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Short communication

Effects of incremental ambulatory-range loading on arch height index parameters

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ABSTRACT

Deformation of the medial longitudinal arch under body weight loading is often assessed using the Arch Height Index Measurement System. This system assesses change in arch height between sitting and standing, estimated to be 10% and 50% of body weight, respectively. However, body weight forces during ambulation exceed these loads, therefore limiting our understanding of arch deformation under ambulatory load ranges. Thus, the study aims were (1) to assess if sitting and standing arch height differed from that seen under 10% and 50% body weight using a force target-matching procedure, and (2) to quantify the assumed linearity of arch stiffness, measured statically, throughout an ambulatory load range. Established sitting and standing arch height measurements were taken from 25 healthy subjects, who also underwent testing from 10% to 120% body weight in sequential 10% increments. Arch deformation in sitting was less than for 10% body weight, whereas the standing and 50% condition did not differ. The incremental loading data revealed linear and curvilinear trends between arch deformation and loading through the ambulatory range, such that further deformation beyond that seen at 120% would be minimal using these procedures. These data suggest that sitting arch loads and deformation are less than those seen at 10% body weight, which affects known parameters such as arch stiffness. Further, the curvilinear trend in the arch height data suggests that most arch deformation occurs in the ambulatory load range for a healthy foot.

1. Introduction

Foot functionality is integral to normal human locomotion. Locomotor impacts, often measured in biomechanical analyses with ground reaction force data, are associated with structural foot deformations under body weight (BW) loading. Perhaps the most commonly assessed foot characteristic is the medial longitudinal arch region.

While a number of approaches exist for the assessment of the medial longitudinal arch, the most reliable is the Arch Height Index Measurement System (AHIMS) (Williams and McClay, 2000; Butler et al., 2008; Pohl and Farr, 2010). The AHIMS approach normalizes dorsum height (taken halfway along the length of the entire foot) to a truncated foot length (the length of the foot from the heel to the first metatarsal head) to derive the arch height index (AHI) metric. The AHI value is then taken in sitting and standing to reflect relatively unloaded and loaded conditions and assess arch stiffness.

As the difference in AHI between sitting and standing reflects arch deformation under a known load, this approach derives a measure of arch stiffness. Clinically, a stiffer arch may be less flexible and therefore prone to bony injuries such as stress fractures, as a less mobile foot may not attenuate shock as well. However, two limitations to assessing stiffness with AHI should be noted. The first is that the AHI assessment is static. The AHI assessment, while concurrently validated against radiographic measures of dorsum height and truncated foot length (Williams and McClay, 2000), may not strongly reflect arch behavior during dynamic loading conditions. The second limitation is that only two loading conditions are generally tested, in sitting and in standing. In sitting, the resting weight of the shank and foot is considered to be approximately 10% of total BW. Williams and McClay (2000) defend the 10% BW estimate by suggesting that BW loading is approximately 10% when the foot becomes plantigrade during the stance phase of walking, and describe the condition as relatively unloaded. Zifchock et al. (2006) also cite cadaveric work and suggest that 10% BW reflects the combined weights of the shank and foot (Dempster and Gaughran, 1957). In standing, it is assumed that BW is evenly distributed between limbs, and the load is approximately 50% BW (McPoil et al., 2009; Butler et al.,

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2006; Pohl and Farr, 2010; Teyhen et al., 2009; Weimar and Shroyer, 2013). These assumptions that sitting and standing produce accurate BW load estimates of 10% and 50% have not been directly tested.

Of importance, testing AHI under dynamic loading is not feasible due to the AHIMS hardware. Further, dynamic ambulatory peak vertical ground reaction forces are generally 120% BW (Keller et al., 1996), well above the 50% tested in the established standing AHI assessment. Therefore, there were two primary aims for this study. The first aim was to assess if the established baseline sitting and standing AHI measures are actually representative of 10% and 50% of BW loading as determined using target-matching of real-time vertical ground reaction force data. It was hypothesized that the 10% sitting condition would differ from the force-matching magnitude at 10% due to variation in sitting forces and early loading during stance across subjects. However, it was hypothesized that the 50% conditions would not differ as healthy individuals would be able to evenly distribute BW between limbs in standing.

The second aim was to statically characterize arch stiffness via the BW load and arch deformation relationship by incrementally increasing BW loading in standing using 10% load increments from 10% to 120% BW. While this method does not incorporate velocity and acceleration-dependent inertial forces or account for muscle activations, using BW loads in the typical ambulatory range allows for an assessment of the assumed linearity of arch stiffness. It was hypothesized that both linear and quadratic trends would be observed, with the linear term reflecting a general progression of arch deformation and the quadratic term reflecting a ceiling effect in deformation with higher loads due to anatomic constraints to the applied loads.

