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Short Communication

A method to investigate the effect of shoe-hole size on surface marker movement when describing in-shoe joint kinematics using a multi-segment foot model

Chris Bishop [a,*], John B. Arnold [a], Francois Fraysse [a], Dominic Thewlis [a,b,c]

[a] School of Health Sciences, University of South Australia, Australia
[b] Sansom Institute for Health Research, University of South Australia, Australia
[c] Centre for Orthopaedic and Trauma Research, University of Adelaide, Australia

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ABSTRACT

To investigate in-shoe foot kinematics, holes are often cut in the shoe upper to allow markers to be placed on the skin surface. However, there is currently a lack of understanding as to what is an appropriate size. This study aimed to demonstrate a method to assess whether different diameter holes were large enough to allow free motion of marker wands mounted on the skin surface during walking using a multi-segment foot model. Eighteen participants underwent an analysis of foot kinematics whilst walking barefoot and wearing shoes with different size holes (15 mm, 20 mm and 25 mm). The analysis was conducted in two parts; firstly the trajectory of the individual skin-mounted markers were analysed in a 2D ellipse to investigate total displacement of each marker during stance. Secondly, a geometrical analysis was conducted to assess cluster deformation of the hindfoot and midfoot–forefoot segments. Where movement of the markers in the 15 and 20 mm conditions were restricted, the marker movement in the 25 mm condition did not exceed the radius at any anatomical location. Despite significant differences in the isotropy index of the medial and lateral calcaneus markers between the 25 mm and barefoot conditions, the differences were due to the effect of footwear on the foot and not a result of the marker wands hitting the shoe upper. In conclusion, the method proposed and results can be used to increase confidence in the representativeness of joint kinematics with respect to in-shoe multi-segment foot motion during walking.

1. Introduction

The measurement of foot kinematics inside footwear typically relies on holes cut in the shoe upper to allow placement of markers directly on the foot [1–3]. Although surface-mounted marker techniques are susceptible to soft tissue artefacts (STA), they remain the most commonly used technique, and most practical based on current methods, to quantify foot and ankle motion [4–6]. Based on the preliminary work of Stacoff et al. [7], one critical consideration in describing in-shoe foot movement is the diameter of holes cut in the upper. Although an oval-hole shape of up to 2.7 cm × 2.3 cm has been said to not affect a shoe's structural integrity [8], the effect of hole size on individual marker movement has not been fully investigated. Therefore, the aim of this study was to expand on this preliminary work and demonstrate a method to investigate the effect of shoe-hole size on individual marker movement and segment motion during walking in a systematic manner.

2. Methodology

2.1. Participants

Eighteen adults participated in this study (10F:8M, mean age 22.7 ± 3.7 years, height 1.74 m ± 0.08 m, mass 71.2 ± 8.5 kg, median Euro shoe size 42 [range = 37.5–46]). Exclusion criteria were any medical history that could adversely affect gait. Institutional ethics approval was granted for this study.

* Corresponding author at: School of Health Sciences, University of South Australia, City East Campus, North Terrace, Adelaide, SA 5000, Australia. Tel.: +61 8 83021312.
E-mail address: Christopher.bishop@mymail.unisa.edu.au (C. Bishop).

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2.2. Data collection

All participants underwent three-dimensional (3D) gait analysis walking barefoot and wearing three pairs of single-density shoes (Gel Pulse 3, ASICS, Japan). Shoes were fitted by a podiatrist with 10 years' experience. Each shoe had different diameter circular holes cut in them (15 mm, 20 mm, 25 mm) to allow placement of wand-mounted surface markers on the foot. Although this marker-set has been shown to have good intra-rater reliability [ICCs = 0.70–0.99, see [9]], the location of the marker was both marked on the skin, and then checked in each subsequent condition to ensure the marker was in the centre of the shoe-hole. Kinematic data were captured using a 12-camera system at 100 Hz (MX-F20, Vicon, Oxford, UK). Force platforms (9286b, Kistler, Switzerland, 400 Hz) defined gait events. Walking speed was measured using timing gates (Speedlight V2, Swift Performance Equipment, QLD). Five trials were collected barefoot and in each footwear condition. The order of testing was randomised.

2.3. Data processing

Marker trajectory data were captured, tracked and labelled in Vicon Nexus (Version 1.8.2, Vicon, UK) and post-processing performed in Visual3D (Version 4, C-Motion Inc., USA). Marker trajectory data were filtered using a 7 Hz low-pass, zero-lag 4th order Butterworth filter [10]. Data were time normalised to 0–100% of stance. To assess individual marker, two reference frames were defined (the hindfoot [HRF] and forefoot [FRF], see Fig. 1). This transformed the marker trajectories from the lab frame of reference to the ellipse frame, with the dimensions of the ellipse defined by the diameter of the respective shoe-hole. The movement of each marker within the ellipse was defined at each frame of stance as the difference between the original length in the static trial and the planar vector length at frame *i*. Accounting for marker-wand diameter (4 mm), a marker was deemed to not be hitting the surrounding shoe-upper when the maximum length of the planar vector was less than the radius of shoe-hole size.

