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Effects of Foot Type on Multi-Segment Foot Motion in High- and Low-Arched Female Recreational Athletes

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Effects of Foot Type on Multi-Segment Foot Motion in High- and Low-Arched Female Recreational Athletes

A Dissertation

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DEDICATION

To my mother, Janice, who has always been an inspiration and guardian angel, I could not have made it here without your support. To my father, Warren, who has been the voice of drive, reason and composure, who motivated me when quitting would have been easier. To my brother, Christopher, who has been a wonderful example both academically and as a man, thank you. To my sister, Abigail, who has shown me that family is always present, thank you for your unending support.

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Abstract

Introduction: Mal-alignment and dysfunction of the foot have been shown to result in an increased rate of injury and unique injury patterns. Aberrant foot function has been shown to contribute to repetitive stress and acute injuries. High-arched athletes have been shown to experience a greater rate of bony injury to the lateral aspect of the lower extremity while low-arched athletes experience greater rates of soft-tissue injury to the medial aspect of the lower extremity. Though foot type has been linked to these injury patterns, the mechanism by which these injury patterns occur remains unknown. Multi-segment foot models have been developed and allow for direct examination of motion within the foot. Therefore, the purpose of the current studies is to directly examine motion within the foot during vertical loading and dynamic loading tasks. **Methods:** Ten high- and 10 low-arched female athletes performed five trials in each of the following randomized conditions: walking, running, downward stepping, landing and a sit-to-stand exercise. Three-dimensional kinematics and ground reaction forces were collected simultaneously using a 7-camera motion capture system and force platform, respectively. **Results:** The HA athletes were less everted than the LA athletes in the ankle and mid-forefoot joints in all activities. The HA and LA athletes exhibited similar excursion values in all joints. Additionally, the HA athletes had a greater arch index and greater arch deformity during in the sit-to-stand task. **Discussion and Conclusions:** The HA athletes are less everted in all movements than the LA athletes; however excursion values were similar between the two groups. These data suggest the reason for different injury patterns within these two groups is not due to greater frontal plane ranges of motion. Furthermore, the sit-to-stand exercise showed that the HA athletes have a greater arch index but have greater deformation in response to a vertical load. The LA athletes exhibited less arch deformity but this deformity appears to be limited by

the floor. The current study suggests the mechanism leading to different injury patterns in the HA and LA athletes is vertical compression of the arch.

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Chapter 1: Introduction

The foot is a highly mobile and complex structure consisting of 26 bones, 30 joints, and over 100 ligaments. Human feet have been stratified into three foot types, normal, high and low arched, with each foot type associated with unique kinematic and kinetic patterns during dynamic movements (Williams, 2001, Williams, et al., 2004). Dysfunctions and mal-alignments of the structures of the foot have been linked with increased risk of injury to the foot as well as other structures (Kaufman, et al., 1999, Williams, et al., 2001). Individuals with either high- or low arched feet exhibit a two-fold increase in incidence of stress fractures (Kaufman, et al., 1999) and it has been suggested that up to 77% of knee injuries in runners can be explained by foot dysfunction (Lutter, 1980). Additionally, high arched feet are associated with increased internal leg rotation (Nigg, et al., 1993) and pronation creating instability. Through the same mechanism, the rigid foot is also more susceptible to Achilles tendon injuries, and it has been estimated that foot dysfunction is a causative factor in up to 58% of Achilles tendon injuries (Kvist, 1991).

Aberrant foot functions associated with rigid and dynamic feet places added demand on the neuromuscular system during dynamic movements. The instability associated with rigid feet and mechanical inefficiency of dynamic feet require unique kinematic and kinetic patterns compared to normal feet (Butler, et al., 2003, Williams, et al., 2001). These unique mechanical parameters are the manifestation of underlying neuromuscular responses to altered demands due to foot dysfunction. The extrinsic muscles of the foot control movements within the foot during standing and dynamic movements. It has been shown that dysfunction of extrinsic foot muscles produces patho-mechanics within the foot (Rattanaprasert, et al., 1999). In addition, extrinsic foot muscles are activated later in the stance phase in individuals with dynamic feet to stabilize the mid- and forefoot during push off (Hunt and Smith, 2004). It has also been shown that muscular activation decreases when orthotics that mimic normal foot function are applied to dynamic feet (Mundermann, et al., 2005). This further suggests that the neuromuscular system adapts to irregular foot function.

It is known that abnormal mechanics of the foot may result in stress fractures (Butler, et al., 2003, Milgrom, et al., 1985, Williams, et al., 2001), shin splints (Detmer, 1986), osteoarthritis (Radin, et al., 1972) and low back injury (Carpintero, et al., 1994, Voloshin and Wosk, 1982). It has also been shown that static measures of the foot have limited use in the prediction of dynamic function (Hamill, 1989), however, many clinicians use static or quasi-static measures of the foot to infer on dynamic foot functions. A considerable amount of research has been conducted in the classification of foot types using measurements that are readily available to clinicians including arch index (AI) (Cavanagh, et al., 1997, Cavanagh and Rodgers, 1987, McCrory, 1997, Williams and McClay, 2000), relative arch deformity (RAD) (Nigg, et al., 1998, Williams and McClay, 2000) and arch stiffness (Zifchock, et al., 2006). While none of these measurements are of dynamic nature, they have been primarily used to classify foot types and/or to relate to dynamic foot functions. However, there is currently no strong evidence pertaining to the accuracy of these static or quasi-static measurements in predicting dynamic foot mechanics.

The foot is commonly modeled as a single segment in most biomechanical and clinical studies. This simplification is necessary in calculating ankle joint kinematics and kinetics, but does not allow for the description of movements within the foot segments. In response, many researchers have developed multi-segment foot models (Carson, et al., 2001, Hunt, et al., 2001, Leardini, et al., 1999, MacWilliams, et al., 2003, Rattanaprasert, et al., 1999, Stebbins, et al., 2005, Woodburn, et al., 2004). Many of these models have been created for specific populations such as children and patients of varying movement disorders (MacWilliams, et al., 2003, Stebbins, et al., 2005, Woodburn, et al., 2004). In addition, few of these models have been validated using other kinematic measurement tools that may require invasive procedures such as bone pins (Rattanaprasert, et al., 1999). Leardini et al. created a multi-segment foot model (Leardini, et al., 1999) using reflective, skin mounted markers. It divides the foot into four functional segments: the rearfoot, midfoot, forefoot and hallux (big toe). The model is non-invasive in nature and has been validated using video fluoroscopy (Myers, et al., 2004). The Leardini model, by its design, allows for the movement tracking of each of the four functional segments of the foot. Specifically, this model will allow for the 3-dimensional tracking of the midfoot segment relative to the adjacent segments. Single-segment models do not allow for the tracking of the midfoot and cannot describe movement within the foot.

The purpose of this study is to examine the biomechanical characteristics of different foot types (high- compared to low-arched) under a variety of loading conditions. Specifically, this study will investigate the effects of vertical loading on arch dynamics. Additionally, the effect of loading direction (forefoot compared to rearfoot) and magnitude will be examined in dynamic activities. Finally, inter-segmental kinematic data calculated using two methods of implementing a multi-segment foot model will be compared.

Problem Statement

The purpose of this study was three fold. One purpose was to examine the effect of vertical loading on inter-segmental foot motion. The second purpose was to examine the differences in inter-segmental foot motion between high- and low-arched female recreational athletes during different dynamic loading conditions.

Hypotheses

The following hypotheses were tested:

1. The high-arched group would exhibit less eversion at the ankle and within the foot.
2. The high arched group would demonstrate smaller eversion excursion values at the ankle and within the foot.
3. The high-arched group would exhibit less deformity than the low-arched group in response to a vertical load.

Delimitations

The study was conducted with the following delimitations:

1. 10 males and 10 females were selected from the student population at the University of Tennessee. Subjects were apparently healthy and participating in a recreational sport at the time of the study.
2. Each subject performed six test conditions, which included barefoot walking, running, downward stepping, landing from a height of 30cm, squatting and a sit-to-stand exercise.

3. Data were collected at 240Hz from a motion analysis system and 1200 Hz from a force platform for each trial. An infrared timing system was used to record speed for walking and running trials.

Limitations

The study was limited by the following factors:

1. Subjects were limited to those drawn from the University of Tennessee student population.
2. Errors may occur due to marker placements on the subjects. Efforts were made to correctly identify appropriate landmarks in the body to minimize the potential errors introduced. Errors due to marker vibrations were minimized by using cluster marker on rigid shells and attaching them to elastic wrap.
3. Errors may occur due to the limitations in the motion capture system during data collection process. However, every effort was made to complete the process adherent to sound biomechanical principles and practices and strict instructions of the manufactures.

Assumptions

1. Biomechanical instruments were accurate
2. All subjects were healthy, active participants in a recreational sport at the time of data collection.
3. Motion analysis equipment was sensitive enough to determine small differences in movement between groups.

Chapter 2: Review of Literature

The purpose of this study was to investigate the effect of foot type on inter-segmental motion of the foot as well as examining inter-segmental kinetics of the foot during dynamic loading tasks. The objective of this literature review is to present methodologies of foot type assessment as well as the effect of foot type on kinematic and kinetic patterns. Further research is reviewed on the implication of foot type on injury and modeling of the foot.

Foot Type Assessment

The foot is a complex, highly dynamic structure consisting of 26 bones. It is flexible during the loading response and rigid during push-off in normal gait. Dysfunctional and mal-aligned feet have been associated with increased risk of injury to the foot as well as other structures in the lower extremity and trunk (Carpintero, et al., 1994, Kaufman, et al., 1999, Williams, et al., 2001). Foot structures and hypothesized functions are described by foot types. Three foot types have been identified: high arched, normal and low arched. While these foot types have been associated with unique kinematic, kinetic and injury patterns, there are several methods of determining foot function including arch index, navicular drop and arch stiffness.

The arch index is a method of assessing the structure of the medial longitudinal arch of the foot. Several methods can be used for determining the arch index including foot print analysis (Cavanagh and Rodgers, 1987, Chu, et al., 1995, Clark, 1933, Hawes, et al., 1992), radiography (Cavanagh, et al., 1997, Nawoczenski, et al., 1998) and anthropometric foot measurements (Williams and McClay, 2000, Zifchock, et al., 2006). Using foot prints obtained from either a Harris mat or digital imaging, the arch index (AI) is described as the ratio of the area beneath the mid-foot (B) compared to the area beneath the truncated foot (A+B+C) as defined in Equation 1 (Cavanagh and Rodgers, 1987). An advantage of foot print analysis is that it captures the structure and relative function of the foot and its ease of use for clinicians. However, there are disadvantages of foot print analysis. It is not ideal for use with overweight or obese individuals (Wearing, et al., 2004) and for best results, some foot print analysis methods may be expensive and time consuming, requiring expensive equipment and computer programs.

$$AI = \frac{B}{A + B + C} \qquad \text{Equation 1.}$$

Arch characteristics may also be obtained using x-ray technology, and is advantageous in that it measures the location of the source of muscular and ligamentous stability in the foot. However, this methodology requires each subject be exposed to x-ray radiation and is not a clinically viable assessment tool of arch characteristics (Cavanagh, et al., 1997, Nawoczenski, et al., 1998).

The arch index has been has also been defined anthropometric measurements of the foot. From these measurement data, arch index (AI) is calculated as the height of the dorsum (DORS) divided by the truncated foot length (TFL) (Williams and McClay, 2000). Anthropometric foot measurement is a simple and clinically viable method of assessing arch characteristics.

$$AI = \frac{DORS}{TFL} \qquad \text{Equation 2.}$$

In addition, this methodology has been shown to be valid and reliable with intra-tester reliability values of 0.939, inter-tester reliability values of 0.811 and intra-class correlation coefficient of 0.844 with radiography (Williams and McClay, 2000). The simple nature of the calculations associated with this method of arch type assessment allows for quick assessment in a clinical setting.

While the arch index calculated from anthropometric foot measurements has been shown to be a good descriptor of arch structure and a reliable measure in a clinical setting, it is a static measure of foot structure and its application to dynamic movement of the foot is questionable as it has been previously shown that static foot measurement is not a good predictor of dynamic foot function (Cashmere, et al., 1999, Cavanagh, et al., 1997, McPoil and Cornwall, 1996, McPoil and Cornwall, 1996). Alternatively, quasi-dynamic measurements have been used to describe the function of the arch such as navicular drop (Mathieson, et al., 2004, Menz, 1998, Sell, et al., 1994, Vinicombe, et al., 2001) and arch stiffness (Powell, 2006, Zifchock, et al., 2006) calculations. The navicular drop is defined as the difference in vertical height of the tubercle of the navicular of the foot in the relaxed and subtalar neutral positions. The navicular drop is commonly taught in physical therapy programs making it relatively easy to use clinically, however, the position of subtalar neutral is based on palpation of the talus within the ankle mortise and is subjective creating variability (Mathieson, et al., 2004, Vinicombe, et al., 2001). Arch stiffness calculations are based on the anthropometric foot measurements associated with arch index and can be defined as 40% of body weight (BW) normalized to the difference in arch indexes between sitting ($AI_{sitting}$) and standing ($AI_{standing}$) as defined in Equation 3 (Zifchock, et al., 2006).

$$Stiffness = \frac{40\% * BW}{AI_{Sitting} - AI_{S\tan ding}} \qquad \text{Equation 3.}$$

Arch stiffness is a simple, quasi-dynamic assessment of foot type that can be applied immediately in a clinical setting without special software or equipment. However, no validity or reliability data have been presented to date.

Foot Models

In most biomechanical and clinical studies, the foot is modeled as a single, rigid lever. This simplification does not allow for accurate description of inter-segmental motions or forces within the foot during dynamic movements. In response some researchers have developed multi-segment foot models (Carson, et al., 2001, Hunt, et al., 2001, Leardini, et al., 1999, MacWilliams, et al., 2003, Woodburn, et al., 2004), dividing the foot into two or more functional segments. Two seminal models within this body of literature are the Leardini foot model (Leardini, et al., 1999) which divides the foot into four functional segments (rearfoot, midfoot, forefoot and hallux) and the Carson foot model (Carson, et al., 2001), which divides the foot into three functional segments (rearfoot, forefoot and hallux). The Leardini (Leardini, et al., 1999) used bony landmarks to define the location and local reference system for each segment of the foot. The bony landmarks were identified using a digitizing pointer. Foot segments were tracked using clusters of retro-reflective markers placed on plexiglass plates mounted on each segment of the foot. Furthermore, the Leardini foot model has been validated using digital fluoroscopy (Myers, et al., 2004), which is a form of video x-ray allowing for documentation of 3-dimensional motion of bony structures in the body. Although repeatability studies have been conducted on other models, however the Leardini foot model is the only multi-segment foot model to have been validated using video fluoroscopy.

The Carson foot model divides the foot into three segments and uses skin mounted retroreflective markers to track each segment. The Carson foot model does not have a midfoot segment as it assumed that the limited motion within the midfoot is transmitted to the forefoot. A limitation of the Carson model is that limited motion does occur within the midfoot and the joints between bones of the midfoot have gliding and rotary motion, up to several degrees (Snell, 2000).

Further applications of multi-segment foot models have been seen in patient (Woodburn, et al., 2004) and adolescent (MacWilliams, et al., 2003, Stebbins, et al., 2005) populations. However, these models are complex and define up to eight rigid segments to describe inter-segmental foot motion. The Leardini foot model (Leardini, et al., 1999) has been validated using video fluoroscopy (Myers, et al., 2004) and for the purposes of the current study, is an appropriate model describing multi-segment motion of the rearfoot, midfoot and forefoot.

Kinematic Patterns

Foot type assessment has identified three types of feet within the population: high arched, normal and low arched. The kinematic patterns of the normal foot-ankle complex have been examined using skin mounted markers (Scott and Winter, 1991, Westblad, et al., 2002), bone anchored markers (Arndt, et al., 2004, Westblad, et al., 2002) and fluoroscopy (Myers, et al., 2004, Wearing, et al., 1998). Known differences exist in the lower extremity kinematic and kinetic patterns of high and low arched individuals (Butler, et al., 2003, Ledoux, et al., 2003, McClay and Manal, 1998, Williams, et al., 2004). It has been shown that high arched runners have less knee flexion during the stance phase of running while low arched runners have greater eversion excursion, eversion velocity and eversion-tibial internal rotation ratios compared to normal arched runners (Williams, 2001).

