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The relationship between foot arch flexibility and medial-lateral ground reaction force distribution

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A R T I C L E I N F O

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A B S T R A C T

Background: Overuse running injury susceptibility has previously been associated with the magnitude and slope of ground reaction force profiles, most often in the vertical axis. However, despite the implications of excessive pronation and supination on injury susceptibility, very little research has examined the factors that might affect distribution of force in the medial-lateral directions.
Research question: The purpose of this study was to consider how foot structure, specifically arch flexibility, affects the distribution of ground reaction force between the medial-lateral and vertical planes of motion.
Methods: Twenty-five participants were classified as having stiff or flexible arches, and three dimensional kinetic data were gathered while the volunteers ran at 7 mph on an instrumented treadmill. A mixed-effects ANOVA was used to analyze the effect of arch flexibility type on distribution of ground reaction force impulse in the medial and lateral directions.
Results: The results suggest that individuals with relatively stiff arches experience a greater proportion of ground reaction force in the medial-lateral plane of motion, as compared with those with more flexible arches ($p = 0.03$). Further, the results suggest that most individuals, regardless of foot structure, experience greater impulse of force in the lateral than in the medial direction ($p < 0.01$).
Significance: Considering previously explored relationships between ground reaction force, foot pronation/supination, and chronic running injuries, the results of this study suggest that arch flexibility could be used as a criterion for assessing injury susceptibility. Further, conclusions drawn from this study add to the discussion on the pros and cons of training or using devices to increase or restrict arch flexibility while running.

1. Introduction

Overuse running injuries cause restricted physical activity in up to 18% of recreational runners and military soldiers [1,2]. These rates can be even higher for novice runners [3]. The relationships between ground reaction forces (GRF) and injuries in the leg, knee, and hip are well-explored. Previous studies have found that peak vertical GRF, mean vertical GRF, and vertical GRF loading rate are directly related to bony injury susceptibility, particularly tibial stress fracture [4,5]. Vertical forces are the largest component of GRF and the most widely studied. While not as well-explored, medial-lateral GRFs may contribute to injuries in the lower leg and the knee and hip joints [6]. Powers et al. [7] have suggested that medial GRF produces a valgus in the knee that is related to decreased hip muscle strength and knee injuries, including ACL injury and patellofemoral joint dysfunction.

Less research has been done on the factors that affect the magnitude and distribution of GRF. Extrinsic factors including gait speed, running style, footwear, and running surface have been shown to affect GRF profile during running [8–11], and intrinsic factors such as foot structure, leg length, and muscle structure may also affect GRF [12]. Foot structure may be described by a number of features. Arch height is often quantified using Arch Height Index, which is the height of the dorsal surface normalized to foot length [13,14]. Arch Height Flexibility (AHF) has been defined as the difference between arch height in the seated and standing positions, normalized to body weight [15]. While not a dynamic metric, arch flexibility is an easily-acquired metric that

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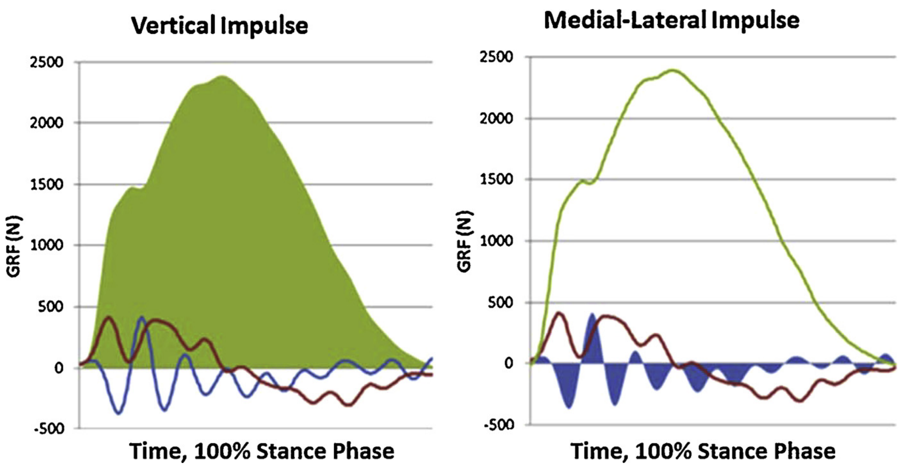

Fig. 1. Illustration of GRF Impulses in the vertical (green), anterior-posterior (red), and medial-lateral (blue) directions during a single foot strike (during stance phase). GRF impulses were calculated over 10 sequential foot strikes for each participant (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

captures two phases of the foot loading paradigm, loaded and unloaded, and therefore may be indicative of how the foot adapts dynamically to load.

