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The effects of enhanced plantar sensory feedback and foot orthoses on midfoot kinematics and lower leg neuromuscular activation

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ABSTRACT

Excessive foot pronation has been associated with injuries of the lower extremity. No research has investigated the effect of enhancing plantar sensory feedback on foot pronation. The aim of this study was to determine whether a shoe with enhanced plantar sensory feedback reduces midfoot pronation. Midfoot kinematics and electromyography of the peroneus longus, tibialis anterior and medial gastrocnemius of 21 males (age: 21.0 ± 4.0 years, height: 176.8 ± 5.0 cm, mass: 73.3 ± 6.5 kg) were recorded whilst walking in a neutral shoe, a neutral shoe with a prefabricated foot orthotic and a neutral shoe with nodules located on the plantar-medial insole (experimental shoe). Friedman's ANOVA and Wilcoxon tests were used to evaluate differences between shoe conditions. Mean midfoot-tibia angles during ground contact were significantly more supinated when wearing the experimental shoe (+7.14°, $p = 0.023$) or orthotic (+3.83°, $p = 0.006$) compared to the neutral shoe. During the loading phase, midfoot angles were significantly more supinated when wearing the experimental shoe compared to the orthotic (+5.53°, $p = 0.008$) or neutral shoe (+6.20°, $p = 0.008$). In the midstance phase, midfoot supination was significantly higher in the orthotic compared to the neutral shoe (+2.79°, $p = 0.006$). Finally, supination was increased during the propulsive phase when wearing the experimental shoe compared to the orthotic (+7.43°, $p = 0.010$) or neutral shoe (+10.83°, $p = 0.009$). No significant ($p < 0.05$) differences in muscle activation were observed. These results suggest that increasing plantar sensory feedback to the medial aspect of the foot reduces midfoot pronation during an acute bout of walking. Further work is needed to explore whether these effects remain over longer time periods.

1. Introduction

Abnormal foot motion or posture has frequently been cited as a risk factor for lower extremity injuries. In particular, research has investigated the association between excessive foot pronation and injury [1,2]. Although pronation is essential for normal locomotion, injury risk may increase when this motion is excessive [2]. For example, excessive pronation has been associated with a number of lower extremity injuries such as plantar fasciitis [3], stress fractures [4] and patellofemoral pain syndrome [5]. As such, much work has been done to establish interventions designed to reduce excessive pronation.

One method that has been shown to reduce pronation is foot orthoses [1]. Many studies have indicated that foot orthoses decrease rearfoot eversion angle [6–10], rearfoot eversion velocity [10,11] and ankle and rearfoot inversion moments [10–12]. In addition to orthotic interventions, other work has explored alternative methods of altering lower limb mechanics. One such method involves altering plantar sensation, achieved by either modifying the ability of cutaneous receptors to detect sensation or altering the stimulus level. For example, there is evidence that reducing plantar sensation using ice baths alters plantar pressures [13,14] and muscle activity patterns [14], whilst increasing plantar sensation using a vibrating insole decreases measures of gait variability [15]. Other methods of increasing plantar sensory feedback, through techniques such as sandpaper insoles [16], socks with gravel of differing size and grade glued to the inside of the plantar surface [17], and textured insoles [18–21], have also been shown to alter lower limb mechanical variables. As such, altering plantar sensory feedback might provide a method of improving abnormal mechanical factors known to increase injury risk. To date however, no published studies have explored whether altering sensory feedback during walking reduces abnormal mechanics, such as excessive pronation. Consequently, the aim of this study was to determine if increased plantar sensory feedback can be used to reduce measures of foot pronation during an acute bout of

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walking in healthy young adults. It was hypothesized that a shoe with increased medial plantar sensory feedback will reduce foot pronation during the stance phase of gait when compared to a neutral shoe, and that this would be achieved via alterations in neuromuscular activation.