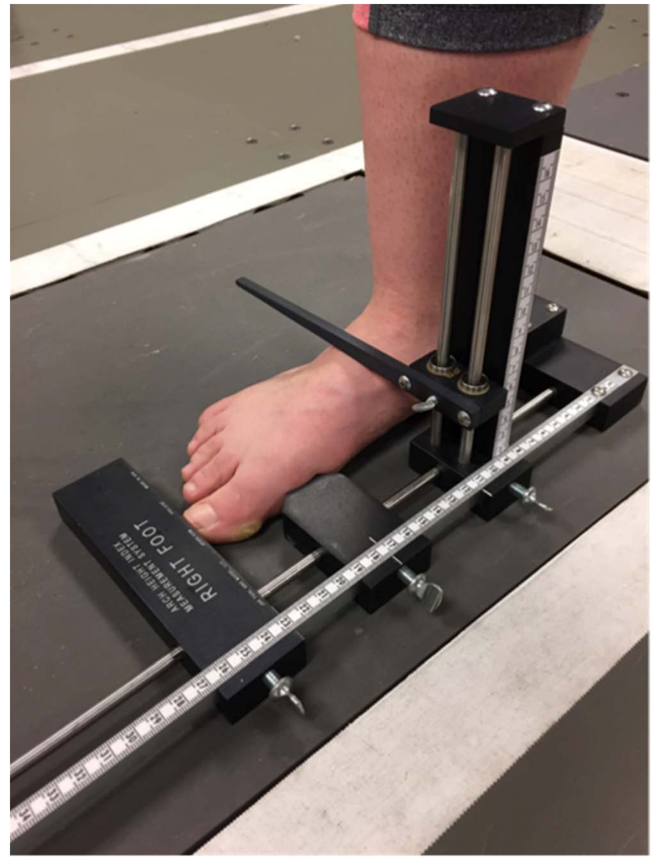

Fig. 1. Arch Height Index Measurement System. The device used to measure arch height parameters in this study. Measures were taken on the force platform.

2. Methods

2.1. Participants

Twenty-five (17 females) healthy individuals were recruited from a university setting to participate in this study (age = 20.12 ± 0.97 years; height = 1.72 ± 0.08 m, weight = 73.7 ± 14.5 kg). All subjects reported no current or prior lower extremity injury. Subjects were excluded with a history of any condition preventing prolonged standing or shifting weight on their foot. The study procedures were approved by the university institutional review board, and subjects provided written consent to participate in the study in accordance with the approval.

2.2. Experimental protocol

Subjects completed all testing barefoot. Height was measured using a stadiometer. Each subject was first weighed on a floor-mounted force plate (Bertec Corp., Columbus, OH, USA) to establish baseline and 10% increments in body weight (BW). These increments were established with the aim of representing body weight loading from 10% to 120%. Overloading beyond 100% occurred with the use of an adjustable weighted vest (ZFO Sports, San Jose, CA, USA) loaded to 20–25% of BW. The right lower extremity was used for all testing.

First, sitting and standing AHI were measured using the well-documented AHIMS procedure. For the sitting assessment, the subject sat down in a chair with hips and knees flexed to 90 degrees. Using the AHIMS, the arch measurement was taken on the right foot. This included foot length, truncated foot length and dorsum height (Fig. 1). Next, the subject would stand on both feet with weight evenly distributed, and the AHIMS procedure was repeated for the standing assessment. Finally, AHI was calculated for both sitting and standing:

AHI = Dorsum Height/Truncated Foot Length

After baseline measurements were collected, a force target-matching procedure was carried out for each BW increment from 10% to 120% BW in standing. The weight of the AHIMS device (Jevek Solutions, Matawan, NJ, USA) was tared off so the force plate data did not include the device weight. The vertical force data (N) was then graphically streamed as a real-time line graph (Vicon Nexus, Centennial, CO, USA) to a 42 in. high definition monitor placed approximately 2–3 m in front of the plate. All subjects confirmed clear visibility of the data stream. The y-axis of the force data stream was positioned and scaled such that the entire vertical screen represented ± 1% of the % BW target for the condition for each subject. In effect, subjects adjusted body weight force to visualize the streaming data on the monitor while standing in the AHIMS device. Errors within 1% were observable on the screen, but errors beyond this range were not. Once the subject could steadily hold this position within the acceptable error range, arch height was measured. This process was repeated for each condition from 10% up through 120% in progressive fashion. At the 70% weight condition, the subject put on the weighted vest. This vest was used for the remaining conditions, up to 120%. The vest was used only for the higher load conditions to improve subject comfort, as wearing the loaded vest was reportedly uncomfortable when worn for a prolonged period of time. Subjects were allowed to use a balance aid to facilitate the weight shifting needed to target-match the force data. After each measure, subjects were asked to unload and re-position their foot for the following condition. Subjects were also allowed to rest between conditions in sitting. The same standing AHIMS procedures as described above were used for each condition.

2.3. Analysis

SPSS (version 21.0, IBM Corp., Armonk, NY, USA) software was used to calculate means and standard deviations for both the sitting and standing AHI, and each force target-match condition. A paired t-test was performed between the baseline sitting and the 10% condition, as well as between the baseline standing and 50% condition. The condition data were assessed using repeated measures analysis of variance, and pairwise comparisons were conducted between each pair of sequential loading conditions. Within-subjects contrasts were assessed for linear and polynomial trends. Significance was determined using an alpha level of 0.05, and a Bonferroni p-value adjustment was applied.

3. Results

The means and standard deviations for AHI for baseline sitting and standing were 0.365 (0.020) and 0.326 (0.023), respectively. The baseline sitting AHI was observed to be 7% greater than the force target-matched value at 10% of 0.342 (0.023) ($p < 0.001$). The baseline standing AHI did not statistically differ from the force target-matched value at 50% at 0.323 (.020) ($p = 0.206$).

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