The relationship between foot structure and injury has been the subject of research for decades. In the early twentieth century, individuals with flat feet were excluded from the United States military draft, because it was thought that flat arches increased an individual's injury susceptibility [16]. However, work by Cowan et al. [17] suggested that lower arches might actually be protective from overuse injury in military infantry trainees. Several years later, research on the arch height and injury rate of 449 United States Naval Special Warfare trainees suggested that individuals with either extremely flat arches or extremely high arches are more susceptible to injury compared to individuals with normal arches [18]. Further research has refined this conclusion, finding that high arches correlate with bony injuries on the lateral portion of the lower extremity and foot, such as tibial stress fracture and lateral ankle sprains, while low arches correlate with soft tissue injuries on the medial side of the lower extremity and knee, such as patellar tendinitis, general knee pain, and shin splints [19,20]. Despite the overwhelming focus on arch height as a predictor for overuse injury, there is evidence to suggest that arch stiffness may also be a key factor. In a study of high-arched runners, Williams et al. [21] found that arch stiffness varied within the sample and that this correlated to a different movement and loading patterns between those individuals with stiffer and more flexible arches. Although the link to injury susceptibility was not explicitly measured by Williams et al, the implications for this work was supported by Kudo et al. [22], who found a correlation between flexibility of the transverse arch and medial tibial stress syndrome. GRF impulse may be a more useful metric in understanding differences in gait patterns than the peak or average GRF values that are typically used [23]. The impulse can be calculated throughout stance phase, and may give more information about the entire gait profile, as well as the momentum that the individual must overcome in order to change direction as required by the cyclical nature of gait.

Despite the many studies demonstrating links between GRF and injury, and between foot structure and injury, few studies have examined the relationship between GRF and foot structure. Therefore, the purpose of this study was to examine the relationship between the distribution of GRF between the vertical and medial-lateral directions, and arch flexibility. Due to the due to the propensity for more flexible arches to splay under a load, it was hypothesized that individuals with more flexible arches would experience a greater proportion of total GRF in the medial-lateral plane.

2. Methods

Twenty-five active military cadets participated in this study (24 male, 1 female, 21 ± 2 years of age, 173.7 ± 5.9 cm in height, 72.7 ± 8.2 kg). All subjects were rearfoot strikers, stated that they were free from foot or ankle pathology, and able to run on a treadmill at 7 mph for at least 15 min. All procedures were approved by the Institutional Review Board, and all subjects granted informed consent before participating in this study.

Participants' arch height flexibility (AHF) was measured for their right feet only. AHF was defined as the difference between arch height in the seated and relaxed standing positions, normalized to 40 percent body weight (Equation 1) [24]. Arch height was measured using the Arch Height Index Measurement System, which has been previously validated as a reliable tool [25]. Body weight was scaled by 40 percent to account for the difference in the weight supported by the feet while in the seated and standing positions; a foot assumes roughly 50 percent of bodyweight while standing and 10 percent of bodyweight while sitting [14,24].

$$AHF = \frac{AH_{standing} - AH_{sitting}}{0.4\,x\,BW} x\,100$$

2.1. Equation 1. Arch height flexibility (AHF)

Previous research on a large sample with similar demographics to those in the current study suggests that 14.8 mm/kN is the median AHF [26]. Therefore, participants in the current study were categorized into one of two groups — stiff arches (AHF < 14.8 mm/kN) and flexible arches (AHF > 14.8 mm/kN). According to this categorization method, 11 participants had stiff arches and 14 had flexible arches.

Participants ran for 8 min on a single belt of an instrumented treadmill (Bertec Corp; Columbus, OH) at 7 mph and without incline. All participants wore the same clothing and shoes (GEL-Rocket® 7; ASICS, Irvine, CA) during testing. During the final 10 s of running, GRF data were sampled at 1000 Hz and filtered at 35 Hz with a two-way, low-pass Butterworth filter. From these data, the medial, lateral, and vertical components of GRF impulse were determined for each of ten sequential right foot strikes (Fig. 1). This study considered the impulse of force, instead of other metrics such as loading rate or peak force, because impulse characterizes the distribution of force in each direction over the entire stance phase.

The ratio of medial:vertical and lateral:vertical GRF impulse was calculated for each participant. The use of a ratio allowed for a self-normalizing, unitless metric that described the distribution of forces in the medial, lateral, and vertical directions. Medial-lateral GRFs are quite variable, and small in comparison to the vertical GRF component throughout stance. This study included the medial-lateral impulses

