The reliability, accuracy and minimal detectable difference of a multi-segment kinematic model of the foot–shoe complex

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A B S T R A C T

Kinematic models are commonly used to quantify foot and ankle kinematics, yet no marker sets or models have been proven reliable or accurate when wearing shoes. Further, the minimal detectable difference of a developed model is often not reported. We present a kinematic model that is reliable, accurate and sensitive to describe the kinematics of the foot–shoe complex and lower leg during walking gait. In order to achieve this, a new marker set was established, consisting of 25 markers applied on the shoe and skin surface, which informed a four segment kinematic model of the foot–shoe complex and lower leg. Three independent experiments were conducted to determine the reliability, accuracy and minimal detectable difference of the marker set and model. Inter-rater reliability of marker placement on the shoe was proven to be good to excellent (ICC = 0.75–0.98) indicating that markers could be applied reliably between raters. Intra-rater reliability was better for the experienced rater (ICC = 0.88–0.99) than the inexperienced rater (ICC = 0.83–0.97). The accuracy of marker placement along each axis was <6.7 mm for all markers studied. Minimal detectable difference (MDD90) thresholds were defined for each joint: tibialcalcaneal joint – MDD90 = 2.17–9.36, tarsometatarsal joint – MDD90 = 1.03–9.29 and the metatarsophalangeal joint – MDD90 = 1.75–9.12. These thresholds proposed are specific for the description of shoe motion, and can be used in future research designed at comparing between different footwear.

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1. Introduction

Kinematic models are commonly used to quantify foot and ankle kinematics during activities of daily living. However, most of these models were developed with the intention of studying barefoot biomechanics [1,2], when typically activities of daily living are performed while wearing shoes. The translation of these models to the study of shod kinematics is problematic. It has been previously identified that tracking the motion of shoe-mounted markers does not indicate the movement of the foot inside the shoe [3,4]. Although methods have been developed to apply markers on the skin surface through the shoe, the analysis of in-shoe foot kinematics is not always required [5]. In this case, it is essential to consider the segments of the shoe, which are conceptually similar to the anatomy of the foot, rather than the foot itself. When the structure of the shoe is added to the complexity of the foot, it is possible to model a foot–shoe complex (i.e. the foot and shoe together) rather than just a shoe or the foot in isolation. In this example, the foot remains the major factor determining the kinematics, however the shoe changes the basic assumptions of the segments.

While the concept of a shoe model appears relatively logical, there are methodological issues that must be dealt with. Firstly, one must define the segments of the model based on standard palpable anatomical landmarks. Palpation through the surface of a shoe comes with a degree of complexity and a number of unknown factors. Palpation guidelines, such as those documented by Van Sint Jan [6], that are commonly followed in surface marker sets were not developed for use through clothing or shoes. By following these methods, it is likely the application of markers on the shoe surface will come with a degree of inaccuracy in regards to the location of the underlying anatomical landmark. This will have a direct impact on the accuracy of anatomical frame definition. We have previously described a method for palpating anatomical landmarks through the shoe upper [7]. Using these guidelines we have proposed a set of offset values, which account for the difference between the shoe upper and anatomical landmark [7]. The second problem encountered is that of technical componentry and material thickness common to shoes such as rigid heel counters.

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Both single-segment and multi-segment marker based models of the foot have been published, with demonstrated good intra- and inter-rater reliability of marker placement and model output [1,2,8–13]. A recent review highlighted that the current trend is to consider the foot as a number of segments [14]. This trend can be extrapolated to the study of footware kinetics as shoes are typically thought to consist of a heel counter, mid-sole and toe box. Despite demonstrated reliability, the absence of marker placement accuracy assessment makes it difficult to interpret the accuracy of anatomical frame definition relative to the underlying bone embedded frame [15]. In addition to reporting static or dynamic measures of marker placement reliability and accuracy, it is important to determine the minimal detectable difference and understand the limitations of a given kinematic model. Therefore, the aim of the study was to demonstrate the reliability and static and dynamic accuracy of a marker set we have previously proposed [7] (albeit to describe the offsets between the shoe upper and anatomical landmark), which could be used in future research investigating the effectiveness of interventions that can only be tested under shod conditions, e.g. foot orthotics. The minimal detectable differences of the model will be defined to avoid over emphasis on small differences, which might otherwise be considered type I errors.