While these kinematic differences have been observed between high and low arched runners in a single-segment foot, little is known as to kinematic patterns of the multi-segment foot in high- and low arched individuals. Several researchers have examined the multi-segment kinematics of the foot in normal adults (Carson, et al., 2001, Hunt, et al., 2001, Leardini, et al., 1999, Myers, et al., 2004). The Carson foot model was designed with no midfoot segment. It was suggested that minimal movement occurs within the midfoot and movement of the rearfoot would be transmitted through the midfoot to the forefoot (Carson, et al., 2001). However, it has been shown that approximately 10° of rear-midfoot range of motion occurs in the sagittal plane during the stance phase of gait using a multi-segment foot model that has eight rigid segments including two midfoot segments (MacWilliams, et al., 2003). Additionally, a transverse plane range of motion of approximately 10° also occurs between the midfoot and forefoot during the stance phase. The findings of Leardini (Leardini, et al., 1999) also suggest that there is substantial motion at the rearfoot-midfoot and midfoot-forefoot junctions.

While multi-segment foot motion has been examined in the normal foot, to the knowledge of the authors, little is known as to the kinematic patterns of high and low arched individuals. No research has been conducted to examine the motion in the multi-segment foot of healthy individuals with high and low arches, however, individuals with Posterior Tibialis dysfunction (TPD) may have similar kinematics within the foot when compared to low arched individuals. The Tibialis Posterior is a strong invertor of the foot and controls the forefoot during walking and running. Dysfunction of this muscle results in the progressive collapse of the medial longitudinal arch, called the acquired flatfoot. In this patient population, bone pin markers were used to assess the kinematic patterns of the rearfoot and forefoot (Rattanaprasert, et al., 1999). Unfortunately, the author used a single patient and 10 normal subjects to compare movement patterns of each group. During walking, the TPD patient had less plantarflexion prior to foot flat and during the push off phase of gait suggesting the TPD foot does not become rigid during late stance. In addition, the TPD foot had less dosiflexion-plantarflexion and adduction-abduction range of motion compared to the normal foot. These results suggest alternative kinematic patterns are adopted by those with flat foot, further suggesting that individuals with a low arch may have similar kinematic patterns.

Implication for Injury

The foot is the point in the body where it interacts with the ground. Forces associated with ground contact are transmitted through the foot to the rest structures including the ankle, knee, hip and trunk. The function of the foot is to absorb force and to transfer muscular force to the ground for propulsion. Mal-aligned or dysfunctional foot mechanics may adversely affect the pattern of loading. Therefore, mal-alignment or improper foot function increases an individual's risk of injury.

Relationship between foot types and risks of injury has not been well established and the literature is inconsistent regarding these associations. High arched feet have been suggested to be rigid and develop unique injury patterns compared to the hyper-mobile low arched foot (Kaufman, et al., 1999, Williams, 2001, Williams, et al., 2001). Additionally, it has been shown that high arched individuals have different kinematic patterns in the ankle and knee compared to low arched individuals (Williams, 2001). Williams et al (Williams, 2001) found that low arched runners had greater rearfoot eversion excursion, rearfoot eversion velocity and eversion-tibial internal rotation ratio than high arched runners. High arched runners exhibited less knee flexion and a shorter ground contact time compared to low arched runners (Williams, et al., 2004). Additionally, high arched runners had greater vertical loading rates creating increased leg and knee stiffness values compared to low arched counterparts (Williams, 2001, Williams, et al., 2004). The center of pressure was found to be more laterally displaced in high arched runners compared to low arched runners (Williams, et al., 2001). These findings suggest the lower extremity of individuals with high- and low-arched feet are subjected to different movement and loading patterns. Altered movement and loading patterns along with abnormal structures may lead to increased risks of injury. It has been shown that high arched runners have a greater propensity to suffer bony injuries while low arched runners have a greater frequency of soft tissue injuries (Williams, et al., 2001). Additionally, high arched runners are more likely to incur injuries to the foot and ankle compared to low arched runners who have a tendency to have knee and hip injuries (Williams, et al., 2001). It has also been suggested that individuals with either a high or low arch are nearly twice as likely to suffer stress fractures than individuals with a normal arch (Kaufman, et al., 1999). The association between foot function and injury is not exclusive to the lower extremity as atypical structure of the foot has also been associated with injury to other structures along the chain including the knee and back. Pes cavus (high arched feet) has been suggested to have a causative relationship for idiopathic scoliosis in some patients (Carpintero, et al., 1994). Additionally, further research has shown that high arched individuals experience less loading at the level of the spine compared to low arched individuals (Ogon, et al., 1999).

Foot structure is a determining factor in an individual's movement pattern and the forces experienced by the skeletal and connective tissues. Individuals with each foot type seem to incur unique injury patterns as a function of their distinctive movement pattern. Much of the current research pertaining to these two functionally different foot types focuses on the effects of foot type on the lower extremity or rear-foot motion. At present, no research directly investigates three-dimensional motion within the foot of high- and low-arched individuals. Therefore, the purpose of this study is to examine three-dimensional motion within the foot and ankle in high- and low-arched individuals.

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Chapter 3: Multi-segment Foot Kinematics in High- and Low-Arched Females during Dynamic Loading Tasks

Multi-segment Foot Kinematics in High- and Low-Arched Females during Dynamic Loading Tasks

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Abstract

Background*:* The functions of the medial longitudinal arch have been the focus of much research in recent years. Several studies have shown kinematic and kinetic differences between high (HA) and low (LA) arched runners. Few studies have examined the intra-segmental motion of the foot during dynamic activities and no data currently exists comparing the intra-segmental foot motion of HA and LA recreational athletes. The purpose of this study was to examine inter-segmental foot motion during walking, running, downward stepping and landing activities. It was hypothesized that HA compared to LA athletes would be more inverted at the ankle and within the foot and have smaller ranges of motion. **Methods:** Inter-segmental foot motion was examined in 10 HA and 10 LA female recreational athletes. All subjects performed five barefooted trials in each of the following randomized movements: walking, running, downward stepping and landing. Ground reaction force (GRF, 1200Hz) and three-dimensional kinematic data (240Hz) were recorded simultaneously. **Findings**: High- compared to low-arched athletes were more inverted and had a smaller eversion excursion at the ankle. At the rear-midfoot joint HA athletes were more inverted at toe-off and reached peak eversion earlier in the stance phase of walking and running gait compared to LA athletes. HA athletes were also less everted and had greater inversion and internal rotation excursions. **Interpretation**: The HA compared to LA athletes exhibited unique kinematic patterns within the foot and ankle during walking and running tasks. These differences occurred mostly in the mid-forefoot joint and no differences were observed in the rear-midfoot joint. Differences did not exist between the HA and LA athletes in the downward stepping and landing tasks suggesting similar mechanisms are used to attenuate shock at the level of the foot and ankle.

1. Introduction

Lower extremity injury is common in athletic events. Athletes often experience overuse injuries which may include stress fractures, tendonitis and patellofemoral syndrome (Hamill *et al.*, 1992, James *et al.*, 1978, Kaufman *et al.*, 1999, Williams, D.S., 3rd *et al.*, 2001a). These overuse injuries are caused by repetitive stress on the lower extremity (Nigg, 1985, Radin *et al.*, 1984, Radin and Paul, 1971, Radin *et al.*, 1991) and the risk of over-use injuries in an athlete is increased by poor lower extremity biomechanics during athletic movements (Bates, B.T. *et al.*, 1979, Hamill et al., 1992, James et al., 1978, Nigg, 1985). Previous research has shown that high- (HA) and low-arched (LA) athletes exhibit different injury patterns within the lower extremity and both have a greater propensity for lower extremity injury compared to their normal counterparts (James et al., 1978, Kaufman et al., 1999, Williams, D.S., 3rd et al., 2001a). A possible mechanism by which these unique injury patterns occur could include the role of foot structure and ankle function in the timing of lower extremity kinematics (Hamill et al., 1992, James et al., 1978, Stergiou, N.a.B., B., 1997). It has been suggested that over-pronation, a movement pattern often associated with low-arched feet, creates an asynchrony between peak pronation and knee flexion which does not exist in normal subjects (Bates, B.T., James, S.L., Osternig L.R., 1978, Stergiou, N.a.B., B., 1997). Furthermore, HA athletes exhibit decreased knee flexion, greater vertical loading rate and increased lower extremity stiffness during level running tasks compared to LA athletes (Ledoux *et al.*, 2003, McClay and Manal, 1998, Williams, D.S., 3rd *et al.*, 2004, Williams, D.S. *et al.*, 2001b).

The injury patterns suffered by HA and LA athletes are manifestations of the mechanical function of the foot and lower extremity during dynamic activities. It has been shown that HA athletes experience more bony injuries such as tibial and fifth metatarsal stress fractures and tend to have these injuries on the lateral aspect of the lower extremity (Williams, D.S., 3rd et al., 2001a). LA athletes have a greater rate of injury to soft-tissues including patellar and achilles tendonitis and have a greater incidence of injury to the medial aspect of the lower extremity (Williams, D.S., 3rd et al., 2001a). The foot is the point of interaction with the ground during most athletic tasks. Therefore, these unique injury patterns may be associated with altered loading patterns within the foot which are transmitted through the foot to the rest of the lower extremity. It has been shown that HA have more rigidity (less flexibility) (Franco, 1987, Zifchock *et al.*, 2006) and greater supination during walking and running exercises (Hintermann, 1994, James et al., 1978, Stacoff *et al.*, 2000b) than LA individuals. Evidence has also shown that HA individuals have greater stiffness within the foot compared to LA individuals during a quasi-static measurement (Zifchock et al., 2006). This suggests that HA feet are less capable of attenuating shock during athletic movements. A diminished capacity to absorb impact loads during running would result in greater forces being applied to the lower extremity.

Though aberrant foot function has been known to increase the propensity of injury in both HA and LA individuals, research investigating possible mechanisms leading to these different injury patterns is still relatively rare. Most biomechanical studies model the foot as a single rigid segment. Many studies investigating lower extremity injury patterns have focused on topics including rearfoot motion, tibial-calcaneal timing and lower extremity coordination patterns. However, it is known that the foot does not act as a single, rigid segment mechanically. The recent development of several multi-segment foot models allows for direct investigation of kinematics within the foot (Carson *et al.*, 2001, Hunt *et al.*, 2001, Leardini *et al.*, 1999, MacWilliams *et al.*, 2003). The Oxford multi-segment foot model was initially developed for use in a clinical setting and consisted of three segments: the rearfoot, forefoot and hallux (Carson et al., 2001). Though the Oxford multi-segment foot model did describe motion within the foot, the focus of the study did not pertain to foot type or aberrant foot function (Carson et al., 2001). Hunt *et al*. used a multi-segment foot model similar to the Oxford model to describe the mechanics as well as control of the low-arch compared to normal arch in walking (Hunt and Smith, 2004). Few differences were observed in the kinematics of low-arched and normal individuals. It was also suggested that the low-arched group may be under tighter control than the normal group as evidenced by smaller rearfoot and forefoot motions in the frontal and transverse planes (Hunt and Smith, 2004). These differences in multi-segment foot motion between low-arched and normal feet would likely be exacerbated in comparisons to high-arched feet. A limitation of Hunt's study, however, is that subject grouping was conducted using a subjective analysis of arch height and function made by a clinician's visual assessment (Hunt and Smith, 2004), rather than objective measurement. Leardini *et al* developed a multi-segment foot model designed to allow three-dimensional (3D) kinematic analysis of motion within the foot (Leardini et al., 1999). However, no kinematic patterns with high and low arched individuals were examined using the Leardini model. At the time of this study, no 3D data exist in the literature comparing multi-segment foot motion of HA and LA athletes. Therefore, the purpose of this study was to use a multi-segment foot model (Leardini et al., 1999) to examine the biomechanical characteristics of high- and low-arched females in movements under different dynamic loading conditions using a multi-segment foot model. It was hypothesized that high-arched females compared to low-arched females would have less inter-segmental motion of the foot and be less everted at the ankle and within the foot segments.

2. Methods

2.1 Subjects

Fifty-five healthy female recreational athletes were screened for inclusion in this study. A total of 20 subjects participated in the current study. Subjects were between the ages of 18 and 28 (HA: 20.8 ± 2.5; LA: 21.1 ± 2.331 yrs) and both groups had similar height (HA: 1.62m ± 0.07m; LA: 1.63m ± 0.07m) and mass (HA: 58.32kg ± 5.39kg; LA: 58.89kg ± 10.92kg). Subjects had arch index values greater than 0.377 or less than 0.283 and were placed into a high- (n=10) or low-arched (n=10) group, respectively. Foot type was determined using arch index which is defined as the dorsum height at half the total foot length, divided by the truncated foot length (Williams, D. S. and McClay, 2000). Arch index values used to define each group were determined as 1.5 standard deviations from a mean collected using 604 feet (0.330 ± 0.031) (Zhang, S. *et al.*, 2007). All participating subjects were free of injury at the time of testing and signed a written informed consent form approved by the Institutional Review Board at The University of Tennessee prior to participating in the study.

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2.2 Experimental Protocol

Each subject participated in two testing sessions. During the first session, subject information and anthropometric measurements including height, weight, total foot length, truncated foot length and dorsum height were collected. During the second session, subjects performed five trials in each randomized condition: walking, running, downward stepping and step-off landing. All movements were conducted barefooted. During the walking and running conditions, subjects performed the movement at a constant self-selected speed determined during three practice trials prior to testing. The downward stepping trials were performed from a 15 cm box while the step-off landing trials were conducted from a 30 cm box. Three-dimensional (3D) kinematic and ground reaction force (GRF) data were collected simultaneously.

2.3 Instrumentation

A seven-camera motion analysis system (240Hz, Vicon Motion Systems Ltd., Oxford, UK) was used to collect 3D kinematic data from the right side lower extremity of each subject. The foot was modeled as three segments: rearfoot, midfoot and first metatarsal (Leardini et al., 1999). All segments were defined and tracked using retro-reflective markers. The rear-foot was defined and tracked using retro-reflective markers placed on the inferior and superior calcaneus, peroneal tubercle and sustentaculum tali. The mid-foot was defined and tracked using markers placed on the cuboidal tubercle, lateral cuneiform, medial cuneiform and navicular tuberosity. The first metatarsal was defined by markers placed on the base of the first metatarsal, the shaft of the first metatarsal, and the medial and lateral sides of the first metatarsophalangeal joint. In addition, clusters of retro-reflective markers were used to track the shank, thigh and pelvis. Anatomical markers were placed over the medial and lateral malleoli, medial and lateral epicondyles, left and right greater trochanters, and left and right iliac crests to determine the centers of joint rotation for the ankle, knee and hip, respectively. The standing calibration was taken during quiet standing with the arms placed across the chest and the feet pointed forward in line with the global coordinate system. Anatomical joint markers were removed prior to dynamic trials. A force platform sampling at 1200Hz and synchronized with the motion capture system (OR6-7, AMTI Watertown, MA, USA) was used to measure GRF data. The subject's right foot contacted the force platform during each of the four test conditions. Two pairs of photo cells and an electronic timer (63501 IR, Lafayette Instruments Inc., IN, USA) were used to determine and monitor walking and running velocities.

2.4 Data Analysis

Data collected during walking, running and downward stepping conditions were analyzed from heel contact to toe-off. Data collected during the landing condition were analyzed from initial contact to peak knee flexion. All original marker data were filtered using a lowpass digital filter with 6 Hz cut off frequency while GRF data were filtered using a lowpass filter with 50 Hz cutoff frequency. Selected ankle and multi-segment foot angles and GRF variables were computed using Visual 3D (C-motion, Inc., Germantown, MD, USA). A customized computer program (Microsoft Visual Basic 6.0; Microsoft Corporation, Redmond, WA, USA) was used to determine peak angles and excursion values in the selected kinematic and GRF variables. Range of motion was defined as the total range of motion or the difference between the maximal and minimal joint angles. Excursions were defined as the range of motion from heel strike to the peak value of the variable of interest (Zifchock et al., 2006).

