Effects of Vertical Loading on Arch Characteristics and Intersegmental Foot Motions

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The medial longitudinal arch plays a major role in determining lower extremity kinematics. Thus, it is 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- and low-arched feet during a vertical loading condition. 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. The high-and low-arched athletes had no differences in vertical deformation of the arch. High-arched participants were less everted than the low-arched athletes; furthermore, the high-arched athletes had smaller mid-forefoot eversion excursions. Differences between the high-arched and low-arched athletes occur through and motion at the mid-forefoot joint.

Keywords: arch, foot, multisegment foot

The foot is a complex structure made up of 26 bones and over 100 ligaments (Hamill, 1995). Malalignment and dysfunction of the foot creates altered loading patterns resulting in a greater propensity of injury (Kaufman et al., 1999; Williams et al., 2001, 2004). Furthermore, aberrant foot function has been associated with overuse injuries from repetitive stresses (Bates et al., 1979; Hamill et al., 1992; James et al., 1978; Nigg, 1985; Radin et al., 1984, 1991; Radin and Paul, 1971) as well as acute traumatic injury including rupture of the ACL (Beckett et al., 1992; Jenkins et al., 2007; Loudon et al., 1996; Woodford-Rogers et al., 1994). Many methods have been developed to aid clinicians in assessing foot function including arch index (Cavanagh and Rodgers, 1987; Razeghi & Batt, 2002; Wearing et al., 2004; Williams & McClay, 2000) and arch stiffness (Zifchock et al., 2006). The arch index as described by Williams (Williams & McClay, 2000) 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 (Williams & McClay, 2000). 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 (Cashmere et al., 1999; Cavanagh et al., 1997; Hamill, 1989). Another method of assessing foot function is arch stiffness (Zifchock et al., 2006). 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 (Zifchock et al., 2006). Though these measures have been shown to be valid (Williams & McClay, 2000; Zifchock et al., 2006), reliable (Williams & McClay, 2000; Zifchock et al., 2006) and have a direct relationship with increased injury rates (Kaufman et al., 1999; Williams et al., 2001) and unique injury patterns (Kaufman et al., 1999; Williams et al., 2001), 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 hyperflexible (Williams & McClay, 2000; Williams et al., 2001; Zifchock et al., 2006). However, it is unknown as to whether the hypermobility 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 (Zifchock et al., 2006). Another research study examined kinematics within the foot using a multisegment foot model during dynamic activities and revealed that high- and low-arched athletes exhibit similar range of motion values (Powell et al., 2011). However, these kinematic measures were taken during highly dynamic tasks including walking, running, stepping and landing activities and could be...
heavily influenced by extrinsic muscle activation as well as the physical constraints of these tasks (Hunt & Smith, 2004; Hunt, Smith, & Torode, 2001; Hunt, Smith, Torode, et al., 2001; Mundermann et al., 2003a, 2003b; Powell et al., 2011). It remains unclear what differences exist, if any, in how high- and low-arched feet respond to increasing load. 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.

Methods

Subjects

Fifty-five healthy female athletes participating in university club sports 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 the vertical height of the dorsum divided by truncated foot length (Williams & McClay, 2000). 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 (Zhang et al., 2007). All subjects were free of injury at the time of testing and signed a written informed consent form approved by the Institutional Review Board before participating in the study.

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) during bilateral stance (Richards et al., 2003).

During the second session, participants first performed a warm-up and stretched for 5–10 min. 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.

Instrumentation

An arch height index measurement system (AHIMS JAK Tool and Model, LLC) (Richards et al., 2003) 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 previously described (Williams & McClay, 2000).

A seven-camera motion analysis system (240 Hz, 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 forefoot (Leardini et al., 1999). 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 as well as the medial and lateral epicondyles of the femur. The rearfoot was tracked using markers placed on the superior and inferior portion of the posterior aspect of the calcaneus, lateral aspect of the peroneal tubercle and medial aspect of the sustentaculum tali. The midfoot was tracked by retro-reflective markers placed on the medial aspect of the navicular tubercle, superior aspect of the medial cuneiform, superior aspect of the lateral cuneiform and lateral aspect of the tubercle of the cuboid. The forefoot was tracked using retro-reflective markers placed on the head of the medial aspect of the first metatarsal, medial and lateral aspects of the first metatarsophalangeal joint and along the superior aspect of the first metatarsal. Axes of the three segments were defined as previously described (Leardini et al., 1999).

