated, separate models were fit for each structural factor with a random intercept for the orthotic condition nested within a random intercept for the specimen. When the structural features modified by the orthotic condition were evaluated, separate models were also fit for each structural factor but included an interaction between the structural factor and the orthotic condition. The estimated association between the structural factors within each orthotic condition was then contrasted with the sneaker-alone condition. *P* values and 95% CIs from both the orthotic strain associations and the sneaker-alone associations were adjusted for multiple comparisons using the Dunnett method. All analyses were performed using R Version 3.6.2 (R Core Team 2021).

RESULTS

Cadaveric Simulation

When considering all orthotic conditions, we noted a more consistent decrease in strain within zone III, the proximal diaphysis, than in zone II, the metaphyseal-diaphyseal junction. In general, most orthotic conditions reduced the maximum principal tensile strain of the proximal fifth metatarsal bone during simulations of level walking. The FPLW condition was the only condition to provide a significant decrease in strain in both zones compared with the sneaker-only condition.

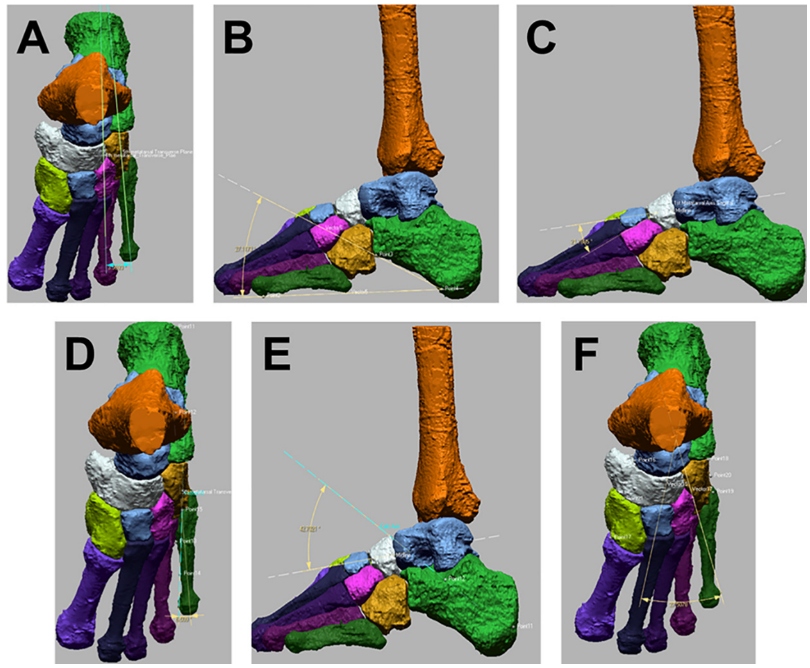

Figure 3. Structural features previously correlated with fifth metatarsal fractures were measured in the cadaveric specimens represented in the standing pose on the robotic gait simulator. Measurements of the foot and ankle anatomic features from computed tomography scans included (A) fourth-fifth intermetatarsal angle, (B) calcaneal pitch, (C) Meary's angle, (D) fifth metatarsal lateral deviation angle, (E) talocalcaneal angle, and (F) metatarsus adductus angle.