A 2 x 2 (Group x Movement) mixed design repeated measures ANOVA with Group as the between subjects factor was used separately to evaluate selected GRF and kinematic variables (SPSS, Chicago, Il, USA) for each pair of movement trials (walking and running; downward stepping and landing). The alpha level was set at $p < 0.05$.

3. Results

3.1 Walking & Running

For the ankle joint, the HA and LA athletes exhibited significantly greater plantarflexion at toe-off in running ($F = 51.73$, $p<0.001$) compared to walking (Table 1). Additionally, the HA athletes had significantly greater peak inversion than the LA athletes in walking and running ($F=7.30$, $p=0.019$), while both groups exhibited less eversion in running ($F=12.57$, $p=0.004$). There was a significant group x movement interaction ($F=9.13$, $p=0.008$) for eversion excursion. The HA athletes showed less eversion excursion in walking ($F=10.20$, $p=0.006$), but greater eversion excursion in running compared to the LA athletes ($F= 7.51$, $p=0.025$; Table 1; Figure 1A). No differences were observed in peak eversion angle. The HA compared to LA athletes exhibited significantly less external rotation at toeoff in walking and running (Walking: $F=7.58$, $p=0.014$; Running: $F=7.97$, $p=0.012$), while both groups exhibited significantly smaller external rotation angles ($F=6.14$, $p=0.025$) at toe-off in running.

For the rear-midfoot joint, the HA athletes had significantly greater peak plantarflexion in walking ($F=5.48$, $p=0.037$) while no group differences were observed in the running condition (Table 2). Both the HA and LA athletes reached peak eversion earlier in the running compared to walking conditions ($F=25.35$, $p<0.001$; Figure 1B), while the LA athletes reached peak eversion earlier in the stance phase of walking compared to their HA counterparts ($F=5.85$, $p=0.028$). Peak eversion angles and eversion excursions were similar between the HA and LA groups. Furthermore, the HA and LA athletes exhibited similar peak inversion and inversion excursion values in walking and running.

Table 1. Mean ankle joint angles (degrees) of high- (HA) and low-arched (LA) athletes: mean (SD)

Movement	Group	PF_{TO}	Inv_{max}	Ev_{exc}	Ev_{max}	ER_{HS}	ER_{TO}
Walking	HA	-36.3 (9.4) [b]	3.5 (4.4) [a, b]	-1.5 (3.8) [b, *]	-9.9 (3.0)	-13.3 (4.2) [a]	-10.1 (3.8) [a, b, *]
	LA	-28.1 (7.6)	-2.0 (4.5)	-5.4 (2.2)	-10.2 (5.3)	-16.2 (3.3)	-16.2 (3.8)
Running	HA	-46.5 (7.9)	-0.2 (3.6) [a]	-8.0 (2.0)	-11.5 (3.5)	-13.7 (3.2) [a]	-13.1 (3.8) [a]
	LA	-37.0 (10.2)	-6.7 (5.5)	-5.6 (1.5)	-12.6 (3.6)	-17.4 (2.6)	-16.0 (3.3)
Stepping	HA	-38.2 (8.8) [d]	2.6 (4.8)	-11.7 (5.4) [a]	-7.7 (4.2)	-15.9 (4.9)	-13.6 (5.4)
	LA	-33.7 (6.9)	-.5 (3.6)	-6.2 (5.1)	-9.6 (3.5)	-18.5 (3.5)	-16.4 (2.8)
Landing	HA	-8.4 (5.7)	-0.7 (4.7)	-7.7 (2.1)	-4.4 (4.4)	-15.5 (4.4)	-12.3 (4.7)
	LA	-5.2 (10.2)	-4.2 (4.0)	-6.5 (3.1)	-9.9 (4.8)	-18.2 (3.6)	-13.0 (2.0)

Note: Inv – Inversion
Ev – Eversion
ER – External Rotation
PF - Plantarflexion
$_{max}$ – Peak
$_{exc}$ – Excursion
$_{HS}$ – Beginning of the movement
$_{TO}$ – End of the movement
[a] Significant group effect between HA and LA groups
[b] Significant movement effect between walking and running
[*] Significant group x movement interaction in walking and running
[d] Significant movement effect between stepping and landing

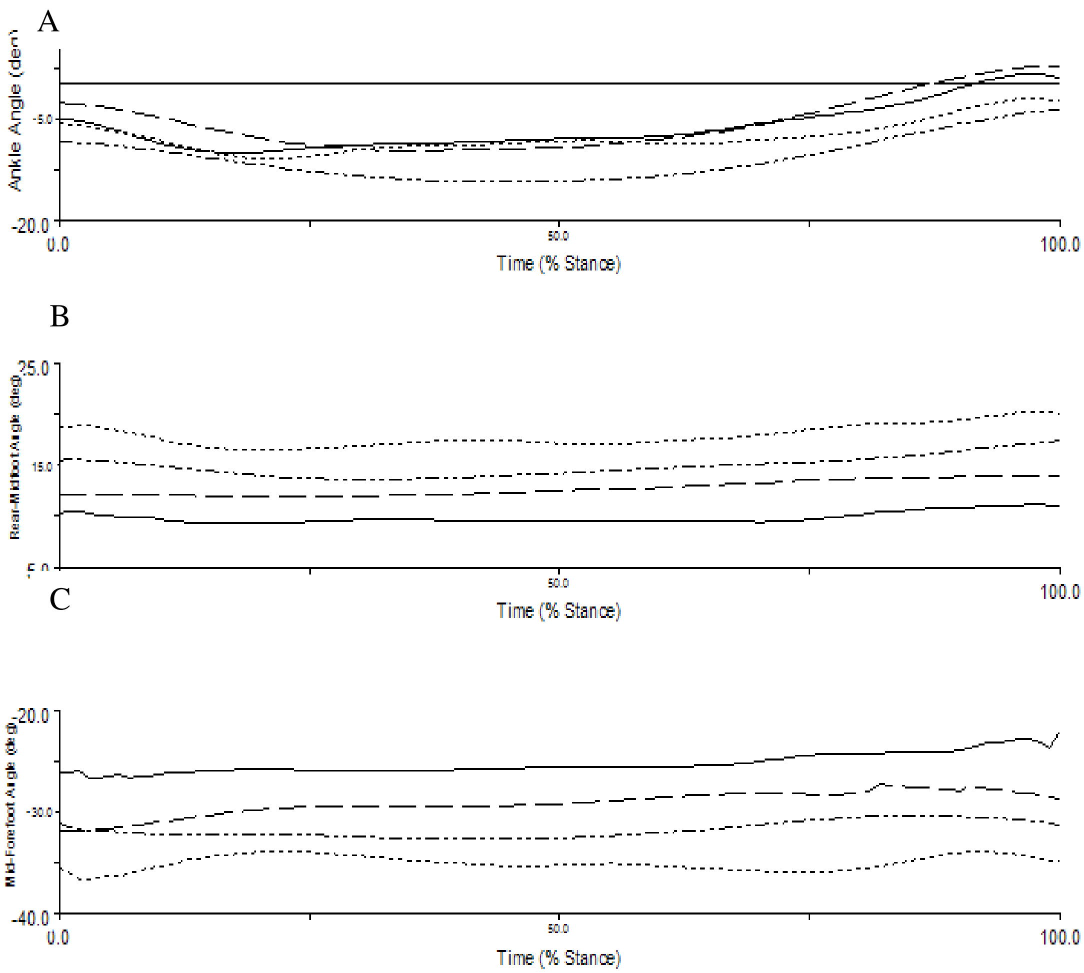

Figure 1. Ensemble frontal plane joint angle curves for the ankle (A), rear-midfoot (B) and mid-forefoot joints (C) in the HA walking (solid) and running (---) and LA walking (···) and running (–··–··) movements.

In the mid-forefoot joint, the HA athletes had significantly less eversion at heel strike in walking than their LA counterparts (F=5.15, p=0.037, Table 3; Figure 1C). Moreover, the HA athletes exhibited significantly smaller peak eversion angles in walking and running (F=4.88, p=0.041). Additionally there was a significant group x movement interaction for eversion excursion (F=6.47, p=0.022). Though no differences in eversion excursion were observed in walking, in the running condition the HA athletes exhibited an inversion excursion while the LA athletes had a greater eversion excursion compared to walking (F=5.12, p=0.038). In the transverse plane, smaller internal rotation angles were observed during running compared to walking in both the HA and LA athletes (F=5.38, p=0.033). In addition, there was a significant group x movement interaction for internal rotation excursion (F=4.91, p=0.040). In the running compared to walking conditions, the HA athletes reduced internal rotation excursion from 9.4° to 6.4°. The LA athletes, however, increased their internal rotation excursion from 6.4° to 7.7°. Furthermore, the HA athletes had greater external rotation excursion compared to their LA counterparts in the walking movement (F=5.84, p=0.028).

3.2 Downward Stepping & Landing

For the ankle, the HA and LA athletes exhibited significantly less plantarflexion at the end of the landing movement compared to the downward stepping movement (F=216.31, p<0.001; Table 1). Additionally, the HA exhibited significantly greater eversion excursion compared to their LA counterparts in downward stepping (F=5.87, p=0.026). In the rear-midfoot joint the HA and LA athletes exhibited comparable kinematic patterns including peak inversion and eversion values as well as inversion and eversion excursions (Table 2). Similarly, in the mid-forefoot joint the HA athletes exhibited few significant differences in frontal plane mechanics compared to the LA athletes. No differences were observed between the two groups in peak inversion or eversion and the HA and LA athletes exhibited similar inversion and eversion excursions during the downward stepping task (Table 3). However, the landing task resulted in greater inversion excursion compared to the downward stepping task (F=4.709, p=0.044; Table 3).

Table 2. Mean rear-midfoot joint angles (degrees) of high- (HA) and low-arched (LA) athletes: mean (SD).

Movement	Group	PF_{max}	Ev_{max}	$T\text{-}Ev_{max}$	Ev_{exc}	Inv_{max}	Inv_{exc}
Walking	HA	-3.8 (0.6) [a]	5.8 (9.3)	0.274 (0.107) [a, b]	-0.8 (3.3)	12.2 (5.8)	1.0 (2.8)
	LA	-2.2 (1.6)	12.2 (17.3)	0.179 (0.072)	-1.7 (2.0)	15.6 (4.3)	0.9 (1.8)
Running	HA	-4.1 (3.6)	5.1 (9.5)	0.128 (0.038)	-2.3 (2.6)	10.7 (7.8)	1.7 (2.7)
	LA	-0.7 (4.0)	9.4 (13.8)	0.103 (0.038)	-1.7 (3.4)	16.7 (3.3)	1.5 (2.7)
Stepping	HA	-6.4 (3.9)	6.4 (8.9)	0.364 (0.174)	-2.7 (2.0)	13.9 (6.2)	0.6 (1.8)
	LA	-9.0 (5.6)	13.2 (17.4)	0.326 (0.210)	-2.2 (1.4)	19.1 (8.7)	0.6 (1.1)
Landing	HA	3.0 (2.9)	6.8 (8.3)	0.081 (0.036)	-2.8 (2.5)	10.2 (9.3)	-0.6 (2.2)
	LA	4.0 (4.5)	13.9 (17.2)	0.092 (0.035)	-1.2 (2.2)	18.7 (6.8)	-0.1 (1.9)

Note: T – Time to event
Inv – Inversion
Ev – Eversion
PF – Plantarflexion
$_{max}$ – Peak
$_{exc}$ – Excursion
[a] Significant group effect between HA and LA groups
[b] Significant movement effect between walking and running

Table 3. Mean mid-forefoot joint angles (degrees) of high- (HA) and low-arched (LA) athletes in the frontal and transverse planes: mean (SD)

Movement	Group	Ev_{HS}	Ev_{max}	Inv_{exc}	Ev_{exc}	IR_{max}	IR_{exc}	ER_{exc}
Walking	HA	-25.2 (7.7) [a]	-27.9 (8.5) [a]	3.2 (5.6)	-0.4 (3.7) [*]	3.8 (5.1) [b]	9.0 (4.1) [*]	3.1 (2.4) [a]
	LA	-38.4 (11.8)	-37.5 (12.5)	3.9 (4.0)	-0.1 (3.1)	0.6 (4.6)	6.4 (5.2)	-1.6 (8.2)
Running	HA	-27.8 (9.8)	-25.7 (6.9) [a]	6.0 (4.3)	3.0 (4.5) [a]	0.2 (6.3)	6.4 (3.0)	-0.2 (3.6)
	LA	-33.2 (10.7)	-34.2 (9.7)	1.3 (4.9)	-2.3 (4.3)	-1.6 (4.3)	7.7 (5.2)	-1.1 (5.5)
Stepping	HA	-24.7 (10.4)	-28.3 (8.4)	3.1 (2.9) [d]	-1.3 (3.0)	4.2 (7.9)	6.2 (3.7)	-1.5 (3.2)
	LA	-34.2 (12.4)	-37.4 (11.9)	3.5 (3.8)	-1.8 (0.86)	-0.13 (4.6)	7.7 (5.9)	-1.7 (5.1)
Landing	HA	-25.8 (8.2)	-27.1 (8.5)	2.4 (2.3)	-0.72 (3.8)	-3.4 (6.4)	-3.2 (9.1)	-6.7 (9.4)
	LA	-33.9 (13.0)	-37.1 (12.3)	0.5 (0.9)	-1.8 (1.3)	-8.0 (5.2)	-1.1 (4.2)	-3.8 (4.2)

Note: Inv – Inversion
Ev – Eversion
IR – Internal Rotation
ER – External Rotation
$_{max}$ – Peak
$_{exc}$ – Excursion
$_{HS}$ – Heel Strike
[a] Significant group effect between HA and LA groups
[b] Significant movement effect between walking and running
[*] Significant group x condition interaction
[d] Significant movement effect between stepping and landing

4. Discussion

4.1 Walking & Running

In shod running most subjects experience a heel strike followed by foot flat; however, it has been shown that a more horizontal foot position at initial contact is preferred in barefoot running (De Wit *et al.*, 2000). Though a midfoot to forefoot strike pattern will not reduce contact forces and increases vertical loading rate (De Wit et al., 2000), it has been suggested that it optimally reduces plantar pressures under any given portion of the foot with specific reference to the heel region (De Wit et al., 2000). In the current study the HA and LA athletes exhibited similar forefoot segmental angle patterns during walking and running. These similarities could be explained by the presence of a midfoot or forefoot strike pattern during the walking and running tasks. A forefoot strike would create similar angular kinematics in the forefoot as movement of the forefoot would be constrained by the floor. Furthermore, the unique motion patterns associated with aberrant foot function that was expected to be found in these structurally different feet may be minimized by an altered foot position at initial contact. Although differences have been observed in the sagittal plane foot contact position, it has been shown that runners exhibit similar frontal plane mechanics in shod and barefoot running (Stacoff *et al.*, 2000a). However, it is suggested that this relationship may not persist in individuals with aberrant foot structures (Stacoff et al., 2000a). The current study did not compare shod and barefoot running, but measured multi-segment foot motion obtained during barefoot walking and running tasks. As was consistent with previous research, it was expected that the HA athletes would exhibit a more rigid foot and would be less everted at the ankle and within the foot compared to the LA athletes. The findings of this study do not support the hypothesis that the HA athletes will exhibit smaller range of motion as evidenced by excursion values at the ankle and within the multi-segment foot, however the hypothesis that the HA athletes are less everted than their LA counterparts was supported by these data.

Only a single statistically significant difference was observed in excursion values between the HA and LA athletes in all joints within the foot and ankle in both walking and running tasks (Tables 1, 2 & 3). During the running condition the HA athletes exhibited an inversion excursion at the mid-forefoot joint, however the LA athletes exhibited an eversion excursion (Table 3). These different responses to the added load of running created a statistically significant group x movement interaction. However, these discrete data do not completely describe motion of the mid-forefoot joint. Eversion excursion is defined as the deviation from heel strike to peak eversion. In the LA athletes in walking and running and in the HA athletes during the walking condition, an initial eversion excursion was observed in the mid-forefoot joint (Figure 1C). However, the initial eversion movement was absent after initial contact in the HA athletes during the running condition. As no initial eversion occurred in the mid-forefoot joint in the HA athletes during running (Table 3), the eversion excursion value at the mid-forefoot joint did not represent a shock attenuation mechanism as it does in the LA athletes or HA athletes in walking, and does not accurately depict the changes in range of motion in response to loading. As this was the only difference between the HA and LA athletes in excursion values, these data show that the HA and LA athletes exhibit similar joint excursions during walking and running. Furthermore, these data do not support the hypothesis that the HA athletes have smaller eversion excursion values within the foot and ankle during walking and running.