2. Method

2.1. Participants

Participants in this study included 21 male volunteers (age: 21 ± 4 (range = 18–37) years, height: 176.8 ± 5.0 (range = 167.3–186.5) cm, weight: 73.3 ± 6.5 (range = 60.1–86.2) kg). Only males were recruited as recent research suggests lower limb function and gait variability fluctuate throughout the menstrual cycle [22,23]. All participants were screened by the same investigator, and were required to have a neutral or pronated foot posture (defined as a six-item Foot Posture Index score > 0) [24], no recent lower limb injuries and intact plantar sensation (tested using 10 g monofilament and 64 Hz Rydel-Seiffer graduated tuning fork). All testing procedures were approved by the Human Research Ethics Committee at the Australian Catholic University and informed consent was obtained from all participants.

2.2. Gait analysis

Lower extremity kinematics were measured using a six camera VICON 3D motion analysis system (Vicon, Oxford, United Kingdom) sampling at 200 Hz. A customized kinematic model incorporating a multi-segment foot was created to examine lower extremity and foot mechanics, with the marker set encompassing the pelvis and the right leg only. The custom model comprised 21 markers placed on anatomical landmarks of each participant's lower limbs, as shown in Fig. 1 and outlined in Table 1. Windows were cut in each shoe to enable the markers to be placed directly on the skin (see Fig. 1B) and to allow for the shoes to be switched without affecting foot marker placement. Preliminary testing revealed that removing windows from the heel cup had a negative influence on the structural integrity of the shoe, and therefore these four markers were placed on the shoe itself. However, after preliminary analysis of the rearfoot segment output of the model with respect to angles derived from skin-mounted markers, it was deemed that the heelcup of the shoe did not accurately reflect the motion of the foot. For this reason, rearfoot angles were not analyzed.

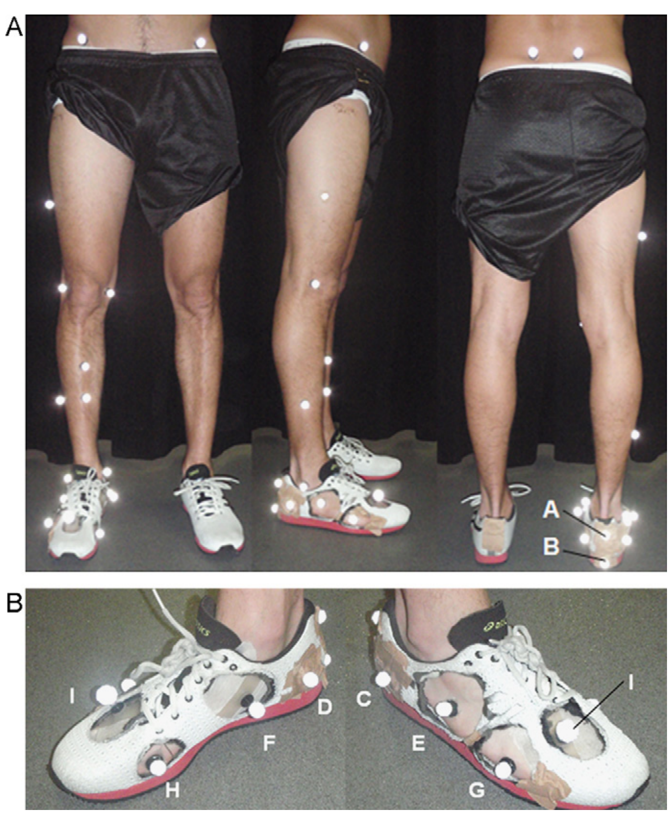

Fig. 1. Marker positions for the customized gait model. (A) From left, the frontal, lateral and rear views of the marker set. (B) The markers located on the foot segments and their anatomical references are described in Table 1. The remaining markers and their definitions are described in detail by Schache and Baker [25].

Table 1
Marker names and anatomical descriptions for the custom gait model markers.