2. Methodology

In order to define the accuracy and reliability of marker placement and the minimal detectable difference of the model, three experiments were conducted and are reported independently:

- Experiment 1 – marker placement accuracy;
- Experiment 2 – marker placement reliability;
- Experiment 3 – determination of the model’s minimal detectable difference.

Each of the experiments recruited a sample of university staff and students. Participants were included if they were aged between 18 and 40 years old, had a normal arched right foot [16] and reported no medical history that could adversely affect gait. Written informed consent was obtained [17]. The Human Research Ethics Committee of the University of South Australia approved the protocol [protocol number 0000020984]. A basic, commercially available shoe (Mexico 66, ASICS, Japan) was used in this study. This shoe is a straight-lasted, enclosed leather shoe with a midsole and outsole, yet no rigid heel counter. Shoe sizes were measured using a Brannock device (The Brannock Device Co. Inc, USA) and fitted by a qualified podiatrist. All shoes were tightened to a self-reported comfortable fit. A Shimadzu computed radiography machine (Shimadzu, Japan) was used to take all weight-bearing X-rays. To capture kinematic data, a 12 camera Vicon MX-F20 system (Vicon, Oxford, UK) was used. All kinematic data were sampled at 100 Hz. The use of each of these instruments/systems is expanded further in the following sections.

2.1. Kinematic model

2.1.1. Model segments

A four-segment model of the foot–shoe complex and lower leg was developed. The four segments were assumed to act as rigid bodies and were defined as:

- leg (consisting of the tibia and fibula);
- heel (consisting of the hindfoot of the foot and the rear of the shoe);
- midfoot (consisting of the midfoot and metatarsals 1–5 of the foot and the middle third of the shoe);
- toe box (consisting of toes 1–5 and the toe box).

2.1.2. Model joints

The articulation between two segments defined a joint:

- tibiocalcaneal joint was defined as the articulation between the leg and the heel segment;
- tarsometatarsal joint was defined as the articulation between the heel segment and the midfoot segment;
- metatarsophalangeal joint was defined as the articulation between the midfoot segment and the toe box segment.

The median position between the proximal medial and lateral markers defining the segment was defined as a joint centre. Right-handed, bone-embedded local coordinate systems (LCs) were used to define each segment. Each joint was modelled with three degrees of rotational freedom. The joint pose was then estimated using the global optimisation technique described by Lu and O’Connor [18]. Rotation of the tibiocalcaneal joint around the x-axis (medial–lateral) was flexion/extension, about the y-axis (anterior–posterior) was abduction/adduction and about the z-axis (superior–inferior) was inversion/eversion. To ensure the z-axis was aligned with the long axis of the segment, the axes of rotations changed when describing the distal foot joints. Rotation around the x-axis (medial–lateral) remained flexion/extension, but the y-axis (superior–inferior) changed to represent abduction/adduction and the z-axis (anterior–posterior) changed to represent inversion/eversion. An XZY cardan sequence was used to represent the order of rotations for each joint [19].

2.1.3. Anatomical landmarks

A marker set consisting of 14, 10 mm retro-reflective markers and one hallux trihedron (three, 10 mm markers) was applied to the shoe surface and four, 10 mm markers and one plate-mounted marker cluster (four, 15 mm markers) were applied to the skin surface of the leg to define anatomical frames (Fig. 1). To apply markers on the skin surface, previously developed guidelines were used [6]. To palpate anatomical landmarks through the shoe upper, custom guidelines were developed (Additional File 1). A technical cluster consisting of at least three non-collinear markers was placed on each segment.