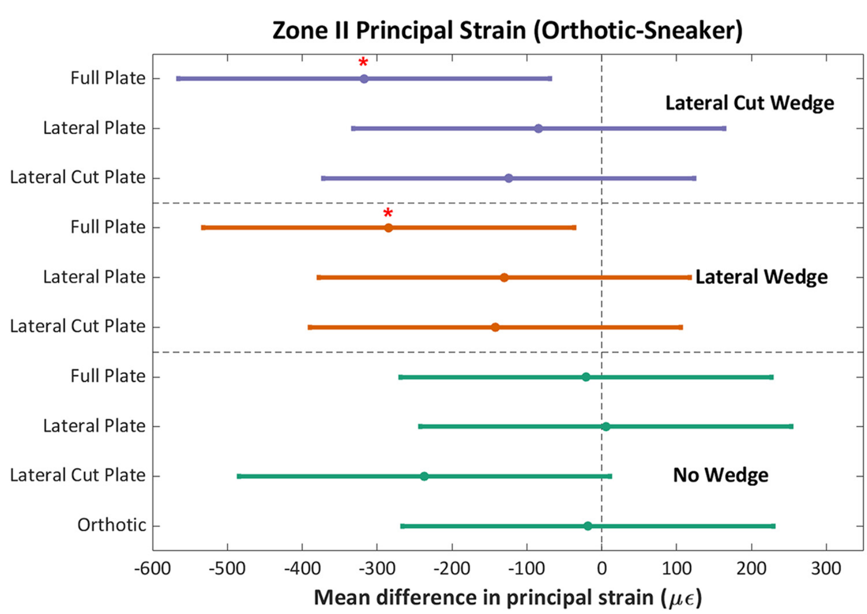

Figure 4. Orthotic conditions with the full plate combined with a lateral wedge or lateral cut wedge significantly reduced strain in zone II of the fifth metatarsal bone during simulations of level walking relative to the sneaker-only condition. Differences in the principal tensile strain and the sneaker-only control condition are reported as the average and 95% CI. *Significant difference ($P < .05$) between the orthotic condition and the sneaker-only condition.

Reductions in principal strains were observed in 2 orthotic conditions in comparison with the sneaker condition (Figure 4). The FPLW and FPLCW conditions significantly decreased strain by an average of 30% (P = .02) and 32% ($P < .01$), respectively. Changes in strain in all other orthotic conditions were not significant in

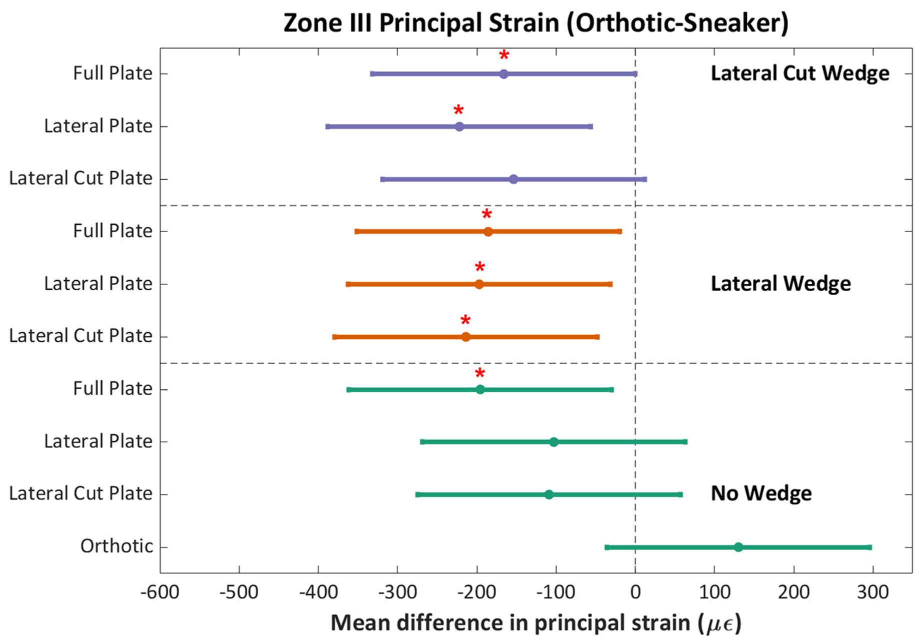

Figure 5. Orthotic conditions with a lateral cut plate reduced strain in zone III of the fifth metatarsal bone during simulations of level walking relative to the sneaker-only condition. Each plate with a lateral wedge was also effective at reducing strain in zone III. Differences in the principal tensile strain and the sneaker-only control condition are reported as the average and 95% CI. *Significant ($P < .05$) difference between the orthotic condition and the sneaker-only condition.