A force platform (1200 Hz, 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.

Data Analysis

Motion capture data were analyzed from the beginning of hip flexion to peak knee extension. Dynamic arch index and arch deformation was calculated during the sit-to-stand exercise (Williams & McClay, 2000). Dynamic arch index was assessed at peak knee extension and 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. 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 before 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 multisegment foot angles were normalized to neutral position during the standing calibration. All original marker data were filtered using a low-pass filter.
<table>
<thead>
<tr>
<th>Group</th>
<th>Age, yr</th>
<th>Height, m</th>
<th>Mass, kg</th>
<th>Dynamic Arch Index</th>
<th>Peak Vertical GRF (BW)</th>
<th>Time to Peak Vertical GRF (BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>20.8 (2.5)</td>
<td>1.62 (0.07)</td>
<td>58.32 (5.39)</td>
<td>0.386 (0.010) &lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.629 (0.065)</td>
<td>1.062 (0.266)</td>
</tr>
<tr>
<td>LA</td>
<td>21.1 (2.3)</td>
<td>1.63 (0.07)</td>
<td>58.89 (10.92)</td>
<td>0.259 (0.043) &lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.682 (0.159)</td>
<td>0.953 (0.312)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Significant group effect between HA and LA groups.

<sup>b</sup> Significant difference between Arch Index (static) and Dynamic Arch Index.
with 8 Hz cut-off frequency while GRF data were filtered using a low-pass filter with 50 Hz cutoff frequency. Three-dimensional (3D) kinematic and kinetic variables were computed using Visual 3D (C-motion, Inc., Germantown, MD, USA). A customized computer program (VB_V3D) 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 16, Chicago, IL, USA) with alpha level set at \( p < .05 \).

**Results**

The high- and low-arched athletes exhibited similar peak vertical GRFs (\( p = .300 \)) and similar time to peak vertical GRFs (\( p = .366 \)). The high-arched athletes also had similar height and mass but significantly greater static (\( p < .001 \)) and dynamic arch index values (\( p = .003; \) Figure 1) compared with low-arched athletes (Table 1).

The dynamic arch index calculated from motion capture data determines smaller arch index values compared with the static arch index determined using the arch height index measurement system (\( p = .003; \) Table 1). Though the high-arched and low-arched athletes did not exhibit statistically different peak arch deformation values, there was a trend toward the high-arched participants having greater arch deformation values than the low-arched participants (\( p = .072, \) Table 1 and Figure 2).

At the ankle, the high-arched athletes exhibited significantly smaller peak eversion angles (\( p = .026 \)) during the sit-to-stand task (Table 2 and Figure 3). In the rear-midfoot joint, peak eversion (\( p = .681 \)) and eversion excursions (\( p = .300 \)) were not significantly different between the high-arched and low-arched athletes (Figure 4). At the mid-forefoot joint, the high-arched athletes exhibited smaller peak eversion angles (\( p = .024 \)) and smaller eversion excursions (\( p = .029 \)) than the low-arched athletes (Table 2 and Figure 5).

**Discussion**

Ankle kinematics showed that the high- and low-arched athletes exhibited different joint angle profiles during the sit-to-stand movement (Table 2 and Figure 3). The HA athletes had significantly less peak eversion at the ankle than the low-arched athletes (Table 2). However, the eversion ranges of motion were similar between the two groups suggesting that the high-arched athletes had a less everted position throughout the movement but did not exhibit a distinctively different curve. Conversely, rear-midfoot kinematics were similar in the high- and low-arched athletes (Table 2 and Figure 4). These findings support previous data which suggest that minimal motion occurs in the rear-midfoot joint (Powell et al., 2011) and this joint does not contribute to the functional differences between the high- and low-arched athletes. At the mid-forefoot joint, the high-arched athletes exhibited significantly smaller peak eversion angles and smaller excursions compared with the low-arched athletes. These
Figure 2 — Representative curves of the vertical height of the dorsum in a single high- (solid) and low- arched (mean: dashed; SD: cross-hatched) athlete during the sit-to-stand task.