2.1.4. Anatomical reference frames

The leg:

\[ O_{\text{leg}} \]

The midpoint between the MFE and LFE;
\[ X_{\text{leg}} \]

The x-axis joins the origin and the LFE marker;
\[ Y_{\text{leg}} \]

The y-axis is orthogonal to the x-axis and lies in the coronal plane;
\[ Z_{\text{leg}} \]

The z-axis is orthogonal to the xy plane.

The heel segment:

\[ O_{\text{heel segment}} \]

The midpoint between the MM and LM;
\[ X_{\text{heel segment}} \]

The x-axis joins the origin and LM marker;
\[ Z_{\text{heel segment}} \]

The z-axis is orthogonal to the x-axis and lies in the transverse plane;
\[ Y_{\text{heel segment}} \]

The y-axis is orthogonal to the xz plane.

The midfoot segment:

\[ O_{\text{midfoot segment}} \]

The midpoint between the NT and SP;
\[ X_{\text{midfoot segment}} \]

The x-axis joins the origin and SP marker;
\[ Z_{\text{midfoot segment}} \]

The z-axis is orthogonal to the x-axis and lies in the transverse plane;
\[ Y_{\text{midfoot segment}} \]

The y-axis is orthogonal to the xz plane.

The toe box segment:

\[ O_{\text{toe box segment}} \]

The midpoint between the 1MTH and 2MTH;
\[ X_{\text{toe box segment}} \]

The x-axis joins the origin and the 2MTH marker;
\[ Z_{\text{toe box segment}} \]

The z-axis is orthogonal to the x-axis and lies in the transverse plane;
\[ Y_{\text{toe box segment}} \]

The y-axis is orthogonal to the xz plane.

2.2. Experiment 1: reliability tests

Twelve participants [mean age of 21.3 years [95% CI = 20.7–24.0 years], height of 1.77 m [95% CI = 1.74–1.85 m], Euro shoe size 41.7 (95% CI = 40.1–43.2) and body mass of 73.0 kg [95% CI = 65.9–81.8 kg]] were recruited. Each participant attended two data collection sessions one week apart and was provided with des. Two raters were used to investigate intra- and inter-rater reliability. The raters were classified as experienced (<5 years) and inexperienced (<5 years) based on the number of years of experience in musculoskeletal science. Prior to data collection, an independent rater affirmed three markers on the rear sole of the shoe to define a shoe coordinate system (SCS). The markers defining the SCS were not removed between sessions. The marker set was applied to each participant and a static trial was captured to define the position of each marker in the global coordinate system (GCS) relative to the origin of the SCS. The markers were removed and the process repeated for the second rater. Each rater was blinded to the positioning of the previous rater. To define inter-rater reliability, participants returned one week later and both raters repeated the process. To describe linear displacement, the distance between each marker and the origin of the SCS was calculated for each marker in each plane. The Euclidean distance of each marker from the origin of the SCS was then calculated. Intra-class correlation coefficients were used as the measure of intra- and inter-rater reliability [20].

and anterior–posterior weight-bearing X-ray was taken of the right foot. The marker set was removed from the skin, the shoe applied and the marker set reapplied on the shoe. A second series of X-rays was taken of the foot–shoe complex. Marker placement accuracy was defined using the method described by Bishop et al. [7]. The mean displacement between skin-mounted and shoe-mounted markers from the anatomical landmark they purported to represent was considered a measure of marker placement accuracy on the shoe.