The second hypothesis was supported as the HA athletes did exhibit less eversion at the ankle and within the foot compared to LA athletes during dynamic tasks. The HA athletes had greater peak inversion at the ankle in both walking and running, however this occurred during terminal stance and was not associated with loading response (Figure 1C; Table 3). In addition to having greater inversion at the ankle, the HA athletes exhibited less mid-forefoot joint eversion at initial contact and less peak eversion in the mid-forefoot joint. The ensemble joint angle curves and discrete variables (Figure 1C; Table 3) revealed that the HA athletes were more inverted in the mid-forefoot joint throughout the stance phase of the walking and running tasks. No differences were found in eversion at the rear-midfoot joint during walking and running. A possible explanation for this may be the large variations in movement exhibited by the LA athletes. The LA athletes exhibited large standard deviations in peak eversion in both movement conditions. Previous research has suggested that large variations in movement patterns are indicative of a lack of control of the joint or segment during a given task (Hamill *et al.*, 1999, Stergiou, N., 2004, Stergiou, N. *et al.*, 2001). Though coordination is beyond the scope of this study, the implications of large variations in movement patterns between subjects suggests a variety of strategies may be used by LA athletes to perform barefoot walking and running tasks.

The Oxford multi-segment foot model, developed by Carson in 2001, does not contain a midfoot segment and assumes that rear-midfoot joint motion is small and transmitted through the midfoot to the forefoot (Carson et al., 2001). The current study found no differences in rear-midfoot kinematic patterns between the HA and LA athletes in the frontal or transverse planes. Small inversion and eversion excursion values show little movement occurred within the rear-midfoot joint. Furthermore, it has been shown that the high- and low-arched feet respond differently to loading (Zifchock et al., 2006) as the high-arch exhibits significantly less deformity compared to the low-arch. If substantial motion occurred in the rear-midfoot joint, these two subject groups with different foot types should have greater differences. The similarity of kinematic patterns within these diverse foot types suggests the motion of the midfoot segment closely follows the rearfoot motion, supporting Carson's assumptions (Carson et al., 2001).

4.2 Downward Stepping and Landing

Few differences were observed between the HA and LA athletes in the downward stepping and landing tasks. It was hypothesized that the HA athletes would have smaller eversion excursion values compared to the LA athletes. The current data do not support this hypothesis. Moreover, these data revealed that the HA athletes exhibited a greater ankle eversion excursion than the LA athletes. The high-arched foot is associated with greater rigidity and greater stiffness in the foot and within the lower extremity. Using the foot as a rigid lever, the HA athletes may preferentially attenuate shock at the ankle. No other group differences were present in the ankle and multi-segment kinematic variables.

The second hypothesis was that the HA athletes would be less everted in the ankle and multi-segment foot compared to their LA counterparts. The current data do not support this hypothesis. No statistically significant differences existed between the HA and LA athletes in peak inversion or eversion. Similarities between the two functionally different groups suggest that differences in shock attenuation during downward stepping and landing tasks do not occur at the ankle or within the foot.

A possible explanation for a lack of significant differences between the HA and LA athletes is that there are no systematic differences between these two groups of athletes based on foot type. Landing is a forceful, dynamic task that requires substantial shock attenuation by the entirety of the lower extremity. Previous research has shown multi-joint adaptation with a shift of contribution of energy absorption from the distal (ankle) to the proximal joint (hip) due to increases in mechanical demand associated with increased landing height (Zhang, S.N. *et al.*, 2000). Strategies used by the HA and LA athletes may be similar at the level of the foot and ankle. However, variability was large suggesting multiple strategies of shock attenuation may have been used within both groups.

While these results provide insight into the differences in high- and low-arched athletes during dynamic loading tasks, the ability to apply these findings to common theories of injury must not be over-stated. Though dynamic barefoot activities allow researchers to easily track the segments within the high- and low-arched foot, the unique adaptations associated with barefoot activities shown by previous research limits the application of these data to foot and ankle motion in shod conditions.

The findings of the current study also provide new information regarding the motion patterns of multi-segment foot kinematics in barefoot running. Barefoot running is becoming more popular as a recreational sport and running shoes are being developed to mimic barefoot running, such as the Nike Freestyle. These data may provide insight into injury patterns based on the increasing popularity of barefoot running. Future research may pertain to the differences between true barefoot running and running in shoes designed to simulate barefoot running.

Another area of interest may be multi-segment foot motion in high- and low-arched athletes within running shoes during dynamic loading activities as these data may provide greater insight into current injury mechanisms within these two groups.

5. Conclusions

The findings of the current study show that the HA and LA athletes exhibit unique kinematic patterns at the ankle and within the foot during barefoot walking and running including peak inversion, peak eversion and inversion and eversion excursions. Few of the observed differences occurred in the rear-midfoot joint suggesting that mid-foot motion closely follows rear-foot motion. Furthermore, no differences were observed in the multi-segment foot during the downward stepping and landing tasks, though a significant difference in ankle eversion excursion was present between the groups.

While these results provide novel insight into the differences in high- and low-arched athletes during dynamic loading tasks, the ability to apply these findings to common theories of injury must not be over-stated. Though dynamic barefoot activities allow researchers to easily track the segments within the high- and low-arched foot, the unique adaptations associated with barefoot activities shown by previous research limits their application to shod injury prevention. However, these data may dispel common misconceptions regarding the nature of motion within the high- and low-arched foot during activity.

The findings of the current study also provide novel data regarding the motion patterns of multi-segment foot kinematics in barefoot running. Barefoot running is becoming more popular as a recreational sport and running shoes are being developed to mimic barefoot running, such as the Nike Freestyle. These data may provide insight into future injury patterns based on the increasing popularity of barefoot running. Future research may pertain to the differences between true barefoot running and running in shoes designed to simulate barefoot running. Another area of interest may be multi-segment foot motion in high- and low-arched athletes within running shoes during dynamic loading activities as these data may provide greater insight into current injury mechanisms within these two groups.

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Chapter 4: Effects of Vertical Loading on Arch Characteristics and Inter-segmental Motions of Foot

Effects of Vertical Loading on Arch Characteristics and Inter-segmental Motions of Foot

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Abstract

Background: The effect of arch structure on injury patterns has been reported by many authors. However, the mechanisms by which aberrant foot structure or function create injury are still not completely understood. The medial longitudinal arch plays a major role in determining lower extremity kinematics. It is therefore necessary to understand the dynamics of the arch structure in response to load. The purpose of this study was to examine arch function in high- (HA) and low-arched (LA) feet during a vertical loading condition. **Materials & Methods:** Ten high- and ten low-arched females performed five trials in a sit-to-stand exercise. Ground reaction force (1200 Hz) and three-dimensional kinematics (240 Hz) were collected simultaneously. **Results:** HA athletes were less everted than the LA athletes; however no differences were exhibited in range of motion values. The HA athletes had greater vertical deformation of the arch than the LA athletes; however, dynamic arch index decreased with the addition of loading. **Conclusions:** Functional differences between the HA and LA athletes occur through vertical compression of the arch rather than increased frontal plane ranges of motion. Though the HA foot has been associated with greater rigidity than the LA foot, low-arched feet exhibited less arch deformation than the high-arched foot as the floor may have limited the arch compression.

1. Introduction

The foot is a complex structure made up of 26 bones and over 100 ligaments. [1] Mal-alignment and dysfunction of the foot creates altered loading patterns resulting in a greater propensity of injury. [2-5] Furthermore, aberrant foot function has been associated with overuse injuries from repetitive stresses [6-12] as well as acute traumatic injury including rupture of the ACL [13-16]. Many methods have been developed to aid clinicians in assessing foot function including arch index [17-20] and arch stiffness [21]. The arch index as described by Williams [20] assesses the height of the dorsum normalized to truncated foot length. The measure has been shown to be reliable and valid in determining foot type [20]. However, the arch index measurement is a static measurement and previous research has suggested that static measurements do not successfully predict dynamic motion of the foot [22-24]. Another method of assessing foot function is arch stiffness [21]. Arch stiffness is a quasi-static measurement that assesses foot function by determining the response of the foot structure to a given vertical load. It accomplishes this task by comparing the arch index in seated and standing positions normalized to the vertical load experienced by the foot [21]. Though these measures have been shown to be valid [20, 21], reliable [20, 21]and have a direct relationship with increased injury rates [2, 4] and unique injury patterns [2, 4] the response of the arch to a vertical load is still not well documented and understood.

It has been suggested that the high-arched foot is rigid and the low-arched foot is hyper-flexible [4, 20, 21]. However, it is unknown as to whether the hyper-mobility of the foot is accomplished by vertical compression of the arch or through frontal plane motion within the foot segments. Prior research has measured arch deformation in response to vertical loading and revealed that low-arched individuals exhibit greater arch deformation in response to a load. These data suggest that the arch deforms vertically in response to load, however no kinematic data were collected [21]. Another research study examined kinematics within the foot using a multi-segment foot model during dynamic activities and revealed that high- and low-arched athletes exhibit similar range of motion values [25]. However, these kinematic measures were taken during highly dynamic tasks including walking, running, stepping and landing activities and could be influenced by extrinsic muscle activation as well as the physical constraints of these tasks [25-30]. Therefore, the purpose of this study was to examine the biomechanical characteristics of high- and low-arched feet under a vertical loading during a sit-to-stand movement task to determine the nature of response within the foot to an increased vertical load. It was hypothesized that high-arched feet would 1) have smaller peak eversion angles at the ankle and within the foot segments, 2) have less eversion excursion, and 3) exhibit less vertical deformation during the sit-to-stand movement than the low-arched feet.

2. Materials & Methods

2.1 Subjects

Fifty-five healthy, recreationally active females were screened for inclusion in this study. A total of 20 subjects participating in a larger study with an arch index of greater than 0.375 or less than 0.290 were placed into a high- (n=10) or low-arched (n=10) group, respectively (Table 1). Arch index was calculated as defined by Williams et al. [20] The high- and low-arched groups were 1.5 standard deviations above and below the mean of 604 feet (0.330 ± 0.031) previously reported. [31] All subjects were free of injury at the time of testing and signed a written informed consent form approved by the Institutional Review Board prior to participating in the study.

2.2 Experimental Protocol

Each subject participated in two testing sessions. During the first session, anthropometric measurements and subject information were obtained. Anthropometric measurements including total foot length, truncated foot length, and dorsum height were measured using an Arch Height Index Measurement System (AHIMS JAK Tool and Model, LLC). [32]

During the second session, participants first performed a warm-up and stretched for 5-10 minutes. Each participant then performed five trials of a sit-to-stand exercise. The sit-to-stand exercise required the participant to stand from a seated position on a stool from an adjustable height to maintain an approximate 90° of knee flexion with the right foot placed on a force platform. The participant then stood while the hands and arms were extended in front of the body. The end of the movement was defined as peak knee extension. Each movement was conducted barefooted. Three-dimensional (3D) kinematic and ground reaction force (GRF) data were collected simultaneously.

2.3 Instrumentation

An arch height index measurement system (AHIMS JAK Tool and Model, LLC) [32]was used to measure dorsum height, total foot length and truncated foot length of the right foot. These measurements were used in the calculation of arch index as described by Williams and McClay. [20]

A seven-camera motion analysis system (240Hz, Vicon Motion Systems Ltd., Oxford, UK) was used to collect 3D kinematic data from the right side of the lower extremity of each subject. The foot was modeled as three segments: the rearfoot, midfoot and first metatarsal (forefoot). [33] All segments were tracked using retro-reflective markers. A cluster of four retro-reflective markers was used to track the shank and the thigh while two clusters of two retro-reflective markers each were used to track the right and left side of the pelvis. Anatomical markers were placed over the medial and lateral malleoli, medial and lateral epicondyles, right and left greater trochanters, anterior superior iliac spines, iliac crests, and posterior superior iliac spines. A force platform (1200Hz, OR6-7, AMTI, Watertown, MA, USA) was used to measure GRF data. The right foot of the subject contacted the force platform during each trial.

2.4 Data Analysis

Motion capture data were analyzed from the beginning of hip flexion to peak knee extension. Dynamic arch index was calculated as the height of the retro-reflective marker placed on the dorsum divided by the linear distance between the retro-reflective markers placed on the calcaneus and head of the first metatarsal. Dynamic arch index and arch deformation was calculated throughout the sit-to-stand exercise. In addition, arch deformation was calculated by comparing the vertical height of a retro-reflective marker placed on the dorsum of the foot during the sit-to-stand movement to the vertical height of this retro-reflective marker prior to the beginning of the movement. Excursion variables were defined as the difference between peak angle and the angle at the beginning of the movement. All original marker data were filtered using a lowpass filter with 8 Hz cut off frequency while GRF data were filtered using a lowpass filter with 50 Hz cutoff frequency. Selected linear and angular kinematic variables and GRF variables were computed using Visual 3D (C-motion, Inc., Germantown, MD, USA). A customized computer program (VB_V3D, Microsoft Visual Basic 6.0; Microsoft Corporation, Redmond, WA, USA) was used to determine critical events in the selected kinematic and GRF variables. The 3D kinematic angles and moments are defined by the right-hand rule in Visual3D and followed a Cardan X-Y-Z rotation sequence.

An analysis of variance (ANOVA) was used to determine the effect of arch type on each GRF and kinematic variables (SPSS, Chicago, Il, USA) with alpha level set at $p < 0.05$.

3. Results

The HA and LA athletes had similar height and mass though they had significantly different arch index values (Table 4). The HA and LA athletes exhibited different kinematic patterns at the ankle and mid-forefoot joints (Table 5). At the ankle, the HA athletes exhibited significantly smaller peak eversion angles (p = 0.026) though no differences in peak inversion angles (p =

0.093) during the sit-to-stand task (Table 5 and Figure 2). No statistically significant differences were observed between the HA and LA athletes in the rear-midfoot joint (Table 5). At the mid-forefoot joint, the HA athletes exhibited greater peak inversion (p = 0.026) and smaller peak eversion angles (p = 0.048) during the sit-to-stand task (Table 3 and Figure 5). The HA and LA athletes had similar inversion and eversion excursions at the ankle and in the multi-segment foot (Table 5).

The dynamic arch index calculated from motion capture data reveals smaller values than static arch index determined using the arch height index measurement system (Table 4). The HA athletes had significantly greater static arch index (p < 0.001, Table 4) and peak dynamic arch index measurements (p = 0.003, Table 4) than the LA athletes. Though the HA and LA athletes did not exhibit statistically different peak arch deformation values, an interesting trend did exist (p = 0.072, Figure 3).

Table 4. Anthropometric measurements of the HA and LA athletes: Mean (SD).