Figure 3 — Representative frontal plane motion of the ankle in a single high- (solid) and low- arched (mean: dashed; SD: cross-hatched) athlete during the sit-to-stand task.
Figure 4 — Representative rear-midfoot frontal plane motion in a single high- (solid) and low- arched (mean: dashed; SD: cross-hatched) athlete during the sit-to-stand task.

Figure 5 — Representative mid-forefoot frontal plane motion in a single high- (solid) and low- arched (mean: dashed; SD: cross-hatched) athlete during the sit-to-stand task.
The vertical GRF calculations show that as load increases the vertical height through the movement. In addition, arch deformation demonstrates similar dynamic arch index patterns and changes 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 2). The vertical GRF of the dorsum decreases (Figure 2). The high-arched athletes had a smaller excursion compared with the low-arched foot. However, no differences were observed in excursion values between the high- and low-arched athletes suggesting the two groups exhibited similar rigidity within the foot. The findings of the current study also support previous research by demonstrating that functional differences between high- and low-arched athletes occur at the ankle and mid-forefoot joints (Hunt & Smith, 2004; Hunt, Smith, Torode, et al., 2001; Powell et al., 2011).

Though the high-arched athletes were less everted at the ankle and mid-forefoot joints, the high-arched athletes had smaller excursions at the mid-forefoot joint. 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 characterized by smaller deformations under a given load suggesting smaller excursion values would be observed within the high-arched athletes (Zifchock et al., 2006). Smaller excursion values in the high- compared with low-arched athletes at the mid-forefoot joint support previous research by demonstrating that the high-arched foot exhibits smaller changes in alignment in response to a given vertical load compared with the low-arched foot. The findings of the current study suggest the functional differences between the high- and low-arched athletes may be due in part to differences in the rigidity of the mid-forefoot joint. However, the high- and low-arched athletes had similar movement patterns at the rear-midfoot joint suggesting that these two groups are functionally similar at the midtarsal joint.

The functional differences between the high- and low-arched athletes may also be reflected in the vertical deformation of the arch in response to vertical loading. The dynamic arch index can be visualized using the vertical height of the dorsum. Dynamic arch index calculations show that as the subject stands, the arch index decreases (Figure 1). The high-arched athletes had a greater dynamic arch index value than the low-arched 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 2). The vertical GRF data show that the high- and low-arched athletes had similar peak GRFs and similar times to peak GRF suggesting that movement velocity was similar between the high- and low-arched athletes. Therefore it is reasonable to conclude that the differences in vertical arch deformation were not due to differences in the magnitude or rate of loading between the groups. A possible reason that low-arched athletes exhibited a trend of smaller vertical arch deformation values is that the arch is supported by the floor earlier in the loading phase and it can no longer be deformed. In the high-arched athletes, the arch may continue to deform until peak deformation is reached at the full standing position. However, arch deformation values were not statistically different between the high- and low-arched athletes. It is difficult to interpret how meaningful the vertical height of the dorsum or arch deformation data are in these two functionally different groups. Arch stiffness is a clinically relevant, quasi-static measure of arch function (Zifchock et al., 2006). Arch stiffness examines the response of the arch to vertical loading comparing arch indices in the seated and standing positions. A limitation of the methodology used by Zifchock et al. to calculate arch stiffness was the removal of the effect of the floor by having the arch unsupported. In activities of daily living and athletic tasks the arch is rarely unsupported, which may limit the application of those findings. The findings of the current study do not support previous research as the high-arched athletes did not have significantly less arch deformation than the low-arched athletes (p = .072). However, these data did show a trend toward significance suggesting a meaningful relationship may exist. A larger sample size would increase the statistical power of this comparison and may lead to results similar to those previously published (Zifchock et al., 2006). Furthermore, it is possible that removing the floor effect by using a methodology similar to Zifchock’s may allow for greater arch deformation in these two groups.