2.4. Experiment 3: determination of the minimal detectable difference

Twenty-four participants (12 males and 12 females) with a mean age of 22.6 years (95% CI = 20.0–23.6 years), height of 1.76 m (95% CI = 1.71–1.80 m), Euro shoe size 41.4 (95% CI = 40.3–42.5) and body mass of 72.5 kg (95% CI = 65.5–76.4 kg) were recruited. The marker set was applied to the foot–shoe complex and leg by the experienced rater. A static reference trial was captured to define the static pose of the segments. Each participant was required to perform five walking trials along an 8-m walkway. Marker trajectory data were captured, labelled and tracked in Vicon Nexus (Vicon, UK, Version 1.6). After tracking and labelling of markers, all data were saved to CID format and imported to Visual3D (C-Motion, Inc., MA, USA) for post-processing. All kinematic data were filtered using a lowpass 4th order recursive Butterworth filter with a cut-off frequency of 7 Hz [21]. Initial contact and toe off were defined based on the velocity of foot marker trajectories [22]. Additional gait events were created at 15% stance, 50% stance and the time of peak toe box dorsiflexion (PHD). Joint angles were extracted at each gait event for each of the three joints. Inter-rater ICCs were used as the reliability coefficient to calculate the standard error of measurement (SEM) and from these the minimal detectable difference (MDD0) of the model was calculated [23].

3. Results

3.1. Experiment 1: reliability

The intra-rater reliability of applying markers on the skin and shoe was consistently better and the ICC range less for the experienced rater (ICC = 0.70–0.99) than the inexperienced rater (ICC = 0.38–0.97, see Table 1). Apart from one marker (inexperienced rater – medial femoral epicondyle [mean-difference (MD) = 12.63 mm]) the mean-difference in marker placement between sessions was < 8.0 mm. Inter-rater reliability resulted in ICC values >0.75 for all markers (ICC = 0.75–0.98). When describing marker placement error by plane, the largest differences in marker placement between raters were identified in the coronal plane (MD = 13.0–20.8 mm), followed by the sagittal (MD = 10.1–14.3 mm) and transverse planes (MD = 0.9–7.5 mm).

3.2. Experiment 2: accuracy

The 2-D accuracy of marker placement on the medial–lateral and anterior–posterior X-ray images are presented in detail in Bishop et al. [7], with the results indicating all markers were placed on the shoe <5 mm further away from the anatomical landmark relative to the marker placed on the skin [7]. Table 1 reports marker placement accuracy along each axis. On the medial–lateral and anterior–posterior axis, all markers were placed ≤6.7 mm of the anatomical landmark. Despite the presence of a toe box on the medial–lateral X-ray view, all markers were placed ≤5.6 mm on the dorso-plantar axis.

3.3. Experiment 3: determination of the model's minimal detectable difference

The mean joint angles for the population are presented in Fig. 2. The SEM and MDD0 values are also presented for each degree of freedom of the three joints (Table 2). The MDD0 threshold values ranged from 2.17° to 9.36° when estimating tibiocalcaneal joint kinematics, from 1.03° to 9.29° when estimating tarso-metatarsal joint kinematics and from 1.75° to 9.12° when estimating metatarsophalangeal joint kinematics.
4. Discussion

The first aim of this study was to establish a marker set of the foot–shoe complex and investigate its accuracy and reliability. The inter-rater reliability of marker placement on the shoe ranged from good to excellent, which indicates that markers can be applied reliably on the shoe between raters when using well-developed palpation guidelines. While the reliability of marker placement has been demonstrated, it is seemingly worthless if the bone-embedded anatomical frame is defined incorrectly [7]. The results of this study indicate that the accuracy of shoe-mounted marker placement (regardless of plane) was <6.7 mm for all markers studied; more detail can be found in Bishop et al. [7]. The variability in accuracy values on the toe box segment can be partially explained by the shoe toe box, where the surface of the shoe often does not articulate with the dorsal surface of the foot.

Based on the accuracy and reliability results, we propose a series of thresholds that describe the ability of the model to describe a true difference. Although the calculation of the minimal detectable difference conducted in this study is informed by pilot research, the SEM values calculated are consistent with previous kinematic SEM\textsubscript{MMD} values reported in the literature [10]. Although MDD\textsubscript{MMD} values <5° have been identified in some instances, they directly correspond to joints that have small ranges of motion. When considering a difference as a percentage of total joint ROM, it is likely that a large percentage difference will still need to be identified to identify a significant difference. Therefore, it must be questioned whether a foot–shoe complex model can detect small difference in joint kinematics (i.e. <5°) as any such difference is likely to be subject to a combination of material/tissue artefact and measurement noise.