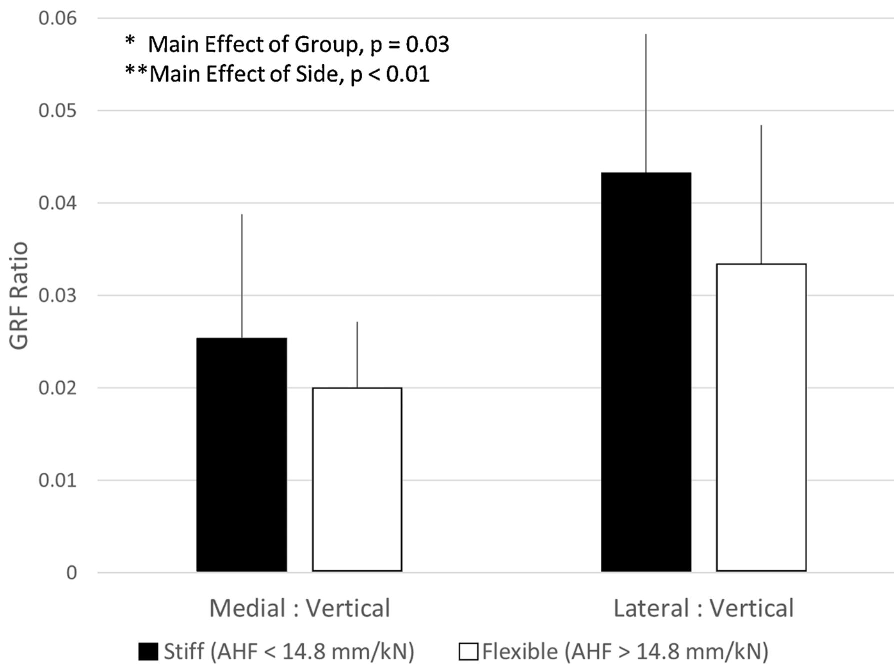

Fig. 2. Average (+/−SD) proportional distribution of medial and lateral GRFs for individuals in the stiff (black) and flexible (white) groups.

throughout stance to account for all sway in this direction. A two-way, mixed-effects ANOVA was used to detect a difference between the medial and lateral distribution of impulses (within subjects) and between the stiff and the flexible groups, as well as the presence of any interactions. All analyses were conducted using SPSS (SPSS Statistics, v19; IBM; Armonk, NY), and a p-value of less than 0.05 was considered significant.

3. Results

For all groups, medial and lateral GRF magnitudes were approximately 2–4% of the vertical GRFs. The results of the mixed-effects ANOVA suggest no interaction between group membership (stiff or flexible) and the direction of GRF impulse (medial or lateral) ($p = 0.58$). The main effect of group membership suggests that individuals with stiffer arches have a significantly larger proportion of GRF impulse in both the medial and lateral directions than do individuals with flexible arches ($p = 0.03$). Additionally, individuals in both the stiff and flexible group demonstrated a greater ratio of lateral:vertical impulse than in the medial direction ($p < 0.01$) (Fig. 2).

4. Discussion

The purpose of this study was to examine the relationship between foot arch flexibility and the relative proportion of GRF in the medial-lateral plane of motion. The results of the study do not support the hypothesis that, due to the propensity for more flexible arches to splay under a load, individuals with more flexible arches would experience a greater proportion of total GRF in the medial-lateral plane. Conversely, the results suggest that, individuals with stiffer arches have a higher proportion of total GRF directed in both the medial and lateral directions during running. This finding is particularly interesting considering previous work that has linked low-arched runners with increased peak rearfoot eversion excursion and velocity, but decreased vertical loading rates, as compared to high-arched runners [27]. There is an apparent link between arch height and arch stiffness, where low arches are typically assumed to be more flexible and high arches are assumed to be more stiff [26]. Although there are differences between the variables of interest examined by Williams et al. [27] and the current study, the intuitive links between the variables with seemingly opposing findings suggests that the potential relationship between arch stiffness and movement patterns should be further explored. It is possible that exploring measures of both arch height and arch stiffness to classify foot structure could be more useful than either measure on their own for predicting and understanding injury susceptibility- particularly since both of these parameters can be measured quickly and accurately with the same low-cost instrumentation.

This study has several limitations. First, because the participants of this study were relatively homogenous, it may not be valid to generalize the conclusions of this study to a wider and more diverse population. Second, the metric of AHF may not fully describe foot arch flexibility. This metric captures flexibility in the vertical translation of the dorsum of the foot and does not account for medial, longitudinal, and transverse flexibility. Several static and dynamic variables may have confounded the results of this study. With 26 bones, 33 joints, and 112 ligaments, the foot has many static anatomical features that could affect GRF distribution. For example, differences in the anatomy of the first metatarsophanlangeal joint or differences in length-tension relationships of ligaments and muscle-tendon systems could have confounded the results of this study. Further, in addition to static anatomical factors, neuromuscular control during the dynamic activity of running likely affects the profile of GRF. Finally, there may be some slight differences in kinetic running patterns measured on a treadmill that may lead to different results if this study were conducted using overground measurement techniques.

Further studies might be conducted with consideration for these limitations. For example, subsequent studies might involve a more diverse subject population, employ different metrics to describe arch flexibility, control for dynamic activity of the muscles and tendons, or collect data overground. Additionally, future studies might further classify foot structure using both arch height and arch flexibility to explore the effects of both of these factors on both kinetic and kinematic patterns that have been linked to injury susceptibility. Ultimately, the results of further study might be useful for understanding the implications of manipulating foot structure on overuse injury. This information may be important for considering the utility of both intrinsic manipulations such as strength training or surgical intervention at the foot, as well as extrinsic manipulations such as use of orthotics or specific types of footwear.

Discloser

All authors were fully involved in the preparation of this manuscript and corresponding study, the material within will not be submitted for publication elsewhere, and no authors had conflicts of interest.

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