Group	Age, yrs	Height, m	Mass, kg	Arch Index	Dynamic Arch Index
HA	20.8 (2.5)	1.62 (0.07)	58.32 (5.39)	0.386 (0.010)[a]	0.291 (0.021)[a]
LA	21.1 (2.3)	1.63 (0.07)	58.89 (10.92)	0.259 (0.043)	0.256 (0.025)

[a] Significant group effect between HA and LA groups

Table 5. Frontal plane peak angles and excursions: Mean (SD)

Joint	Group	Inv_{max}	Ev_{max}	Inv_{exc}	Ev_{exc}
Ankle	HA	1.5 (4.5)[b]	-2.6 (3.93)[a]	0.8 (1.1)	-1.3 (1.5)
	LA	-2.1 (4.7)	-8.0 (5.2)	0.0 (2.2)	-2.5 (2.5)
Rear-Midfoot	HA	12.6 (6.8)	6.2 (8.9)	0.5 (1.7)	-0.9 (2.2)
	LA	11.3 (13.1)	9.8 (13.4)	0.0 (0.7)	-1.1 (0.9)
Mid-forefoot	HA	-21.3 (7.0)[a]	-27.8 (8.0)[a]	0.0 (0.8)	-1.4 (1.1)
	LA	-32.0 (12.1)	-37.8 (12.5)	0.4 (0.6)	-0.9 (0.6)

Note: Inv – Inversion
Ev – Eversion
$_{max}$ – Peak
$_{exc}$ – Excursion
[a] Significant group effect between HA and LA groups
[b] The HA athletes showed a trend of being different than the LA athletes (0.05<p<0.10)

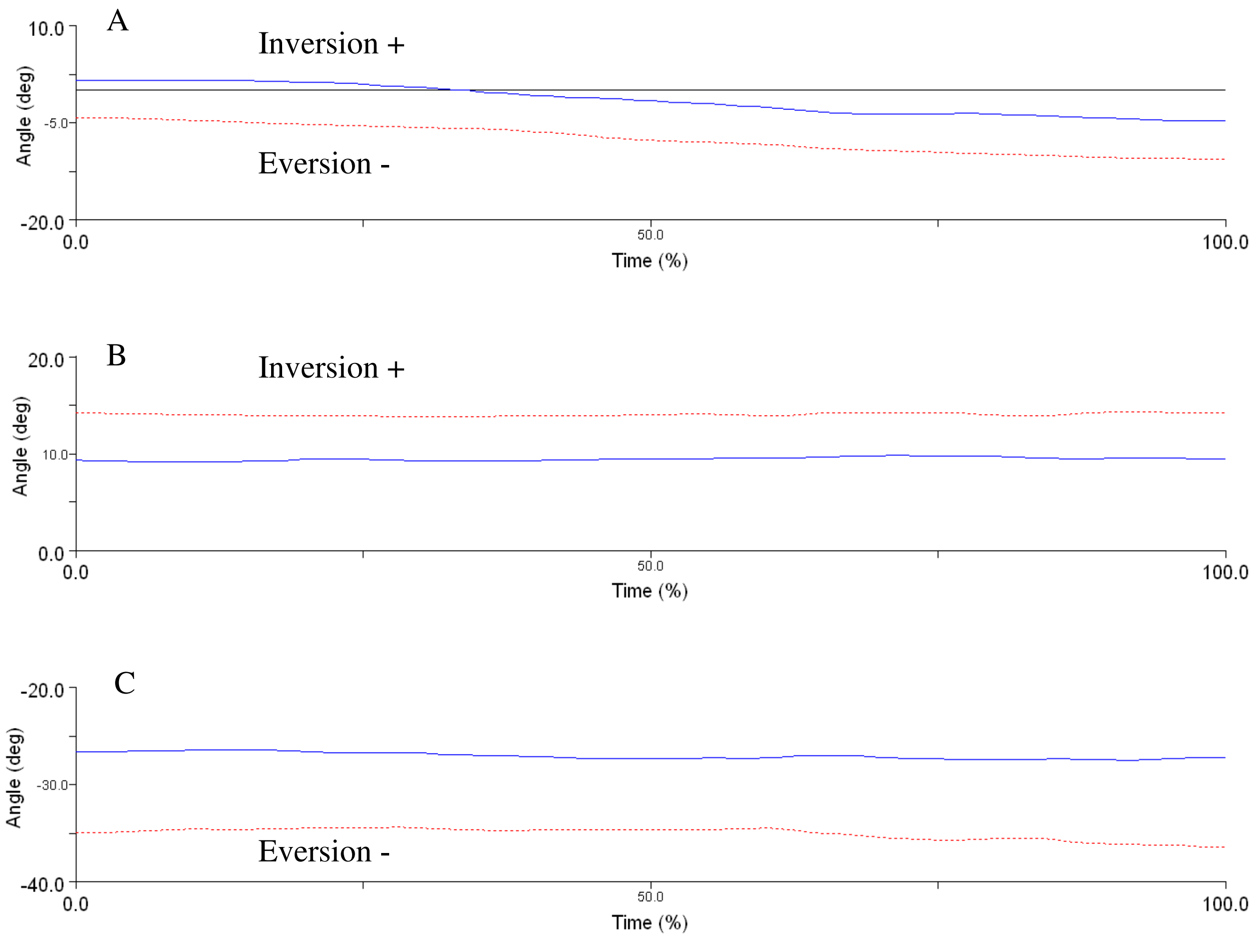

Figure 2. Ensemble curves of frontal plane motion in the ankle (A), rear-midfoot (B) and mid-forefoot (C) joints during the sit-to-stand exercise in the HA (solid) and LA (···) athletes; angles are presented in degrees.

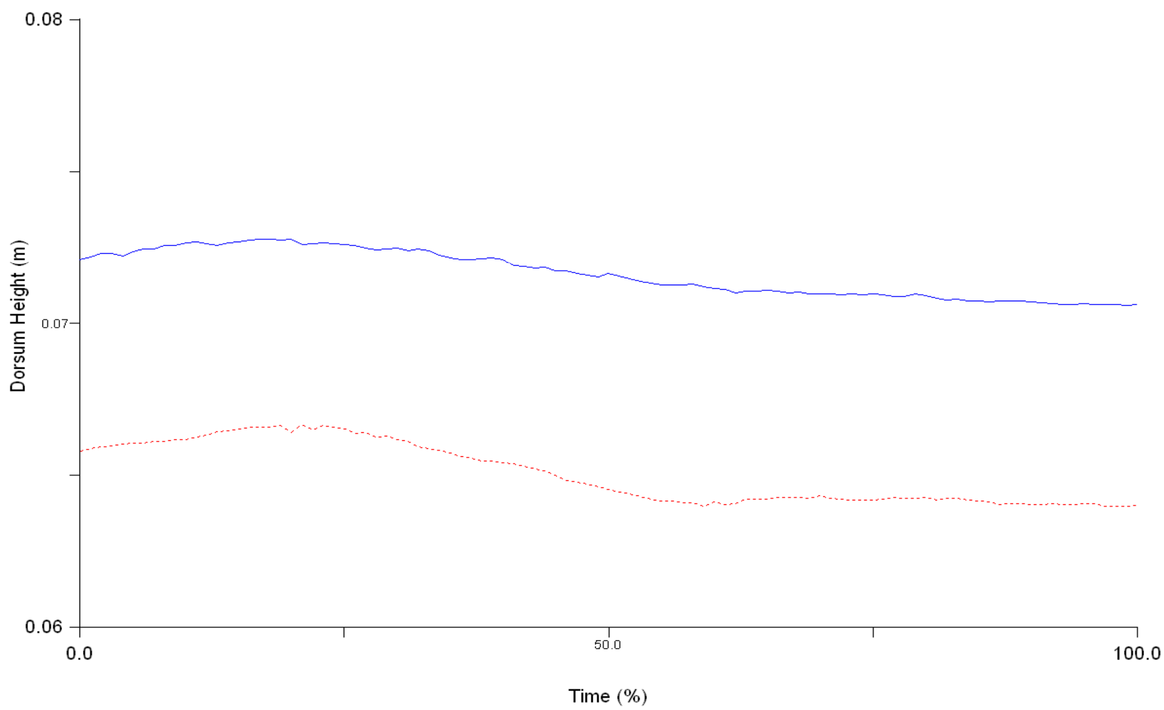

Figure 3. Ensemble curves of vertical dorsum height during the sit-to-stand exercise in the HA (solid) and LA (···) athletes.

4. Discussion

The ankle kinematics showed a trend of greater peak inversion angles and significantly smaller peak eversion angles in the HA compared to LA athletes. However, the HA and LA athletes exhibited similar kinematic patterns in the rear-midfoot joint. These findings support previous data which suggest that small motion occurs in the rear-midfoot joint [25] and this joint does not contribute to the functional differences between the HA and LA athletes. Peak inversion and eversion angles of the joint were not different between the HA and LA athletes. However, the data revealed that the HA athletes exhibited greater peak inversion in the mid-forefoot joint and smaller peak eversion angles than the LA athletes. The findings of the current study support the first hypothesis by suggesting that the HA athletes are less everted at the ankle and within the foot than the LA athletes. These data further support prior research suggesting that the functional differences between the HA and LA athletes occur in the ankle and mid-forefoot joints [25, 26, 28].

Though the HA athletes were less everted than the LA athletes in the ankle and the mid-forefoot joints, the HA and LA athletes exhibited similar inversion and eversion excursions in the ankle and multi-segment foot. Excursion is a measure of the peak range of motion in a given direction from movement onset. Previous research has suggested that the high-arched foot is associated with greater rigidity and less deformation under a given load suggesting smaller excursion values would be observed within the HA athletes. [21] The current excursion data suggest that while the HA athletes were less everted than the LA athletes, both groups exhibit similar range of motion values during the sit-to-stand exercise. These findings suggest the functional differences between the HA and LA athletes are not created through differences in frontal plane range of motion. These data also support previous findings which also showed no range of motion differences within the ankle and multi-segment foot of these HA and LA athletes in the sit-to-stand task. [25] It could be argued that the level of loading of the sit-to-stand task is not sufficient to produce substantial differences in range of motion values in these two structurally different foot types; however, previous research has focused on substantially more dynamic tasks with higher levels of loading and also found no differences in range of motion variables in the ankle and multi-segment foot. [25]

As no differences were present in frontal plane range of motion, the functional differences between the HA and LA athletes may be vertical deformation of the arch in response to loading. The dynamic arch index calculations show that as the subject stands, the arch index decreases (Figure 1). The dynamic arch index is calculated as the height of the dorsum, tracked by a retro-reflective marker, divided by the length of the foot from the first metatarsal head to the calcaneus [20]. The HA athletes had a greater dynamic arch index value than the LA athletes as expected. However the two groups demonstrated similar dynamic arch index patterns and changes throughout the movement. In addition, arch deformation calculations show that as load increases the vertical height of the dorsum decreases (Figure 3). In the HA athletes a relatively linear arch deformation is associated with the progression of the sit-to-stand task; however, in the LA athletes the linear portion of the graph ends at approximately 80% of the completion of the task. At 80% of task completion, arch deformation ceases until the end of the movement in the LA athletes. A possible explanation for these differences in vertical arch deformation is that at approximately 80% of task completion the arch in the LA athletes can no longer be deformed as it is being supported by the floor. In the HA athlete, the arch continues to deform with greater vertical loading until maximum loading is reached at the full standing position. Initial investigation into arch stiffness and arch deformation during vertical loading used a quasi-static assessment measuring arch deformation at loads of 10% body weight and 50% body weight. [21] The methodology used in the arch stiffness research removed the effect of the floor by having the arch unsupported. However, in activities of daily living and athletic tasks the arch is rarely unsupported, which may limit the application of these findings. Zifchock's research did provide a new, functional measure of arch dynamics relating to foot type and the findings of the current study show that arch deformation is the functional difference between the HA and LA athletes in dynamic loading tasks. [21]

The findings of the current study show that the HA and LA athletes exhibit different kinematic and arch deformation patterns. However, these findings may be difficult to apply to athletic tasks. Subjects performed each movement barefoot without the support of a shoe. Most athletic tasks leading to over-use and traumatic injury occur in a shod foot. The role of the shoe in shock attenuation and arch support cannot be ignored and limits the application of the findings of this study. Moreover, the forces applied to the lower extremity during the sit-to-stand task is small compared to the forces associated with acute and over-use injuries further limiting the application of these findings.

The findings of the current study support the notion that the HA athletes are less everted at the ankle and mid-forefoot joints. Furthermore, these data show that the increased flexibility of the foot within the LA athletes reflected by greater arch deformation is not due to greater eversion excursion. The current data show that vertical arch deformation and less eversion are the mechanisms by which the HA and LA athletes differ functionally. The greater eversion associated with the LA athletes leads to a more medial center of pressure location loading the medial aspect of the lower extremity. Moreover, greater eversion may have a torsional effect on the foot and lower extremity resulting in greater rates of injury to soft tissues including the plantar fascia. The Achilles tendon attaches to the calcaneus and continues as the plantar fascia beneath the arch. A more everted position of the foot and ankle could result in a greater stress on the plantar fascia. Additionally, as the ankle is modeled as a mitered-hinge joint, the motion of the foot would create altered loading throughout the entirety of the lower extremity resulting in injuries to the medial aspect of the lower extremity. Conversely, the less everted position of the HA athletes would lead to a more lateral location of the center of pressure in a vertical loading task. As eversion has been shown to be a strategy of shock attenuation, the HA athletes may not attenuate shock as efficiently as the LA athletes leading to a greater magnitude of load experienced by the lower extremity of the HA athletes. Furthermore, that loading pattern would be applied to the lateral aspect of the lower extremity resulting in more lateral injury locations than the LA athletes.

The current data also support previous research that suggests a multi-segment foot model does not require an independent mid-foot segment to accurately describe differences in multi-segment foot motion between HA and LA athletes. [25, 34] Future research may pertain to the effects of orthotics on multi-segment foot motion during dynamic loading tasks.

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Appendixes

Table A-1: Anthropometric measurement

Group	Subject	Arch Index	Mass (kg)	Height (m)	Age (yrs)
1	3	0.391	66.36	1.80	24
1	14	0.378	57.73	1.65	19
1	7	0.381	65.91	1.65	26
1	11	0.383	56.82	1.57	19
1	13	0.377	59.09	1.60	18
1	21	0.41	58.18	1.65	20
1	22	0.385	47.27	1.55	21
1	23	0.386	58.64	1.57	20
1	24	0.377	58.64	1.57	22
1	26	0.392	54.55	1.60	19
2	1	0.274	56.81	1.58	24
2	9	0.271	61.36	1.68	25
2	10	0.269	50.45	1.60	20
2	12	0.137	45.90	1.52	23
2	15	0.26	58.89	1.63	19
2	25	0.274	65.91	1.75	21
2	27	0.275	83.64	1.60	20
2	28	0.266	56.82	1.63	18
2	29	0.283	54.54	1.68	22
2	30	0.28	54.54	1.66	19

Table A-2: Informed Consent Statement

Principal Investigator:
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Introduction
You are invited to participate in a research study on foot structures entitled, "Relationship between foot structures and lower extremity biomechanics". The purpose of the study is to examine relationship between foot structures and biomechanical characteristics during several dynamic movements.

Testing Protocol
You should have had no history of major injuries to the lower extremity and be injury free at the time of testing. You will be asked to attend two biomechanical testing sessions. The first session will take approximately 20 minutes to complete and will involve you will filling out a questionnaire about your age, height, and activity and injury history as well as having several measurements taken of your right foot. The second testing session will take approximately 75 minutes and begin with a standard warm-up using a stationary bike and stretching. During the actual testing, you will perform 5 trials in each of barefoot walking, running, stair descent and landing, body weight squatting and standing from a stool. During the test, biomechanical instruments will be used to obtain measurements. Some of these instruments will be placed/fixed on your body. None of the instruments will impede your ability to engage in normal and effective motions during the test. If you have any further questions, interests or concerns about any instrumentation, please feel free to contact Douglas Powell or Dr. Songning Zhang.

Potential Risks
The activities involved in this study will not require you to exert greater efforts than normal daily activities. A potential risk is bruising of the heel since you are performing these activities without shoes. The barefoot running condition will present a slightly greater risk compared to barefoot walking due to higher impact forces, but the number of trials is small and will help prevent injury from repetitive impact. Barefoot landing will also present an increased risk of injury compared to walking, however the height from which you are landing (20cm) is extremely low compared to normal landing heights of 60 to 120cm. Stair descent should not place you at an increased risk of injury compared to walking. Every effort will be made to reduce the risk of injury through proper warm-up and sufficient practice. The lab is equipped with a level walking/running surface with no intrusive objects in the testing area. All tests will be conducted and the qualified research personnel in the Biomechanics/Sports Medicine lab, who will sign a confidentiality statement, will handle the equipment. The Biomechanics/Sports Medicine Lab has tested more than 500 subjects in many research projects related to dynamic movements over the past nine years and none have been injured in any fashion during the test sessions. You will be encouraged to warm

up actively prior to the testing session so that you feel physically prepared to perform effectively and thus minimize any chance for injury. Should any injury occur during the course of testing, standard first aid procedures will be administered as needed. At least one researcher with a basic knowledge of athletic training and/or first aid procedures will be present at each test session. In the event of physical injury is suffered as a result of participation in this study, the University of Tennessee will not automatically provide reimbursement for medical care or other compensation.