TABLE 2
Marginal Estimated Change in Fifth Metatarsal Strain During Simulations of Level Walking for a 1° Increase in Each Structural Feature in the Sneaker-Only Condition[a]

Structural Feature	Zone II Strain [με]	Zone III Strain [με]
Meary's angle	−32 (−54 to 11)	−29 (−95 to 37)
Calcaneal pitch	38 (8 to 68)	2 (−98 to 103)
Talocalcaneal angle	−68 (−198 to 62)	−5 (−395 to 386)
Metatarsus adductus angle	39 (−1 to 79)	55 (−61 to 170)
Fourth-fifth intermetatarsal angle	0 (−100 to 99)	−113 (−398 to 173)
Fifth metatarsal lateral deviation angle	14 (−175 to 203)	102 (−454 to 659)

[a]Values are expressed as microstrain [με]. The 95% CIs of the estimated change in principal strain in zone II and zone III are presented in parentheses.

comparison with the sneaker condition. This finding indicates that conditions combining a full carbon fiber plate with a laterally placed wedge with or without a cutout for the fifth metatarsal bone were most effective in decreasing strain in zone II.

We found that 6 orthotic conditions significantly reduced the principal strain in zone III of the fifth metatarsal bone compared with the sneaker-only condition (Figure 5). The FPLW, LPLW, and LCPLW conditions decreased zone III principal strain by 18% (P = .02), 19% (P = .01), and 20% ($P < .01$), respectively, indicating the ability of the lateral wedge to decrease zone III strains. Additionally, the FP and FPLCW conditions decreased principal strain by 19% (P = .01) and 18% (P = .05), respectively, indicating the ability of full plate designs to decrease principal strains. Changes in principal strains in the FPLCW, LPLCW, FP, LP, and commercial orthotic conditions were not significant. Overall, any plates with lateral wedges, especially full plates with any wedge combination, were effective in decreasing zone III principal strains.

Structural Features of the Foot

Structural features of the foot were found to influence the amount of proximal fifth metatarsal strain measured during simulations of level walking in the sneaker-only condition in zone II but not zone III (Table 2). In general, zone II strains were most affected by hindfoot alignment, indicating that higher arched feet were more likely to incur higher principal strains during level walking. In zone II, a 1° increase in calcaneal pitch resulted in a 38-με increase in principal strain (P = .01). Additionally, a 1° decrease in

TABLE 3
Comparisons Between the Orthotic-Specific Associations and the Sneaker-Only Association Between Fifth Metatarsal Principal Strain for the Meary's Angle and the Fourth-Fifth Intermetatarsal Angle[a]

	Zone II Strain [με]		Zone III Strain [με]	
Comparison	Meary's Angle	Fourth-Fifth Intermetatarsal Angle	Meary's Angle	Fourth-Fifth Intermetatarsal Angle
FP vs sneaker	24 (−2 to 51)	−76 (−184 to 31)	−22 (−39 to 6)	12 (−57 to 81)
FPLCW vs sneaker	7 (−19 to 34)	−72 (−179 to 36)	−18 (−35 to −1)	−61 (−131 to 8)
FPLW vs sneaker	13 (−13 to 39)	−17 (−125 to 90)	−26 (−43 to −9)	−76 (−145 to −7)
LCP vs sneaker	0 (−28 to 28)	35 (−75 to 146)	−33 (−51 to −15)	−77 (−148 to 6)
LCPLCW vs sneaker	14 (−13 to 40)	−26 (−133 to 82)	−10 (−27 to 7)	−61 (−130 to 9)
LCPLW vs sneaker	0 (−28 to 29)	−35 (−144 to 73)	−14 (−32 to 4)	−49 (−118 to 21)
LP vs sneaker	25 (−1 to 52)	−37 (−144 to 71)	−27 (−44 to −10)	−15 (−84 to 54)
LPLCW vs sneaker	23 (−7 to 53)	−116 (−241 to 10)	−10 (−29 to 9)	−16 (−97 to 65)
LPLW vs sneaker	19 (−7 to 46)	−19 (−127 to 88)	−18 (−35 to −1)	−49 (−118 to 20)
Orthotic device vs sneaker	22 (−4 to 48)	−69 (−177 to 38)	−15 (−32 to 1)	7 (−62 to 76)

[a]Values are expressed as microstrain [με]. The 95% CIs of the estimated change in principal strain in zone II and zone III are presented in parentheses. See Table 1 for expansion of terms used in this table.

