GREATER SKELETAL CONTRIBUTIONS TO LEG STIFFNESS IN HIGH- COMPARED TO LOW-ARCHED ATHLETES DURING RUNNING AND LANDING MOVEMENTS.

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The contributions of skeletal and muscular structures to stiffness may underlie the distinct injury patterns observed in high- (HA) and low-arched (LA) athletes. This study compared skeletal and muscular contributions to leg stiffness in HA and LA athletes during running and landing. Ten HA and 10 LA female athletes performed five over ground running trials and five step off landing trials. Leg stiffness, and skeletal and muscular contributions to leg stiffness were calculated using Visual 3D and MatLab. HA athletes had greater leg stiffness ($p=0.010$) and skeletal stiffness ($p=0.016$) in running. During landing, HA had greater leg stiffness ($p=0.015$) and skeletal stiffness ($p<0.001$) while LA athletes had greater muscular stiffness ($p=0.025$). These findings demonstrate that HA athletes place a greater reliance upon skeletal structures for load attenuation during running and landing which may underlie their distinct injury patterns.

KEYWORDS: Foot, Arch, Kinetics, Stiffness, Running, Landing

INTRODUCTION: Aberrant foot structure is associated with greater incidence and prevalence of lower extremity injury in athletes (Williams, McClay, & Hamill, 2001). Individuals with high-arched feet (HA) experience greater rates of bony injury to the lateral aspect of the lower extremity such as tibial stress syndrome, tibial stress fractures and metatarsal stress fractures.Conversely, low-arched athletes have a propensity to experience soft tissue injuries to the medial aspects of the lower extremity including Achilles tendinitis and patellofemoral pain.
These distinct injury patterns have been attributed to altered force transmission through the lower extremity as a result of the structural and morphological characteristics of the foot (Powell, Hanson, Long, & Williams, 2012; Powell, Williams, Windsor, Butler, & Zhang, 2014; Powell, Queen, & Williams, 2016; Powell, Andrews, Stickley, & Williams, 2016; Williams et al., 2001; Williams, Davis, Scholz, Hamill, & Buchanan, 2004). Zifchock et al (Zifchock, Davis, Hillstrom, & Song, 2006) demonstrated that HA feet are generally rigid while low-arched feet tend to be flexible (non-rigid). The functional differences in foot characteristics in HA compared to LA feet and the translation of foot function to lower extremity biomechanics have been further demonstrated during dynamic tasks such as running and landing (Powell et al., 2012; Powell et al., 2014; Powell et al., 2016; Williams et al., 2004). HA athletes have also been shown to exhibit greater stiffness values compared to LA athletes. Stiffness is a composite measure of a system's response to an applied load. High stiffness values indicate that a given load results in small deformations while low stiffness values indicate that a given load results in large deformations. HA athletes have been shown to have greater leg stiffness than LA athletes during a running task (Williams et al., 2004). Further, HA athletes have been shown to exhibit greater ankle and knee joint stiffness values than LA during running (Powell et al., 2014; Williams et al., 2004). These findings are similar to assessments of vertical stiffness during a landing task (Powell et al., 2016). It has been previously suggested that the greater stiffness values observed in HA athletes results in greater loading to the skeletal system during load attenuation and may underlie the distinct injury patterns experienced by HA athletes. However, no previous investigation has attempted to quantify skeletal and muscular contributions to load attenuation or stiffness in HA compared to LA athletes. Differentiation of muscular and skeletal

components of stiffness has been previously investigated in aged adults in downward stepping (DeVita & Hortobagyi, 2000). Identifying differences in skeletal and muscular contributions to leg stiffness may provide a foundation for clinical interventions to reduce the injury rates in these athletes. Therefore, the purpose of this study was to quantify the muscular and skeletal contributions to leg stiffness during running and landing tasks. It was hypothesized that athletes would exhibit greater leg stiffness values than LA athletes during running and landing. Further, it was hypothesized that HA athletes would exhibit greater skeletal contributions and smaller muscular contributions to leg stiffness than LA athletes.

METHODS: Twenty female recreational athletes (10 HA and 10 LA) were identified and recruited to participate in this study from a pool of seventy-three female athletes that were screened for inclusion. All participants were free of injury for the six months preceding testing. Arch height index (AHI) was calculated as the vertical height of the dorsum at half of the total foot length divided by the truncated foot length (Williams & McClay, 2000) and was measured using the Arch Height Index Measurement System (AHIMS) (Butler, Hillstrom, Song, Richards, & Davis, 2008). Participants were assigned to HA or LA groups based on AHI measurements. The HA group was characterized by AHI values greater than 0.377 while the LA group was defined as having AHI values less than 0.290. The experimental protocol was approved by the University Institutional Review Board and all subjects signed informed consent prior to study participation.