To assess the influence of individual markers on segment motion, a geometrical analysis of hindfoot and midfoot–forefoot cluster deformation was conducted. Three foot segments (hindfoot, midfoot–forefoot and hallux) were defined [9]. Note that in this analysis, the hallux was not included as it is tracked by just one marker. The geometric analysis was adapted from a previous method [11]. Cappozzo et al. used the method to characterise the shape of a marker cluster, whereas in this study, it is used to characterise the shape of deviations from rigid body motion. The spatial distribution of the deviations were characterised by a (diagonal) dispersion matrix [11]:

$$k = \frac{XX^T}{m}, \quad (1)$$

where X is the $3 \times m$ matrix of deviations from rigid-body movement for one marker (m frames) expressed in local coordinate system (LCS):

$$X = [x_1 - \bar{x}, x_2 - \bar{x}, \ldots, x_m - \bar{x}], \quad (2)$$

where x_i is the recorded position of the marker at frame i, expressed in the corresponding LCS, and i, the rigid-body position of the marker, constant in the LCS. The diagonal elements k_{11}, k_{22}, k_{33} ($k_{11} > k_{22} > k_{33}$) represent the mean square distances between the recorded marker motion and the ideal rigid-body motion. They can be visualised as the lengths of the semi-axes of an ellipsoid. The isotropy index d:

$$d = 3\frac{k_{33}}{k_{11} + k_{22} + k_{33}}, \quad (3)$$

represents the shape of the deviations from rigid-body motion. Isotropy indices were computed for each condition, with the indices for barefoot taken as baseline (barefoot represent the shape of the deformations due to STA). The hypothesis was that, in the shod condition, if the holes did not impair marker movement the isotropy indices (indicating the shape of the ellipse) would be similar to barefoot walking as the distribution of the STAs would not have changed.

2.4. Statistical analysis

The marker trajectory data were analysed descriptively with frequency counts for the number of times each marker exceeded the radius of shoe-hole size in each condition. A linear mixed model with post-hoc *t*-tests (Bonferroni adjusted) was used to determine differences in walking speed, and if any significant differences occurred in the isotropy index between each condition relative to barefoot. The level of significance was set at 0.05.

3. Results

There were no statistically significant differences in walking speed between footwear conditions (15 mm = 1.52 $\pm$ 0.09 ms^{-1}, 20 mm = 1.53 $\pm$ 0.09 ms^{-1}, 25 mm = 1.54 $\pm$ 0.07 ms^{-1}, $p > 0.05$). In the 15 mm condition, the marker trajectory exceeded the radius at all anatomical locations at least once. In the 20 mm condition, the marker trajectory exceeded the radius at all sites except the navicular tuberosity. No marker exceeded the radius at any location in the 25 mm condition (Fig. 2). The 25 mm condition resulted in isotropy indices closest to barefoot (Fig. 3). Only CALC1 and CALC3 markers exhibited significant differences (mean difference = 0.219 and 0.104 respectively) between barefoot and the 25 mm condition ($p < 0.05$).

4. Discussion

Where previous studies have either considered the effects of shoe-hole size on joint angles [7] or shoe structural integrity [8], this study considered both individual marker trajectories and segment rotations. Holes with a diameter of 25 mm were sufficiently large to prevent perturbed motion of surface-mounted markers. Although this finding is consistent with previous research [7,8], we suggest the use of marker-wands (which have a 4 mm diameter compared to standard 9 mm markers) increases the available range of movement within the shoe-hole. This method also extends the scope of previous work by considering the effect of shoe-hole size at the cluster level of the hindfoot and midfoot. When comparing isotropy indices, segment motion was most similar between the 25 mm and barefoot conditions. At the hindfoot, although the differences in isotropy indexes were larger, no marker displaced more than 10.5 mm. Therefore the differences in isotropy indexes appear to be due to the shoe affecting soft tissue motion at the hindfoot. Given that no markers displaced more than 10.5 mm in the 25 mm condition, it can be concluded the marker motion was not impeded.

The results of this study indicate that the techniques used to describe in-shoe kinematics may benefit from review. Although Butler and co-authors reported a 10% reduction in heel counter stability after cutting holes in the heel counter [12], there is not currently a method available in the literature to systematically assess changes in structural integrity as a result of shoe modification. A method has been presented based on distance and angle measurements [8]. However, this provides no insight in changes to the material properties (e.g. stiffness) of the shoe, or whether shoe-hole size depends on the foot being investigated (i.e. smaller holes for smaller feet). Based on our results, circular holes