Benefits of Participation

Your benefits include assessment of your performance and biomechanics of walking and running. You are welcome to make an appointment to review the data from your tests. In addition, if you wish to have a copy of the results of the study, please let me know.

Confidentiality

Your participation is entirely voluntary and your decision whether or not to participate will involve no penalty or loss of benefits to which you are otherwise entitled. Your identity will be held in strict confidence through the use of a coded subject number during data collection, data analysis, and in all references made to the data, both during and after the study, and in the reporting of the results. Any information about your identity obtained in connection with this study will remain confidential and will be disclosed only with your permission. The results of the data will be disseminated in forms of presentation at conferences, and publication in journals with your identity only referred as coded numbers. The information sheet, consent form and videotape containing your identity information will be destroyed at the end of three years after the completion of the study. If you decide to withdraw from the study, your information sheet and consent form with your identity and injury history will be destroyed at the conclusion of the study.

Contact Information

If you have any questions at any time about the study you can contact either Douglas Powell or his advisor. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at (865) 974-3466.

Consent

By signing, I am indicating that I understand the potential risks and benefits of participation in this study and that I am agreeing to participate in this study.

Subject’s Name: Signature: Date:

____________________ ___________________ __________________

Investigator’s Signature: Date:

_________________________ _____________________

Table A-3: Ankle plantarflexion angle at toe-off

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	49.698±1.089	48.841±3.509	50.519±1.593	84.999±1.211
1	7	53.518±0.982	49.320±1.159	50.644±2.143	74.096±1.491
1	11	58.873±0.471	57.158±2.583	54.228±2.280	84.999±1.211
1	13	73.246±0.887	50.139±1.333	54.064±7.727	81.947±2.590
1	14	60.640±1.742	54.783±3.709	62.969±1.709	84.574±1.926
1	21	56.820±1.442	49.785±1.238	56.234±1.290	69.992±0.998
1	22	53.830±2.268	53.046±5.002	51.502±2.757	83.141±0.977
1	23	53.592±5.679	53.807±2.538	47.970±4.135	79.170±1.823
1	24	51.577±1.091	53.512±3.557	54.457±0.539	84.310±1.193
1	26	58.607±4.166	37.139±4.559	67.88±8.04	89.017±2.256
2	1	73.559±0.417	60.497±2.512	65.400±2.100	88.111±6.933
2	9	67.956±1.526	48.666±1.440	48.774±1.986	79.220±1.106
2	10	57.675±0.695	48.666±1.440	54.239±2.348	82.419±3.494
2	12	62.908±1.945	58.030±2.195	54.226±2.933	92.605±4.934
2	15	66.975±0.504	60.651±4.699	65.787±0.989	87.714±1.285
2	25	61.074±3.153	60.115±3.239	61.341±5.776	87.0±1.3
2	27	46.289±3.586	35.974±2.546	51.714±4.202	93.182±3.540
2	28	64.252±1.486	61.515±1.520	61.929±1.874	100.029±1.872
2	29	63.463±1.707	60.042±3.230	63.116±1.348	87.159±3.653
2	30	54.453±1.626	44.514±1.505	49.285±3.243	67.866±37.952

Note: Group 1: High-arched
Group 2: Low-arched

Table A-4: Peak ankle inversion angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	7.654±1.806	.	9.063±4.147	5.634±1.056
1	7	-5.803±0.474	.	-5.144±3.238	-5.870±0.495
1	11	.	-5.381±0.000	6.447±1.811	5.634±1.056
1	13	.	.	-3.199±3.020	-3.251±0.861
1	14	6.482±2.452	1.255±8.263	2.028±2.355	-1.866±4.744
1	21	3.436±1.594	-3.551±1.088	4.803±3.103	-3.246±1.077
1	22	10.648±1.967	6.150±0.000	9.078±2.723	-2.253±2.062
1	23	-1.098±3.685	-2.906±0.805	-3.44±0.20	.
1	24	0.828±6.143	-1.535±0.000	1.061±2.763	-0.135±1.876
1	26	0.734±5.013	-0.804±2.753	1.262±4.304	.
2	1	-3.934±0.000	.	-4.957±1.269	-0.221±0.403
2	9	-8.855±0.768	-10.481±0.000	2.518±0.546	-2.710±2.444
2	10	1.828±2.546	-10.481±0.000	0.008±1.687	-3.008±0.850
2	12	-1.766±2.957	-15.379±0.000	.	-10.017±0.897
2	15	-3.615±1.334	-1.824±0.000	-1.922±0.393	1.228±0.775
2	25	-2.096±2.844	-3.017±7.981	0.768±2.274	-3.206±4.977
2	27	6.513±1.703	1.735±1.304	1.869±6.455	-4.165±1.396
2	28	-4.072±1.587	-7.794±2.546	-6.714±3.553	-10.509±1.999
2	29	-2.368±2.270	.	4.395±2.321	-5.339±0.000
2	30	-3.706±3.791	-6.151±1.108	-0.389±0.841	.

Note: Group 1: High-arched
Group 2: Low-arched
. : Missing data

Table A-5: Peak Ankle Eversion Angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	-5.780±1.490	-6.959±0.757	-0.1±1.3	1.903±1.240
1	7	-14.490±1.069	-19.170±1.585	-15.087±3.675	-9.058±0.984
1	11	-8.369±1.115	-9.469±1.569	-5.394±2.900	0.8±0.2
1	13	-11.766±1.205	-12.596±0.732	-10.422±1.436	-4.085±0.920
1	14	-13.010±0.784	-11.660±0.972	-12.091±0.735	-8.693±1.832
1	21	-11.070±1.318	-13.365±1.014	-11.232±1.138	-7.507±1.459
1	22	-10.905±1.367	-13.030±1.235	-6.433±0.702	-4.547±1.905
1	23	-5.458±0.701	-11.239±5.004	-4.407±0.658	-1.4±0.9
1	24	-7.428±1.765	-10.007±1.467	-6.4±1.8	-2.474±0.782
1	26	-10.299±2.307	-7.548±0.470	-5.731±2.064	-10.072±0.000
2	1	-6.242±0.555	-11.601±1.175	-8.241±0.598	-2.963±1.588
2	9	-12.367±1.356	-15.867±3.039	-8.239±1.179	-4.029±1.987
2	10	-7.913±0.873	-15.867±3.039	-7.324±1.673	-7.160±3.794
2	12	-17.189±1.487	-16.419±0.704	-15.779±2.095	-14.978±1.465
2	15	-10.764±1.528	-11.158±1.500	-9.618±0.752	-13.320±0.000
2	25	-10.773±3.369	-14.541±0.476	-8.361±0.913	-12.716±1.177
2	27	-1.20±0.78	-5.367±0.785	-3.728±1.303	-7.148±2.037
2	28	-15.690±0.946	-11.860±0.647	-9.844±1.768	-10.867±2.016
2	29	-9.35±0.56	-8.478±1.307	-9.472±2.119	-8.230±1.670
2	30	-15.293±1.486	-15.237±1.413	-14.997±1.720	-17.932±1.560

Note: Group 1: High-arched
Group 2: Low-arched

Table A-6: Ankle Eversion Excursion

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	-8.39±1.99	-10.625±0.972	-7.151±2.763	-3.830±1.577
1	7	4.182±1.065	-10.157±3.459	-11.109±5.226	-4.332±3.251
1	11	-5.63±2.98	-4.165±3.011	-9.514±4.899	-3.830±1.577
1	13	-4.029±1.654	-3.863±0.652	-5.690±1.407	-1.4±0.5
1	14	-5.865±2.314	-4.412±1.829	-6.516±2.983	-9.250±1.776
1	21	-6.49±1.53	-7.836±3.085	-10.298±1.306	-9.260±1.387
1	22	-5.824±2.490	-7.104±1.697	-9.162±2.453	-7.180±1.246
1	23	-6.09±1.87	-10.983±0.104	-9.889±2.092	-5.707±1.934
1	24	-9.797±1.545	-8.136±3.158	-9.846±4.352	-4.585±2.474
1	26	-3.75±1.94	-8.056±0.590	-6.988±1.828	-12.011±3.178
2	1	-3.542±1.360	-6.808±1.098	-7.889±2.460	-2.6±0.8
2	9	-5.484±1.951	-6.359±1.434	-3.942±0.768	-4.620±2.654
2	10	-3.473±1.119	-6.359±1.434	-6.576±1.489	-3.545±3.686
2	12	-9.511±1.651	-3.185±1.955	-6.416±1.349	-6.589±2.118
2	15	-4.102±2.773	-5.537±1.172	-7.558±0.981	-16.111±4.449
2	25	-12.382±2.138	-14.798±2.129	-10.096±1.426	-9.007±5.349
2	27	-4.337±1.951	-6.526±1.116	-9.027±0.966	-11.841±2.970
2	28	-8.51±1.08	-3.180±2.045	-4.594±0.394	-9.499±2.663
2	29	-8.521±1.785	-5.206±1.601	-9.219±3.246	-9.707±1.499
2	30	-4.096±1.493	-8.826±0.962	-8.054±1.931	-10.434±6.057

Note: Group 1: High-arched
Group 2: Low-arched

Table A-7: Ankle external rotation at heel strike

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	-11.227±1.903	-13.285±0.552	-12.890±0.771	-13.192±0.475
1	7	-16.516±3.268	-17.111±3.001	-22.940±1.309	-20.562±2.309
1	11	-7.644±10.352	-11.973±2.287	-15.358±1.810	-13.192±0.475
1	13	-13.779±0.729	-12.848±0.587	-16.690±1.189	-12.760±0.382
1	14	-19.749±0.894	-19.415±1.800	-17.973±0.447	-19.873±0.752
1	21	-17.042±0.908	-17.382±1.252	-20.026±0.974	-18.596±1.001
1	22	-13.837±2.117	-10.104±0.455	-15.810±1.395	-13.984±0.591
1	23	-13.666±0.547	-13.191±0.384	-18.200±2.282	-17.483±1.348
1	24	-19.563±2.307	-21.314±1.302	-22.864±1.469	-19.398±1.315
1	26	-6.702±4.215	-11.065±0.398	-8.007±1.189	-6.444±1.170
2	1	-12.516±0.748	-12.774±1.026	-14.698±2.074	-12.755±1.174
2	9	-16.111±0.876	-16.651±0.724	-15.825±0.458	-14.853±1.028
2	10	-16.433±0.561	-16.651±0.724	-19.549±0.434	-19.218±0.563
2	12	-18.271±0.670	-17.529±1.323	-22.967±0.492	-22.553±3.037
2	15	-17.510±0.838	-18.787±2.147	-20.136±0.748	-23.512±3.113
2	25	-11.773±2.081	-20.910±2.806	-20.036±2.756	-17.8±1.4
2	27	-16.249±1.400	-16.354±1.277	-16.704±0.840	-16.399±1.790
2	28	-15.645±1.106	-16.421±0.997	-16.726±1.838	-18.958±1.297
2	29	-13.889±0.326	-15.952±0.974	-17.166±0.727	-18.140±0.593
2	30	-23.557±0.899	-27.092±1.473	-24.036±1.586	-26.5±1.7

Note: Group 1: High-arched
Group 2: Low-arched

Table A-8: Ankle external rotation at toe off

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	-11.493±0.775	-14.171±0.862	-12.651±1.052	-9.113±0.303
1	7	-18.487±0.436	-20.732±0.438	-20.544±1.350	-11.816±1.192
1	11	-9.023±0.340	-12.203±1.528	-8.629±1.307	-9.113±0.303
1	13	-10.971±0.994	-14.127±2.327	-14.279±1.083	-13.563±0.534
1	14	-19.430±1.194	-21.812±1.179	-21.282±0.846	-18.694±0.957
1	21	-15.958±1.285	-19.466±1.897	-15.768±0.957	-16.678±0.648
1	22	-10.434±1.517	-12.314±3.521	-11.901±0.893	-8.514±0.455
1	23	-10.337±0.945	-18.609±0.303	-9.657±0.863	-13.906±0.443
1	24	-15.144±0.472	-19.578±0.637	-17.764±0.646	-17.422±1.345
1	26	-2.682±2.221	-5.872±4.288	-7.234±1.771	-3.824±1.069
2	1	-7.577±1.030	-9.280±0.637	-10.701±0.770	-10.709±1.959
2	9	-12.919±1.268	-16.959±0.312	-15.033±0.845	-14.946±0.592
2	10	-16.424±0.783	-16.959±0.312	-16.645±0.841	-11.705±0.925
2	12	-19.914±1.305	-20.052±1.486	-18.078±1.960	-11.070±1.043
2	15	-17.424±1.456	-17.421±0.514	-18.551±1.360	-15.168±0.983
2	25	-17.933±0.965	-11.856±4.960	-17.557±1.160	-13.7±2.3
2	27	-14.323±0.442	-17.211±1.257	-16.753±0.971	-15.420±1.619
2	28	-16.549±1.880	-15.416±2.879	-15.682±0.990	-11.682±1.758
2	29	-18.685±0.688	-15.924±1.408	-18.064±1.136	-13.714±1.362
2	30	-20.526±1.666	-24.064±0.559	-19.617±1.489	-18.8±2.3

Note: Group 1: High-arched
Group 2: Low-arched

Table A-9: Peak rear-midfoot plantarflexion angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	-3.483±0.314	-10.135±0.000	-2.445±0.963	1.775±0.823
1	7	-3.829±0.446	.	-0.948±1.244	-0.059±0.706
1	11	-3.089±2.167	-5.484±4.549	-3.383±3.548	1.775±0.823
1	13	-1.106±1.764	.	-1.661±0.340	.
1	14	-3.306±3.262	-10.12±2.55	-1.190±1.220	1.396±0.000
1	21	-4.801±4.345	-2.768±2.979	-2.270±2.387	-2.603±1.011
1	22	-4.539±1.796	-5.023±3.337	-1.941±4.309	.
1	23	-3.769±1.774	-0.377±0.790	-11.084±4.198	-8.199±3.584
1	24	-0.322±0.493	.	-1.763±1.628	3.358±1.068
1	26	-3.745±0.427	-4.08±0.03	-0.568±1.224	1.858±1.174
2	1	-2.423±0.550	-9.23±2.74	1.695±2.355	2.642±4.616
2	9	-2.184±2.309	-0.331±0.545	-0.011±0.734	5.193±0.604
2	10	-18.201±1.502	-0.331±0.445	-16.459±1.329	.
2	12	0.465±3.230	-1.696±2.184	-1.629±1.202	5.016±0.446
2	15	-4.978±1.185	-3.677±0.724	-4.033±0.758	1.967±0.000
2	25	-2.119±1.729	-6.77±1.275	-2.115±4.681	5.396±0.000
2	27	-5.573±0.281	-6.72±1.537	-3.831±0.978	-3.385±0.633
2	28	-2.607±1.765	-0.083±1.243	-0.209±2.064	.
2	29	-1.765±0.686	0.487±0.745	0.352±0.756	.
2	30	-4.885±0.609	.	-7.327±4.737	.