The findings of the current study show that the feet of high- and low-arched athletes respond differently to vertical loading such as a sit-to-stand task. It is difficult to directly apply these findings to injury associated with physical activity. The forces applied in dynamic loading are substantially greater than the loads experienced during the sit-to-stand task. Moreover, the directional component of loading in athletic tasks is not solely vertical. Though the foot does not experience a purely vertical loading

Table 2  Frontal plane peak angles and excursions; mean (SD)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group</th>
<th>Ankle</th>
<th>Rear-Midfoot</th>
<th>Mid-Forefoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{v_{max}}$</td>
<td>HA</td>
<td>−2.6 (3.9)$^a$</td>
<td>−3.0 (1.2)</td>
<td>−1.7 (2.2)$^a$</td>
</tr>
<tr>
<td></td>
<td>LA</td>
<td>−8.0 (5.2)</td>
<td>−3.3 (1.4)</td>
<td>−4.8 (2.8)</td>
</tr>
<tr>
<td>$E_{v_{exc}}$</td>
<td>HA</td>
<td>−1.3 (1.5)</td>
<td>−2.3 (1.1)</td>
<td>−1.9 (1.2)$^a$</td>
</tr>
<tr>
<td></td>
<td>LA</td>
<td>−2.5 (2.5)</td>
<td>−3.1 (1.7)</td>
<td>−3.2 (1.0)</td>
</tr>
</tbody>
</table>

Note. $E_{v_{max}}$ = Peak eversion angle; $E_{v_{exc}}$ = Eversion excursion.

$^a$ Significant group effect between HA and LA groups.
pattern in the sit-to-stand task, the anteroposterior and mediolateral components of loading are relatively small compared with the vertical force vector. The current data support the notion that the high-arched athletes are less everted within the ankle and multisegment foot. Furthermore, these data do not show increased flexibility within the foot of low-arched athletes as no differences in arch deformation were observed between the two groups. However, the low-arched foot was associated with greater eversion excursion values in the mid-forefoot joint suggesting differences between the high- and low-arched athletes may occur within the frontal plane rather than vertical deformation of the arch. The ankle has been modeled as a mitered-hinge joint suggesting that motions within the foot and ankle are passed along to the knee and hip. The altered alignment of the foot may create altered loading patterns throughout the entirety of the lower extremity, increasing the potential of injury to the lower extremity.

Though the model used for the current study was validated using magnetic imaging, a limitation of the current study includes the use of surface-mounted markers rather than bone pins, magnetic imaging or radiography to track the skeleton (Myers et al., 2004). The use of skin-mounted markers may lead to inherent inaccuracies in the tracking of bone motion due to movement of the skin. Though the differences in multisegment foot positions observed in the current study were statistically significant, they were small in magnitude and should be interpreted in light of the inherent limitations of surface mounted markers, specifically in the feet. Another limitation of the current study was a small sample size. Post hoc power analysis suggests that a sample size of 36 (18 high-arched; 18 low-arched) would have had sufficient power to find statistical differences in arch deformation within the current study. In addition, the current study did not address the motion of the body in conjunction with the sit-to-stand task. Therefore, it is difficult to infer the effects of anteroposterior and mediolateral forces on motions of the arch. Future studies may need to track the whole body and the center of pressure to better address the influence motions of the center of mass have on the dynamics of the arch during a sit-to-stand task. Finally, the multisegment foot model chosen for use in the current study was made up of a rearfoot, midfoot and forefoot. Previous research has used the Oxford multisegment foot model which is made up of only a rearfoot and forefoot. It is possible that the presence of a midfoot segment attenuated differences between these two functionally different groups.

In conclusion, the current study reveals that high- and low-arched athletes exhibit similar vertical arch deformation in response to a vertical load. Moreover, these data demonstrate that high- and low-arched athletes exhibit different peak joint angles but have similar excursion values within the foot and ankle in response to an increasing load. Furthermore, the findings of this study show that the mid-forefoot joint exhibits the greatest rigidity within the foot during vertical loading. Further research may pertain to radiographic or bone pin studies into the motion of individual bones within the feet of these functionally different groups.

References