Meary's angle resulted in a 32-με increase in principal strain ($P < .01$). Conversely, no structural features trended toward a significant relationship within zone III.

Anatomic features were indicators of the ability to reduce strain in zone III for most orthotic conditions compared with the sneaker-only condition, but not in zone II (Table 3). The full plate conditions, FP, FPLW, and FPLCW, had a distinct effect on the ability to alter strain in comparison with the sneaker-only condition. During these conditions, a 1° increase in Meary's angle led to an average 18% ($P < .01$) and 26% ($P < .01$) decrease in strain relative to the sneaker-only condition during the FPLCW and FPLW conditions, respectively. This suggests that pes cavus specimens may be more likely to experience a decrease in principal strain in response to use of the FPLW and FPLCW orthotic devices. Additionally, increased values of the fourth-fifth intermetatarsal angle, indicating the presence of a bunionette, were associated with an average 67% ($P = .02$) decrease in principal strain in comparison with the sneaker-only condition when the FPLW orthotic devices were used. Analysis of zone II principal strains in relation to anatomic features revealed no significant differences between the orthotic conditions relative to the sneaker-only condition. Thus, although zone II strains were associated with the anatomic structure of the foot, there was no correlation between the anatomic measures of the foot and the change in principal strain in the orthotic conditions.

DISCUSSION

In this study, different configurations of orthotic devices decreased principal tensile strains in proximal regions of the fifth metatarsal bone during simulations of level walking. In particular, orthotic devices that combined a full-length plate and a lateral wedge with and without a cutout at the base were most effective in reducing strain in zones II and III of the proximal fifth metatarsal bone. Higher magnitudes of zone II principal strain were associated with either pes cavus or metatarsus adductus. A combination of a full-length plate and lateral wedge with or without a cutout was most effective in reducing zone III principal tensile strains in more cavovarus feet.

Most of the foot orthotic constructs tested demonstrated an ability to reduce strain in at least zone II or zone III. In part, this could be the result of a lateral wedge placed underneath the length of the fifth metatarsal bone. This wedge may be effective in supporting the fifth metatarsal bone by providing another layer of padding to cushion the bone during compression while also medializing the load through the forefoot to decrease the torsional strain throughout the base of the fifth metatarsal bone. In particular, conditions that combined a full-length carbon fiber plate with a lateral wedge effectively reduced strain in both zones, corroborating observations in previous clinical studies.[22,30] The addition of the full-length carbon fiber plate seemed to enhance the ability of the orthotic device to reduce principal strain relative to the sneaker-only condition. This effect could be the result of providing medial support to the foot, partially countering the laterally positioned wedge while also providing a firmer layer of support to prevent placing additional principal strain on the metatarsal bone. Ultimately, the reduction of strain in zones II and III in the FPLW and FPLCW conditions indicates that orthotic devices that provide additional support under the fifth metatarsal bone together with some medial support are most effective in reducing fifth metatarsal strain.

Zone II and zone III of the fifth metatarsal bone responded differently to orthotic conditions during simulations of level walking. Although most orthotic devices reduced the principal tensile strain in zone III, orthotic devices reduced strain in only 2 conditions in zone II. Clinical studies have often differentiated between injuries to the 2 zones via the mechanism of injury, with acute fractures often being attributed to zone II and stress fractures being attributed to zone III.[5,30] Although previous literature on strain reduction in the fifth metatarsal bone is limited, the magnitude of reduction observed in the current study exceeded an 18% reduction in second metatarsal strain in the previous study.[17] Therefore, the orthotic devices used in this study likely produced a clinically meaningful reduction in both acute and stress fracture risk during level walking.