Note: Group 1: High-arched
Group 2: Low-arched
. : Missing data

Table A-10: Peak Rear-Midfoot Eversion Angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	7.719±0.608	7.716±0.981	8.121±0.693	9.648±0.421
1	7	-1.105±0.607	0.329±0.739	-0.226±0.279	0.387±0.252
1	11	17.026±0.840	14.848±2.157	16.951±0.800	9.648±0.421
1	13	18.917±2.472	18.3±0.8	18.332±0.803	19.194±0.863
1	14	0.448±1.636	3.585±1.252	3.093±0.789	5.655±0.397
1	21	8.876±0.498	9.520±0.490	6.672±0.508	9.524±3.196
1	22	14.522±1.081	13.813±1.580	12.996±2.452	15.950±0.566
1	23	1.775±3.572	3.369±2.569	0.837±4.131	6.003±2.641
1	24	-10.496±0.561	-12.3±0.4	-12.330±0.385	-10.534±1.233
1	26	0.603±1.300	0.984±3.033	-3.202±1.672	2.060±2.415
2	1	14.738±1.454	13.987±0.331	10.410±4.769	13.956±1.492
2	9	10.574±2.958	14.469±0.662	13.231±0.197	15.663±0.457
2	10	.	.	.	.
2	12	-7.164±1.194	-6.311±1.509	-9.304±1.004	-7.075±1.391
2	15	20.691±0.403	20.836±0.649	20.652±0.333	21.122±0.409
2	25	4.487±2.284	7.199±1.129	6.782±0.348	8.465±1.285
2	27	-20.008±1.339	-19.073±1.611	-18.298±0.124	-17.357±0.340
2	28	11.342±1.130	11.139±0.860	11.241±1.892	12.559±0.839
2	29	27.502±0.502	27.997±0.509	27.834±0.414	28.616±1.164
2	30	17.346±0.637	17.835±0.307	18.475±0.336	19.318±0.289

Note: Group 1: High-arched
Group 2: Low-arched

Table A-11: Rear-Midfoot Eversion Excursion

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	0.775±0.259	-1.957±1.624	-2.341±1.077	-0.887±0.542
1	7	-2.365±2.954	-2.061±1.075	-0.653±1.002	-1.134±1.141
1	11	1.598±2.922	-1.085±4.770	-6.325±2.594	-0.887±0.542
1	13	-1.773±2.855	-2.769±0.909	-1.549±1.730	-2.331±0.802
1	14	-3.714±2.026	-3.107±2.187	-0.403±1.489	-4.593±1.384
1	21	-3.764±4.810	-4.604±0.769	-3.307±1.110	-5.053±6.473
1	22	-4.177±2.669	-5.504±2.111	-2.143±2.953	-2.576±1.159
1	23	-5.463±4.510	-2.592±1.275	-1.686±0.425	-8.275±24.134
1	24	1.751±3.518	-4.300±1.642	-5.670±3.069	-2.280±2.814
1	26	-1.471±3.397	-3.526±8.579	-4.768±4.169	-0.023±2.403
2	1	3.096±2.772	14.397±3.771	-2.709±0.936	-2.805±1.643
2	9	-2.743±4.447	-4.840±0.764	-0.949±0.822	-0.569±0.310
2	10	-2.644±3.279	-4.840±0.764	-0.516±0.375	-0.250±1.908
2	12	-4.124±1.081	-5.230±2.130	-4.846±1.388	-5.480±1.388
2	15	-1.751±1.035	-2.070±0.932	-1.801±0.584	2.013±3.135
2	25	-4.935±1.807	-3.768±0.830	-1.523±1.566	-1.022±1.057
2	27	3.313±0.339	-2.315±1.124	-3.314±1.486	-0.770±0.305
2	28	-3.119±2.774	-0.867±1.513	-1.493±1.041	1.368±0.859
2	29	-1.912±1.068	-2.295±0.570	-3.635±0.204	-2.963±1.777
2	30	-0.835±0.882	-1.841±0.705	-1.647±1.150	-1.311±0.988

Note: Group 1: High-arched
Group 2: Low-arched

Table A-12: Time to peak eversion angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	0.144±0.040	0.114±0.040	0.463±0.081	0.087±0.043
1	7	0.168±0.081	0.072±0.011	0.421±0.059	0.073±0.014
1	11	0.144±0.025	0.090±0.048	0.153±0.105	0.087±0.043
1	13	0.240±0.056	0.076±0.017	0.510±0.084	0.060±0.009
1	14	0.179±0.156	0.168±0.081	0.438±0.072	0.067±0.006
1	21	0.442±0.078	0.122±0.011	0.271±0.182	0.157±0.126
1	22	0.358±0.170	0.191±0.067	0.274±0.240	0.093±0.014
1	23	0.294±0.078	0.163±0.014	0.190±0.129	0.031±0.025
1	24	0.276±0.103	0.107±0.020	0.322±0.056	0.115±0.048
1	26	0.385±0.115	0.119±0.075	0.222±0.074	0.043±0.031
2	1	0.290±0.070	0.051±0.045	0.373±0.025	0.113±0.118
2	9	0.165±0.099	0.093±0.005	0.393±0.157	0.093±0.049
2	10	0.115±0.021	0.093±0.005	0.529±0.078	0.078±0.048
2	12	0.130±0.036	0.140±0.039	0.443±0.085	0.123±0.020
2	15	0.158±0.038	0.158±0.053	0.373±0.185	0.090±0.057
2	25	0.361±0.153	0.150±0.040	0.328±0.160	0.046±0.026
2	27	0.271±0.237	0.152±0.014	0.343±0.194	0.045±0.010
2	28	0.108±0.060	0.062±0.028	0.428±0.182	0.163±0.034
2	29	0.253±0.157	0.096±0.009	0.151±0.067	0.092±0.019
2	30	0.122±0.059	0.083±0.013	0.291±0.269	0.074±0.007

Note: Group 1: High-arched
Group 2: Low-arched

Table A-13: Peak Rear-Midfoot Inversion Angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	8.833±0.000	.	9.259±1.045	12.577±0.000
1	7	.	2.066±1.458	.	1.065±0.015
1	11	.	20.412±0.605	21.540±1.454	12.577±0.000
1	13	.	20.176±0.868	.	22.212±1.543
1	14	.	5.024±1.572	.	7.160±1.076
1	21	15.012±2.670	13.180±3.391	12.609±3.037	18.085±9.621
1	22	20.922±2.121	16.459±0.929	18.505±1.312	18.168±2.575
1	23	10.004±2.696	5.736±0.949	16.574±5.937	14.881±2.108
1	24	-8.474±2.377	-6.333±2.338	-8.372±0.485	-8.079±1.422
1	26	6.350±4.813	2.199±3.193	4.903±1.935	3.371±0.000
2	1	.	15.956±1.002	.	18.053±1.494
2	9	.	15.87±0.85	13.715±0.000	16.408±0.497
2	10	.	16.216±1.119	.	46.156±0.186
2	12	-5.426±0.000	-6.841±2.033	0.115±0.000	-5.341±2.468
2	15	.	21.683±0.247	21.445±0.054	21.751±0.455
2	25	13.010±5.685	12.537±3.496	10.353±1.034	9.405±0.019
2	27	-16.792±0.321	-16.131±0.898	-16.971±0.270	-16.184±0.822
2	28	13.294±1.652	14.035±2.926	13.667±0.308	13.543±0.848
2	29	32.308±2.371	.	34.399±2.080	30.818±0.000
2	30	20.536±1.187	20.293±0.960	20.877±1.089	20.544±0.000

Note: Group 1: High-arched
Group 2: Low-arched
. : Missing data

Table A-14: Rear-Midfoot Inversion Excursion

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	0.775±0.259	1.039±0.842	1.202±2.050	0.433±1.003
1	7	-2.365±2.954	0.095±1.102	0.506±0.925	-0.515±1.429
1	11	1.598±2.922	2.941±2.334	0.623±2.781	0.433±1.003
1	13	-0.244±1.845	0.122±2.039	0.228±0.826	-0.170±1.199
1	14	-2.817±4.666	-0.554±1.354	0.593±3.256	-3.378±1.199
1	21	3.765±2.552	5.591±3.656	-0.227±3.388	2.350±3.049
1	22	0.507±3.570	-2.273±1.050	1.969±3.017	-1.959±1.401
1	23	1.630±2.400	1.832±3.211	6.940±5.546	-4.808±25.715
1	24	1.526±2.908	1.004±1.748	-3.325±2.013	0.473±1.604
1	26	0.177±2.070	1.348±4.185	-0.850±2.651	1.463±2.581
2	1	4.223±3.410	12.45±2.38	0.161±1.649	0.457±0.388
2	9	-4.526±1.622	-1.757±1.191	2.144±0.370	0.039±0.629
2	10	0.935±0.652	-1.757±1.191	0.953±0.459	1.233±1.205
2	12	3.198±2.017	0.875±5.506	1.546±0.779	-3.843±2.080
2	15	-0.755±0.779	-0.901±0.841	-0.905±0.946	2.376±3.084
2	25	-0.684±4.468	0.932±2.174	1.431±1.574	-0.297±0.956
2	27	1.318±1.467	1.220±2.034	-1.212±0.295	0.404±0.645
2	28	-1.836±2.304	1.729±1.667	0.238±1.560	2.223±1.139
2	29	3.575±2.141	1.963±0.990	1.419±2.801	-2.375±1.683
2	30	2.595±1.214	-0.390±1.400	0.511±1.577	-1.030±0.829

Note: Group 1: High-arched
Group 2: Low-arched

Table A-15: Mid-forefoot eversion angle at heel strike

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	-20.431±1.034	-21.667±2.047	-20.172±0.573	-21.366±0.463
1	7	-14.854±0.563	-15.998±1.866	-10.756±3.403	-10.619±1.250
1	11	-39.981±3.521	-42.741±3.688	-39.030±0.557	-21.366±0.463
1	13	-36.544±3.089	-38.545±0.791	-36.210±0.619	-36.140±1.945
1	14	-24.352±5.757	-24.541±0.936	-24.281±0.551	-30.673±2.594
1	21	-33.412±3.355	-32.862±1.596	-30.037±1.589	-33.753±12.380
1	22	-37.672±0.282	-37.842±2.488	-29.590±7.615	-30.815±2.254
1	23	-15.715±6.404	-27.794±11.864	-15.214±4.074	-18.879±13.981
1	24	-24.456±7.768	-24.200±8.603	-21.969±6.087	-21.443±6.098
1	26	-32.799±5.060	-27.315±7.459	-32.842±4.089	-33.235±3.723
2	1	-23.438±5.075	-23.312±9.805	-29.081±2.224	-26.514±3.200
2	9	-23.775±5.479	-24.788±4.668	-24.178±2.009	-26.492±1.020
2	10	-58.391±0.392	-24.788±4.668	-56.694±1.495	-59.101±1.355
2	12	-33.129±2.251	-32.486±1.920	-28.853±1.619	-28.672±1.034
2	15	-39.071±0.449	-37.620±3.470	-37.437±0.640	-35.375±0.407
2	25	-31.665±1.386	-39.124±4.629	-35.591±2.210	-26.857±15.141
2	27	-15.844±0.505	-17.839±1.027	-14.011±0.662	-14.145±0.813
2	28	-46.014±2.913	-45.035±2.762	-42.674±3.751	-46.014±0.910
2	29	-50.646±1.474	-50.238±1.718	-47.754±2.477	-46.167±1.709
2	30	-39.873±0.850	-37.462±0.675	-37.090±2.379	-29.258±16.390

Note: Group 1: High-arched
Group 2: Low-arched

Table A-16: Peak Mid-Forefoot Eversion Angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	-20.687±0.549	-21.986±1.046	-21.056±0.598	-17.827±0.638
1	7	-15.087±0.512	-15.110±2.508	-14.861±1.416	-14.607±0.924
1	11	-39.532±0.910	-44.112±3.291	-41.649±3.480	-17.827±0.638
1	13	-35.274±0.901	-36.018±1.254	-34.873±0.743	-32.480±1.801
1	14	-26.139±2.856	-22.523±0.088	-24.851±0.501	-27.892±1.364
1	21	-37.303±1.862	-30.649±0.635	-30.279±1.297	-39.875±10.269
1	22	-37.331±1.651	-33.560±3.917	-35.573±4.447	-32.491±1.572
1	23	-19.693±1.348	-21.269±2.050	-27.826±3.596	-30.505±7.719
1	24	-24.480±4.934	-21.152±5.639	-19.136±6.198	-22.702±5.063
1	26	-35.089±2.716	-28.749±2.233	-32.741±0.700	-35.117±2.866
2	1	-29.741±0.760	-28.225±1.602	-29.463±2.133	-27.682±1.712
2	9	-25.262±1.656	-27.120±0.592	-26.255±2.718	-27.781±1.961
2	10	-59.082±3.363	-27.120±0.592	-57.305±1.874	-60.408±0.000
2	12	-29.333±0.935	-30.075±1.237	-30.244±2.484	-29.256±1.343
2	15	-39.258±1.095	-38.874±2.529	-38.641±1.015	-38.109±0.211
2	25	-35.877±2.146	-36.006±3.061	-39.382±4.376	-35.762±1.978
2	27	-18.133±2.014	-18.087±1.465	-17.136±1.492	-18.742±1.880
2	28	-47.017±2.943	-44.434±2.163	-44.795±1.106	-45.869±1.143
2	29	-50.955±2.395	-50.211±2.058	-50.164±1.719	-49.702±1.095
2	30	-40.657±0.497	-41.717±2.220	-40.443±0.603	-37.936±0.615

Note: Group 1: High-arched
Group 2: Low-arched

Table A-17: Mid-Forefoot Inversion Excursion

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	2.908±2.013	5.027±1.171	2.670±2.679	4.583±0.740
1	7	4.565±1.148	5.128±1.886	2.518±4.148	-0.492±1.764
1	11	2.87±5.71	7.528±5.315	2.627±1.482	4.583±0.740
1	13	3.393±2.195	5.179±1.047	2.730±0.971	4.982±1.564
1	14	4.814±3.375	2.794±0.790	0.232±1.114	3.105±1.772
1	21	11.520±3.681	4.247±2.863	3.282±1.370	2.012±11.564
1	22	8.603±6.520	8.119±3.131	7.905±3.561	2.588±1.945
1	23	5.796±6.564	5.734±4.786	0.817±1.823	-1.571±13.091
1	24	4.208±3.357	4.454±3.102	6.780±0.786	4.280±2.628
1	26	6.790±1.764	1.315±9.590	5.589±5.285	0.183±1.394
2	1	-5.401±6.256	-17.715±3.739	1.028±2.144	1.481±1.988
2	9	0.406±4.880	0.669±4.310	1.169±1.406	0.455±0.447
2	10	4.110±0.754	0.669±4.310	0.769±0.811	1.453±0.940
2	12	8.625±2.569	3.913±3.115	8.0±1.848	1.197±0.682
2	15	3.451±1.120	0.169±5.090	2.045±0.745	0.802±0.214
2	25	3.931±2.089	9.529±3.798	3.915±0.750	0.088±1.175
2	27	8.134±3.582	5.961±5.063	7.902±3.971	-0.938±3.306
2	28	5.298±4.429	2.628±2.541	1.752±0.843	1.220±0.731
2	29	6.320±4.667	7.491±4.051	2.519±3.609	-0.236±2.906
2	30	3.713±0.392	0.744±0.245	0.372±3.124	-0.964±2.193

Note: Group 1: High-arched
Group 2: Low-arched

Table A-18: Mid-Forefoot Eversion Excursion

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	2.908±2.013	-0.319±2.693	-0.889±0.758	3.331±1.018
1	7	4.565±1.148	2.591±3.683	-2.903±5.486	-3.944±1.314
1	11	-3.86±1.32	-1.8±2.8	-0.9±1.0	3.331±1.018
1	13	1.703±2.628	1.686±2.514	0.912±1.427	4.394±2.362
1	14	-0.802±3.298	1.113±0.946	-0.773±0.678	2.056±1.757
1	21	-3.695±2.560	-1.170±4.254	-0.242±1.044	-6.040±4.350
1	22	0.710±1.900	6.116±4.502	-2.842±6.982	-0.811±4.426
1	23	-0.518±1.504	0.720±2.386	-12.612±1.481	-5.614±13.828
1	24	-0.462±5.318	3.048±2.964	2.833±1.224	-1.928±3.746
1	26	2.693±3.870	-1.434±5.929	0.101±4.413	-1.997±1.994
2	1	-6.865±4.842	-20.493±5.192	-1.419±2.215	-0.303±3.465
2	9	-3.545±5.919	-2.746±4.506	-1.474±3.195	-1.572±1.624
2	10	-0.691±3.351	-2.746±4.506	-0.612±1.266	-1.298±1.708
2	12	3.797±2.994	1.823±2.916	-1.469±1.848	-0.584±0.904
2	15	-0.187±0.763	-1.254±5.622	-1.205±1.050	-2.789±0.870
2	25	-0.862±4.505	3.541±4.306	-3.609±4.221	-1.753±1.398
2	27	3.819±5.968	1.621±4.316	-3.125±1.697	-4.138±2.130
2	28	2.555±4.947	0.601±2.450	-2.911±4.009	-0.588±0.819
2	29	-0.309±2.126	-1.380±1.356	-2.410±2.625	-3.535±1.565
2	30	-0.785±0.497	-4.791±2.310	-1.774±2.261	-1.587±2.015