2.2 Experimental Protocol: Three-dimensional kinematics and ground reaction forces (GRFs) were recorded simultaneously using an eight-camera motion analysis system (240Hz, Vicon Motion Systems Ltd., Oxford, UK) and force platform (1200 Hz, OR-7, AMTI, Watertown, MA, USA), respectively. Participants wore spandex shorts and a t-shirt during testing to limit marker occlusion. The skeleton was modeled using 9.5 mm retro-reflective markers. Each participant performed five over ground running trials and five step off landing trials in a randomized order. Running trials were performed at a self-selected velocity described as the pace at which the participant would run for approximately 30 minutes. Step off landing trials were characterized by the participant stepping off of a box with a height of 30 cm and performing a bilateral landing with the right limb on the force platform.

2.3 Data Analysis: Three-dimensional kinematic data were filtered using a 4^{th} order, zero-lag low-pass Butterworth filter with a cutoff frequency of 10 Hz. GRFs were filtered using a similar filter with a 50 Hz cutoff frequency. Running and landing data were analyzed during the load attenuation phase of each movement from initial contact to time of peak vertical GRF.

The lower extremity was modeled as a linear spring which included the pelvis, thigh, shank and foot segments as previously described (DeVita & Hortobagyi, 2000). Lower extremity stiffness (kLeg) was calculated as the ratio of the peak vertical GRF (FMax) and the resultant shortening of the lower extremity (ΔL) (DeVita & Hortobagyi, 2000; Farley & Gonzalez, 1996). ΔL was calculated as the difference in the length of the distance between the metatarsal head and the hip joint between IC and FMax. The muscular and skeletal contributions to lower extremity stiffness were partitioned based on a previously developed model (DeVita & Hortobagyi, 2000). This model differentiates muscular and skeletal contributions on the basis of the position of lower extremity segments and the orientation of FMax. Specifically, skeletal and muscular contributions to lower extremity stiffness were calculated as a function between the angle between FMax and the tibia as described in Eq 1.

$$kLeg = kLeg \times \cos^2 \phi + kLeg \times \sin^2 \phi \qquad \text{Eq. 1}$$

where kLeg is the observed lower extremity stiffness, and φ is the angle between the orientation of the GRF vector at FMax and the tibia, k $\cos^2$ φ is the skeletal contribution (kSkel) to lower extremity stiffness and k $\sin^2$ φ is the muscular contribution (kMusc) to stiffness (DeVita & Hortobagyi, 2000).

2.4 Statistical Analysis: Three independent samples t-tests were used to compare dependent variables for running and landing, respectively, including: kLeg, kSkel and kMusc. Post-hoc t-tests were used to compare variables underlying stiffness calculations including ΔL and φ. To adjust for multiple comparisons, a Holm-Bonferroni adjustment was used to alter the level of significance based on the number of comparisons for each movement condition. Cohen's *d* was used to indicate standardized effect size for mean comparisons between HA and LA athletes (Cohen, 1988; Powell et al., 2014; Powell et al., 2016; Williams et al., 2004). Significance was set at $p < 0.05$.

RESULTS: During running, HA athletes had significantly greater kLeg ($p = 0.010$, $d = 1.03$) and kSkel ($p = 0.016$, $d = 0.81$) than LA athletes while no differences were observed between HA and LA athletes for kMusc ($p = 0.134$, $d = 0.52$; Figure 1). ΔL was smaller in HA athletes (0.055 ± 0.012 m) compared to LA athletes (0.067 ± 0.012 m; $p = 0.020$, $d = 1.00$). Moreover, φ was smaller in HA athletes (27.7 ± 3.2°) than LA athletes (31.1 ± 2.2°; $p = 0.038$, $d = 1.24$).
During the landing task, HA athletes had significantly greater kLeg ($p = 0.015$; $d = 1.06$) and kSkel values ($p < 0.001$; $d = 1.84$; Figure 2). Conversely, kMusc was smaller in HA compared to LA athletes ($p = 0.025$; $d = 0.96$; Figure 2). ΔL was smaller in HA (0.044 ± 0.010 m) compared to LA athletes (0.056 ± 0.016 m; $p = 0.024$, $d = 0.90$). Further, φ was smaller in HA (47.3 ± 16.5°) compared to LA athletes (59.9 ± 13.2°; $p = 0.038$, $d = 0.84$).