Marker	Position
Superior calcaneus (A)	Superior aspect of the posterior calcaneus
Inferior calcaneus (B)	Inferior aspect of the posterior calcaneus
Lateral calcaneus (C)	Lateral aspect of the calcaneus
Medial calcaneus (D)	Medial aspect of the calcaneus
Cuboid (E)	The most lateral prominence of the cuboid bone
Navicular (F)	The navicular tuberosity
5th MTPJ (G)	The most lateral point of the 5th metatarsal head
1st MTPJ (H)	The most medial point of the 1st metatarsal head
Dorsal forefoot (I)	Midway between the second and third metatarsal heads, on the dorsal aspect of the foot

Knee and ankle joint centre estimations and definitions were derived as outlined by Schache and Baker [25]. The midfoot segment was created based on the recommendations of a cadaveric study performed by Brown et al. [26] to minimise measurement error associated with foot modeling [27]. The focus of this study was on the frontal plane motion of this foot segment, defined as rotation about a point midway between the navicular and cuboid markers. The axis for this rotation was defined as a line running from this midpoint to a point between the 1st and 5th MTPJ markers, and assessed relative to the longitudinal axis of the tibia.

All gait data were initially collected and labeled using VICON Nexus software (Version 1.4), then filtered using a custom wavelet-based technique based on the work of Ismail and Asfour [28] implemented via a combination of Labview 2009 with the Advanced Signal Processing Toolkit (National Instruments, USA) and C3DServer (Motion Lab Systems, USA). These data were then processed in VICON BodyBuilder (VICON Motion Systems, UK). Once the modeling was complete, the data were exported for further analysis into a custom LabView 2009 (National Instruments, USA) program for the assessment of joint angles relative to the gait cycle.

During these gait trials, surface electromyography (EMG) data for the medial gastrocnemius, tibialis anterior and peroneus longus were collected using a 16 channel Bortec AMT-16 surface EMG measurement system (Bortec Medical, Alberta, Canada). The protocols for the kinematic data filtering and EMG data collection are described in detail in the respective Supplementary material.

2.3. Footwear interventions

To evaluate the effects of enhanced sensory feedback upon lower extremity kinematics, each subject was evaluated whilst walking wearing three different conditions of athletic footwear. The first shoe was a prototype shoe designed to reduce foot pronation using enhanced plantar sensory feedback (EPSF). The innersole surface was permeated by multiple small, 4 mm domes of hard plastic, which were covered with thin cotton material and positioned 12 mm equidistantly in the medial midsole of the shoe (outlined in Supplementary figure). These domes were designed to increase tactile sensory feedback on the plantar medial aspect of the foot as it begins to pronate throughout the gait cycle, and in turn, decrease the magnitude of this pronation.

Additionally, each participant also wore a neutral athletic shoe, and a neutral shoe fitted with a prefabricated foot orthotic. The neutral athletic shoe was identical to the intervention shoe, except that it did not contain the sensory innersole addition and therefore the innersole surface was smooth. To compare the anti-pronatory control of the EPSF shoe, the neutral shoe was also fitted with a prefabricated orthotic designed to reduce foot pronation. The prefabricated foot orthotic used in this study was a three-quarter length Formthotic (Foot Science International, Christchurch, New Zealand) administered according to the manufacturer's instructions. Formthotics were selected as they are commonly prescribed by podiatric physicians [29] and have been shown to be effective in the treatment of foot conditions commonly attributed to foot pronation [30]. All shoes utilized in this experiment were created by ASICS (ASICS Pty. Ltd., Japan).

Prior to recording data for each footwear condition, participants completed four normal walking trials at a self selected speed to ensure familiarization to the testing protocol and footwear condition. Subjects then completed seven acceptable trials along a flat unobstructed 15 m walkway containing an in-ground force plate (Kistler model 9286AA, USA). These data were collected for each footwear condition, performed in a randomized order.

At the conclusion of the session, data were collected regarding the comfort of each condition by asking "Which of the three conditions did you find to be most uncomfortable?" and "Did you find any of the conditions to be uncomfortable?"

2.4. Data analysis

To provide an overall measure of midfoot pronation and supination, the mean midfoot angle throughout the entire ground contact phase of the gait cycle was calculated for each condition. In addition, peak midfoot-tibia supination values were compared in the loading and propulsive phases, whilst peak pronation values were compared in the midstance phase (described in Supplementary