Despite this model being the first known model of the foot–shoe complex, it is not without limitations. Firstly, we must stress that the model was developed for a basic structured shoe. Although

Table 1

<table>
<thead>
<tr>
<th>Marker</th>
<th>Experiment 1 – reliability of marker placement</th>
<th>Experiment 2 – marker placement accuracy</th>
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<tbody>
<tr>
<td></td>
<td>Intra-rater 1</td>
<td>Intra-rater 2</td>
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<tr>
<td></td>
<td>MD</td>
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<tr>
<td>LFE</td>
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<td>1.0–14.3</td>
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<tr>
<td>MFE</td>
<td>2.8</td>
<td>1.6–4.0</td>
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<tr>
<td>LM</td>
<td>2.5</td>
<td>0.1–4.9</td>
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<tr>
<td>MM</td>
<td>1.2</td>
<td>0.4–2.0</td>
</tr>
<tr>
<td>SP</td>
<td>2.3</td>
<td>0.9–3.6</td>
</tr>
<tr>
<td>NT</td>
<td>1.9</td>
<td>0.3–3.5</td>
</tr>
<tr>
<td>5MTP</td>
<td>3.3</td>
<td>0.9–5.7</td>
</tr>
<tr>
<td>1MTP</td>
<td>3.7</td>
<td>1.3–6.2</td>
</tr>
<tr>
<td>2MTP</td>
<td>3.5</td>
<td>0.6–6.4</td>
</tr>
<tr>
<td>Apex 1</td>
<td>2.1</td>
<td>0.6–3.6</td>
</tr>
</tbody>
</table>

(-) Data were not extracted in an individual plane on a chosen X-ray image (see Experiment 2).

Fig. 2. Joint kinematics. The flexion–extension (A), abduction–adduction (B) and inversion–eversion (C) motion at each of the tibiocalcaneal, tarsometatarsal and metatarsophalangeal joints are presented. Individual gait events (IC = initial contact, 15–15% of stance, 50–50% of stance, PHD = peak toe box dorsiflexion and TO = toe off) are presented on the abscissa of each diagram.

future work will investigate this issue in more detail, it is likely that more structured shoes will have a greater impact on marker placement accuracy if anatomical landmarks are palpated through a rigid heel counter. It is acknowledged that the kinematics of the foot inside the shoe are the major influences on the joint motion measured, yet this motion will still be directly affected by the physical constraints of the shoe. We have not suggested that the kinematics described in this study are either those of the foot or the shoe, yet rather those of the foot–shoe complex. Therefore this model must be interpreted as being representative of the interaction between the heel, midfoot and toe box during stance phase of walking gait. In saying this, the kinematics reported in this paper are likely to differ if a different shoe with a different structural design and/or material properties was used. Despite this limitation, the methods proposed here allow for the translation of the marker set and model to different shoe designs. This is especially apparent when there is not the need and/or facilities to cut holes in shoes to quantify in-shoe foot kinematics. By no means does this negate the need for the understanding of in-shoe foot function, and future research utilising this model must begin to describe how the foot and shoe surface interact together during functional tasks that require shoes to be worn.

5. Conclusion

This is the first kinematic model purpose-built for quantifying the kinematics of the foot–shoe complex. We have demonstrated accurate and reliable anatomical landmark palpation comparable to models designed for barefoot investigations. Future applications of this model must use the thresholds proposed as an indicator of measurable change or differences when investigating either between or within group effects. Any angular displacements below these thresholds should be discounted as type I error.

Acknowledgments

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Conflict of interest

None declared.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2012.09.020.

References