Structural features of the foot and ankle were associated with increased magnitudes of principal strain in zone II. These results corroborate those of previous clinical studies that found an increased presence of these structural features in patients with fractures, but our results also lend context to the mechanism of proximal fifth metatarsal fractures.[15,27] Given that calcaneal pitch and the Meary's angle were most associated with increases in zone II strain, these increasing magnitudes of pes cavus seem to be influenced by increasing levels of axial strain within zone II during level walking. Additionally, although forefoot adductus did not significantly affect zone II strain, increased levels of this feature resulted in increased levels of oblique loading at the fifth metatarsal base, further exacerbating the high magnitudes of principal strain. Therefore, it is likely that the oblique loading of the fifth metatarsal bone that results in high magnitudes of principal strain is the result of a combination of forefoot and hindfoot orientation rather than the influence of one feature independently.[1,2,8]

Interestingly, the change in principal strain relative to the sneaker-only condition with orthosis was more associated with structural factors of the foot in zone III than zone II. Previous studies have implicated a relationship between stress fracture risk and these factors,[15] but we did not find an association between structural risk factors and zone III principal strain during level walking with a sneaker. Instead, these factors are likely better used as indicators of the ability for a specific foot orthotic configuration to reduce principal strain within the proximal fifth metatarsal bone. Thus, the ability to reduce strain within zone II or zone III with foot orthosis could depend on the ability of the orthotic configuration to conform to the morphological features of the foot. This finding is particularly interesting when considering that the FPLW orthotic condition, which was the most consistent construct in reducing strain in zone II and zone III, was most sensitive to changes in foot structure. This configuration could effectively accommodate the overall structure of the foot in a way that minimizes or redirects the high magnitudes of principal strain resulting from oblique loading during movement.[1,2,8] Ultimately, this finding provides context to previous clinical studies that reported reduced refracture rates when using some version of the FPLW configuration.[5,6,22,30] Therefore, patients with a cavus alignment may be more likely to benefit from the FPLW or FPLCW orthotic configuration to reduce strain in zone III.

There are limitations to consider in our study. First, the simulations of level walking were not necessarily representative of the magnitude or pattern of loads experienced to induce fifth metatarsal fracture. Although the magnitude of strain may change in full body weight loading, the one-quarter body weight loading at slower speeds produces representative kinematic parameters and strain measurements useful for the relative comparisons between conditions.[4] Further work in simulation of cutting, jumping, or pivoting movements could provide more information on how orthotic devices mitigate strain induced during high-impact activity. Additionally, the ground-reaction forces, tibial trajectory, and muscle activations used to calculate the step trajectory were based on in vivo data where the human participants were barefoot. Therefore, the step may have been less representative than if the in vivo data were taken from human participants who wore sneakers; however, the orthotic conditions were compared with a sneaker-only control with the same step trajectory, so our results still represent differences due to orthosis during representative simulations of level walking. All simulations were conducted with a single-sized basketball sneaker, regardless of the size of the specimen. We mitigated this limitation by selecting specimens with foot sizes that differed by <1 cm. Finally, the small sample size may be a limiting factor in conducting a complete structural analysis of strain. It is likely that a larger cohort of specimens would yield a more direct relationship between principal strain and the structural features analyzed in this study.

In conclusion, our biomechanical study showed that orthotic devices were effective in reducing principal strain in the proximal fifth metatarsal bone during simulations of level walking. Foot structure was correlated with the magnitude of strain experienced by the proximal fifth metatarsal bone during level walking and the ability of orthotic conditions to reduce strain. Therefore, clinicians may use characteristics of foot structure to determine the proper orthotic device to reduce stress fracture risk in high-risk individuals. Further clinical data are needed to determine whether such interventions can ultimately decrease the incidence of these injuries.

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