Note: Group 1: High-arched
Group 2: Low-arched

Table A-19: Peak Mid-Forefoot Internal Rotation Angle

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	10.532±4.398	2.800±1.408	6.525±1.540	5.240±0.824
1	7	.	-1.361±2.631	-1.014±0.936	.
1	11	5.139±2.519	10.2±3.1	10.801±2.344	5.240±0.824
1	13	-6.298±1.276	-5.909±2.928	-4.458±0.909	.
1	14	2.945±4.428	1.977±3.725	2.442±5.329	-6.835±0.465
1	21	4.223±5.965	-9.883±2.412	-5.328±3.042	-11.420±7.913
1	22	3.787±2.384	1.773±2.909	13.519±6.725	.
1	23	4.501±3.279	-2.058±1.772	11.804±1.911	-5.399±1.299
1	24	2.177±4.651	2.150±5.694	3.465±9.184	-1.807±2.174
1	26	1.207±0.725	-1.610±1.244	-2.426±1.455	-9.126±0.366
2	1	-3.269±2.071	-3.851±2.019	-2.305±2.426	-6.355±0.711
2	9	-1.836±1.251	-2.323±1.854	-1.531±1.681	-3.590±0.576
2	10	6.377±0.941	-2.323±1.854	4.020±2.993	-3.902±6.451
2	12	9.790±1.205	-2.833±2.367	1.595±4.046	-0.164±4.128
2	15	-2.527±2.962	-7.027±7.445	-9.829±1.414	-11.914±1.458
2	25	3.615±4.317	4.362±2.847	1.592±1.116	-4.604±1.495
2	27	-2.087±1.812	1.222±5.498	3.205±4.683	-7.650±2.836
2	28	-1.404±0.925	-5.086±2.062	-2.126±2.799	-16.505±1.408
2	29	1.799±5.833	6.588±6.248	6.648±7.192	-11.774±0.738
2	30	-2.544±0.924	-4.763±0.850	-2.549±1.967	-13.159±0.000

Note: Group 1: High-arched
Group 2: Low-arched

Table A-20: Mid-Forefoot Internal Rotation Excursion

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	5.046±3.900	5.786±3.585	4.381±4.574	-0.101±2.117
1	7	5.040±2.074	2.025±1.307	2.392±4.656	-8.681±1.601
1	11	4.570±3.349	13.715±7.423	9.360±3.363	-0.101±2.117
1	13	4.395±2.251	6.497±3.268	5.264±3.651	-3.300±1.350
1	14	9.816±4.600	4.735±2.149	6.396±5.933	14.321±2.622
1	21	18.022±7.950	3.842±2.824	4.263±4.938	0.452±8.757
1	22	6.647±1.016	7.144±5.245	7.692±8.431	-11.193±3.337
1	23	11.582±1.564	7.583±5.285	18.90±2.49	-4.8±3.6
1	24	6.478±6.395	4.134±1.571	2.197±10.151	0.668±3.556
1	26	10.120±6.367	8.850±5.390	6.978±3.350	-4.223±3.957
2	1	11.148±5.239	14.389±4.187	8.819±1.567	3.999±2.120
2	9	4.423±2.549	6.890±2.345	5.337±1.775	-1.278±3.241
2	10	9.392±1.456	6.890±2.345	16.308±2.512	6.300±3.000
2	12	8.754±3.543	12.9±3.0	6.982±1.304	-0.171±3.264
2	15	11.449±2.739	9.276±9.838	18.724±1.146	-1.501±3.396
2	25	-5.527±5.273	4.930±2.596	2.304±1.272	-1.088±3.622
2	27	6.046±5.791	7.070±6.424	0.120±4.964	-8.399±3.637
2	28	5.449±1.323	2.006±9.661	5.289±3.761	-1.645±1.898
2	29	11.978±3.436	4.154±6.157	7.412±6.065	-5.854±6.504
2	30	6.718±4.692	3.329±1.319	8.974±2.902	-1.708±2.198

Note: Group 1: High-arched
Group 2: Low-arched

Table A-21: Mid-Forefoot External Rotation Excursion

Group	Subject	Walking	Running	Downward Stepping	Landing
1	3	5.046±3.900	1.662±3.214	-1.028±2.667	-4.142±0.863
1	7	5.040±2.074	-3.628±2.432	-2.027±2.454	-9.576±1.635
1	11	0.796±2.172	-8.6±3.7	7.884±6.120	-4.142±0.863
1	13	3.410±3.199	1.385±1.824	0.980±1.701	-4.745±1.448
1	14	3.903±4.399	2.227±3.327	0.728±2.902	13.681±2.904
1	21	1.930±3.108	-2.667±1.688	-1.029±3.896	-11.0±1.6
1	22	-3.79±4.03	-4.623±4.130	-6.832±6.238	-11.591±3.571
1	23	-0.140±3.595	1.971±8.440	-2.019±3.692	-7.6±5.7
1	24	0.042±6.315	-7.773±3.698	-7.858±1.912	-3.451±3.109
1	26	4.454±7.539	-1.803±7.447	-2.124±1.446	-6.120±2.686
2	1	9.792±4.265	9.843±5.247	4.310±2.793	1.741±2.574
2	9	3.020±4.130	3.063±2.248	-1.625±1.395	-3.988±1.708
2	10	-0.395±0.401	3.063±2.248	8.197±3.566	3.925±4.223
2	12	-16.20±3.85	-3.537±3.136	-2.999±2.278	-5.186±3.716
2	15	6.286±5.236	-5.441±5.803	-1.134±1.462	-4.371±1.978
2	25	-9.616±4.176	-1.497±6.566	-5.497±4.727	-4.304±2.758
2	27	-2.815±1.969	-4.446±2.758	-11.450±1.367	-10.294±3.033
2	28	-6.089±6.637	-8.297±10.272	-4.665±2.089	-4.021±0.928
2	29	-5.545±6.651	-6.962±7.198	-7.721±5.160	-8.517±5.602
2	30	0.598±2.310	-2.186±1.701	-0.456±3.339	-3.335±2.612

Note: Group 1: High-arched
Group 2: Low-arched

Table A-22: Ankle kinematics during the vertical loading task

Group	Subject	Inv_{max}	Ev_{max}	Inv_{exc}	Ev_{exc}	ROM
1	3	2.692±1.202	-1.886±1.275	2.264±1.954	1.320±3.274	2.963±2.108
1	7	-5.853±0.776	-13.673±1.128	0.345±0.365	-2.995±4.227	3.394±4.524
1	11	0.479±3.452	-5.129±2.210	1.443±2.213	-0.821±1.832	0.090±3.108
1	13	-3.825±1.153	-8.338±1.671	-0.953±2.762	-2.462±3.301	0.104±4.002
1	14	2.692±1.202	-1.886±1.275	2.264±1.954	1.320±3.274	2.963±2.108
1	21	1.497±1.586	-2.179±2.022	-0.181±1.382	-1.400±2.455	-0.757±2.590
1	22	8.331±0.732	4.598±1.450	-0.238±1.459	-2.116±1.707	1.878±1.294
1	23	4.537±2.060	0.309±2.360	0.623±1.637	-1.775±2.026	2.411±1.412
1	24	6.983±1.892	-1.872±1.224	1.725±2.205	-2.705±2.686	4.429±3.742
1	26	-1.726±0.989	-7.299±0.959	0.206±2.898	-1.735±2.359	1.941±1.532
2	1	3.875±0.944	-1.186±0.885	-3.555±2.612	-3.600±2.591	-3.600±2.591
2	9	-1.511±1.615	-6.332±2.472	-0.750±1.798	-0.750±1.798	-0.750±1.798
2	10	-4.034±1.248	-7.725±0.962	2.225±1.974	0.683±3.323	3.076±3.183
2	12	-5.373±1.371	-10.504±1.683	0.511±1.037	-0.821±2.409	-0.011±2.055
2	15	-2.990±0.479	-8.806±0.782	0.335±0.915	-1.778±1.730	-0.409±2.394
2	25	-4.533±2.673	-14.242±2.591	-2.099±3.118	-7.635±2.147	4.695±4.084
2	27	7.991±1.995	0.250±0.558	2.605±3.192	-1.632±0.984	4.236±3.748
2	28	-3.506±1.914	-9.067±1.100	0.471±3.372	-1.344±1.936	2.080±3.599
2	29	-2.410±2.350	-11.298±0.917	2.664±3.550	-2.944±2.256	5.608±4.096
2	30	-8.281±1.587	-16.997±1.107	-2.102±3.294	-5.622±2.923	3.520±3.660

Note: Group 1: High-arched
Group 2: Low-arched

Table A-23: Rear-midfoot kinematics during the vertical loading task

Group	Subject	Inv_{max}	Ev_{max}	Inv_{exc}	Ev_{exc}	ROM
1	3	10.974±0.271	7.873±0.985	-0.477±2.223	-0.477±2.223	-0.477±2.223
1	7	2.781±0.272	0.086±0.368	-0.708±0.853	-0.659±0.760	-0.659±0.760
1	11	18.129±1.802	7.302±6.620	1.057±4.305	-0.737±1.707	0.649±4.507
1	13	20.576±1.361	15.829±1.354	4.940±9.651	4.254±9.991	4.940±9.651
1	14	10.974±0.271	7.873±0.985	-0.477±2.223	-0.477±2.223	-0.477±2.223
1	21	16.630±3.324	13.049±1.040	-0.367±1.773	-1.611±2.727	-1.243±3.126
1	22	19.955±1.416	17.369±0.428	1.446±1.439	-0.542±0.463	1.988±1.547
1	23	10.736±1.115	7.752±1.578	0.313±0.743	-1.456±0.845	1.769±0.408
1	24	-5.599±1.266	-11.057±1.674	-0.970±2.135	-3.217±2.227	2.247±2.049
1	26	2.741±3.116	-4.120±3.549	0.328±0.844	-4.277±2.797	4.604±2.987
2	1	17.999±0.987	11.802±1.426	-1.130±2.548	-1.626±2.926	-1.130±2.548
2	9	16.849±2.568	12.437±3.654	-0.900±1.424	-2.063±2.287	-0.900±1.424
2	10	49.273±0.861	45.327±2.129	0.569±2.840	-0.010±3.096	0.604±2.800
2	12	-1.892±1.678	-5.486±1.401	0.253±2.226	-0.026±2.195	0.244±2.246
2	15	23.202±0.624	20.989±0.569	0.150±1.174	-0.990±0.682	0.296±1.660
2	25	11.849±1.735	7.077±1.441	0.856±1.761	-1.463±1.270	2.318±1.216
2	27	-14.861±0.916	-16.586±0.699	0.360±0.457	-0.644±1.017	1.004±0.921
2	28	15.732±0.486	13.025±0.552	0.722±0.811	-1.123±0.812	1.845±1.057
2	29	30.805±0.311	26.545±2.619	-0.494±2.833	-2.793±2.195	2.299±3.168
2	30	21.257±0.433	18.770±0.433	-0.771±1.738	-1.609±1.515	0.694±0.534

Note: Group 1: High-arched
Group 2: Low-arched

Table A-24: Mid-forefoot kinematics during the vertical loading task

Group	Subject	Inv_{max}	Ev_{max}	Inv_{exc}	Ev_{exc}	ROM
1	3	-14.678±0.866	-21.398±0.910	-0.518±9.845	-0.518±9.845	-0.518±9.845
1	7	-10.337±0.712	-15.405±2.082	-0.102±0.916	-0.102±0.916	-0.102±0.916
1	11	-30.030±6.460	-42.347±0.680	0.625±3.151	-1.966±4.428	-1.230±5.409
1	13	-26.744±2.209	-31.725±2.385	-0.611±2.626	-1.989±3.396	-0.611±2.626
1	14	-14.678±0.866	-21.398±0.910	-0.518±9.845	-0.518±9.845	-0.518±9.845
1	21	-31.782±1.741	-36.005±5.191	1.212±3.863	-0.239±2.113	0.764±2.640
1	22	-21.363±5.616	-28.564±3.555	0.048±0.752	-2.794±1.802	1.971±2.825
1	23	-19.187±0.894	-22.539±1.060	1.415±1.888	-0.768±1.139	2.183±1.315
1	24	-20.122±1.033	-27.687±1.048	2.163±2.000	-1.838±2.561	4.001±2.424
1	26	-23.961±4.543	-31.053±2.195	1.185±1.587	-3.234±2.783	4.419±2.853
2	1	-22.488±1.649	-32.027±1.234	0.058±4.206	0.058±4.206	0.058±4.206
2	9	-22.055±2.730	-27.240±2.085	1.029±2.900	-0.887±2.856	0.303±2.910
2	10	-54.767±2.071	-62.024±1.831	0.365±3.482	-1.045±4.464	-1.045±4.464
2	12	-27.284±1.364	-30.938±1.132	-0.175±1.060	-1.155±0.834	-1.155±0.834
2	15	-29.121±0.844	-32.339±0.977	1.398±1.133	-0.314±1.345	1.630±2.449
2	25	-32.012±1.296	-37.318±2.511	2.206±2.306	-0.562±1.418	2.768±2.338
2	27	-14.871±1.022	-18.780±1.503	0.081±0.493	-2.165±2.182	2.246±2.550
2	28	-41.637±1.091	-44.845±0.867	-0.094±0.502	-1.428±0.890	1.333±0.788
2	29	-45.891±2.174	-50.939±0.985	0.489±1.333	-0.597±1.802	1.086±1.083
2	30	-30.323±16.952	-41.044±0.850	9.236±18.207	-0.757±1.329	9.993±17.180

Note: Group 1: High-arched
Group 2: Low-arched

Table A-25: Arch dynamics in the vertical loading task

Group	Subject	Arch Index (AI)	Peak Dynamic AI	Minimum Dynamic AI	Peak Arch Deformity
1	3	0.391	0.292±0.010	0.272±0.005	-0.003±0.004
1	7	0.381	0.314±0.000	0.305±0.000	-0.003±0.006
1	11	0.383	0.284±0.001	0.260±0.000	0.000±0.007
1	13	0.377	0.315±0.011	0.304±0.009	-0.003±0.007
1	14	0.378	0.292±0.010	0.272±0.005	-0.003±0.004
1	21	0.410	0.279±0.000	0.270±0.000	-0.001±0.002
1	22	0.385	.	.	.
1	23	0.386	0.316±0.006	0.315±0.006	0.007±0.010
1	24	0.377	0.268±0.003	0.266±0.003	0.006±0.011
1	26	0.392	0.286±0.003	0.282±0.007	0.002±0.004
2	1	0.274	0.271±0.014	0.248±0.012	-0.102±0.140
2	9	0.271	0.298±0.003	0.274±0.002	-0.061±0.129
2	10	0.269	0.292±0.010	0.268±0.001	0.000±0.011
2	12	0.137	0.256±0.006	0.223±0.004	-0.002±0.010
2	15	0.260	0.247±0.002	0.222±0.003	0.004±0.006
2	25	0.274	0.253±0.001	0.253±0.002	0.010±0.013
2	27	0.275	0.237±0.003	0.237±0.003	0.004±0.008
2	28	0.266	0.253±0.001	0.253±0.002	0.010±0.013
2	29	0.283	0.253±0.001	0.253±0.002	0.010±0.013
2	30	0.280	0.253±0.001	0.253±0.002	0.010±0.013

Note: Group 1: High-arched
Group 2: Low-arched
. : Missing data

VITA

Douglas Powell was born in Richmond, Virginia. Shortly afterward he moved to Angier, North Carolina where he was raised and attended primary, elementary, and high school. Following graduation from Harnett Central High School in June of 1998, he attended East Carolina University and majored in Exercise and Sport Science with a concentration in exercise physiology. He received his bachelor's degree in the summer of 2002. Following graduation, he attended graduate school in the Department of Health and Human Performance at East Carolina University where he completed his master's degree under the tutelage of Dr. Tibor Hortobagyi, successfully defending and publishing his master's thesis "Inertial loading during gait evokes unique neuromuscular adaptations in old adults". In August of 2004 he was admitted to the Ph.D. program in Education in the Department of Exercise, Sport and Leisure Studies at the University of Tennessee, Knoxville. Under the guidance of Dr. Songning Zhang, Douglas received the Andy Kozar Graduate Student Research Award for research excellence in April of 2007. In May of 2013 he received his Doctor of Philosophy degree with an emphasis in Biomechanics and Sports Medicine.