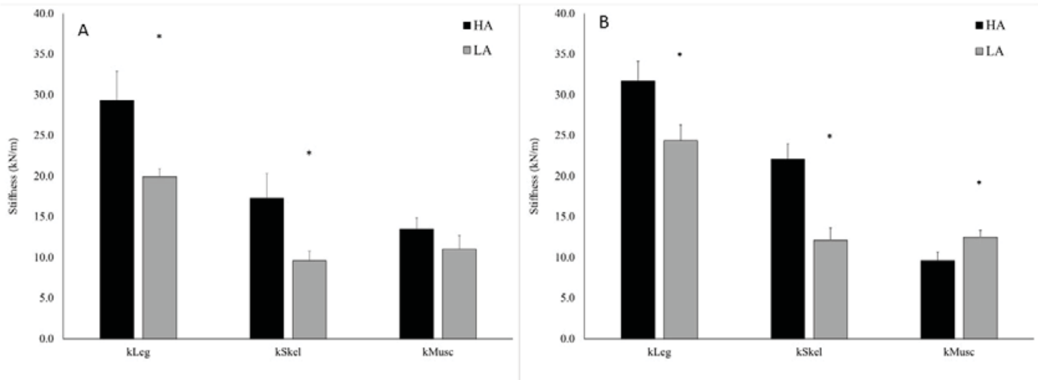

Figure 1. Stiffness values in HA and LA athletes during running (A) and landing (B) tasks.

DISCUSSION: This is the first study to quantify skeletal and muscular contributions to stiffness during dynamic loading tasks in HA compared to LA athletes. In agreement with our first hypothesis, HA athletes exhibited greater leg stiffness during running and landing compared to LA athletes. These data are consistent with previous findings of greater stiffness values in HA compared to LA athletes during running and landing movements. HA compared to LA athletes have been demonstrated to have greater leg stiffness, ankle joint stiffness and knee joint stiffness during running (Powell et al., 2014; Williams et al., 2004) and greater vertical stiffness in landing (Powell et al., 2016). These greater stiffness values have been suggested to be the result of smaller center of mass excursions and knee flexion excursions in HA athletes than in LA athletes (Powell et al., 2016; Williams et al., 2004).
Our second hypothesis was partially supported as greater skeletal and smaller muscular contributions to leg stiffness were observed in HA compared to LA athletes during the step off landing task. However, greater skeletal contributions to leg stiffness were found in HA athletes with no differences in muscular contributions to leg stiffness between groups during running. In HA athletes, the skeletal component (kSkel) contributed 58% and 70% of leg stiffness (kLeg) during running and landing, respectively, while contributing only 40% and 48% of leg stiffness in LA athletes. The implications of skeletal contributions to leg stiffness may be more important during landing since only a moderate effect magnitude was observed in running ($d = 0.81$) while

a large effect was found during the landing task (d = 1.84) between HA and LA athletes. The model used to quantify kSkel and kMusc in the current study (DeVita & Hortobagyi, 2000) defined skeletal and muscular contributions to leg stiffness as a function of the length of the limb (ΔL) and the angle of the tibia (φ) with smaller ΔL and φ values associated with greater kSkel and smaller kMusc values. These variables (ΔL and φ) could be considered analogues of center of mass and knee flexion excursions. Post-hoc comparisons of ΔL and φ revealed significantly smaller ΔL and φ values in the HA compared to LA athletes. These data support previous research findings and suggest that HA athletes performed the running and landing tasks in a more erect lower extremity posture characterized by smaller center of mass excursions and knee flexion angles than their LA counterparts. The running and landing biomechanics observed in HA athletes, including the greater relative contributions of the skeletal component, may be responsible for the distinct skeletal injuries reported in HA athletes (Williams et al., 2001). Conversely, the LA athletes were shown to have a greater muscular component of leg stiffness as well as a greater relative reliance upon muscular structures for load attenuation. This finding may provide mechanistic evidence for the greater reported soft tissue injuries in LA athletes (Williams et al., 2001).

CONCLUSIONS: The current study provides novel findings that HA athletes have greater skeletal contributions to leg stiffness and load attenuation during both running and landing but, smaller muscular contributions to leg stiffness during landing only compared to LA athletes. These unique running and landing contributions to lower limb stiffness may underlie differences in injury patterns experienced by HA and LA athletes during different movement tasks.

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