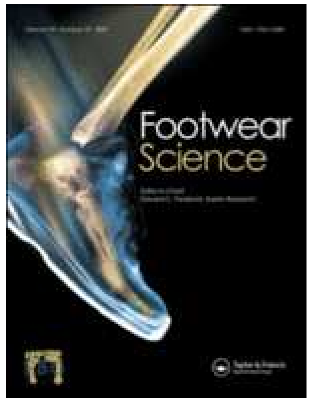

A radiological method to determine the accuracy of motion capture marker placement on palpable anatomical landmarks through a shoe

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Abstract

The accuracy of marker placement on palpable surface anatomical landmarks is an important consideration in biomechanics. Although markers may be able to be applied consistently in the same position on the foot between rater's or sessions, it remains unknown whether these markers accurately reflect the location of the underlying anatomical landmark they are intended to represent. A novel method was developed to identify the accuracy of markers placed on the shoe surface by palpating landmarks through the shoe. An anterior-posterior and lateral-medial x-ray were taken on 24 participants with a custom marker set applied to both the skin and shoe. The vector magnitude of both skin and shoe mounted markers from the anatomical landmark was calculated, as well as the mean marker offset between skin and shoe mounted markers. The mean difference in displacement of the shoe mounted marker relative to the skin mounted marker, accounting for shoe thickness, was less than 10 mm for all markers studied. Further, when using the developed guidelines provided in this study, the method was deemed reliable (Intra-rater ICC's = 0.61-0.96). In addition to proposing a method to determine marker placement accuracy, this paper also provides a series of offsets to account for shoe-marker thickness in an in-shoe kinematic model.

Keywords

Anatomical markers; Kinematic Model; X-ray; Reliability; Foot and ankle

Background

Kinematic marker sets are commonly used to quantify the foot and ankle mechanics during gait and have interchangeably been applied to both the skin surface of the foot and on the shoe surface with little consideration for accuracy in the latter condition (Carson et al., 2001, Nester et al., 2007, Leardini et al., 2007, Cheung and Ng, 2007, Stacoff et al., 1992, Nigg and Morlock, 1987, Lundgren et al., 2008). The markers are intended to define anatomical frames that allow for the description of joint kinematics (Cappozzo et al., 1995). The focus of the majority of the literature over the past twenty years has been on reliability. It is widely accepted that the intra-rater reliability of marker application is good (Kadaba et al., 1989), yet the largest source of marker placement variation is found between raters from different laboratories (Gorton et al., 2009).

While reliability is essential, it is seemingly worthless if the accuracy of the anatomical frame is defined incorrectly, as marker placement errors as small as 10 mm have been shown to significantly alter joint moments (Thewlis et al., 2008, Holden and Stanhope, 1998). Where reliability analyses will show whether marker researchers and scientists can place markers in the same position, it gives no information in regards to whether the markers are placed on the anatomical landmark of interest. Achieving acceptable marker placement accuracy may be enhanced with strict adherence to guidelines designed to improve the consistency in identifying anatomical landmarks on the skin surface (Van Sint Jan, 2007). Inaccuracies in marker placement as small as 10 mm are conceivable at large joints; however this problem is much aggravated for feet covered by shoes. The relatively small surface area and close proximity of palpable anatomical landmarks on the foot presents a problem where marker misplacement is a genuine possibility.

This paper presents a method we have developed to quantify the accuracy of marker placement on palpable anatomical landmarks of the foot through shoes. The paper will also develop a set of offset values for the compensation of shoe thickness in models used to investigate in-shoe foot kinematics.

Methods

This study was approved by the Human Research Ethics Committee, University of South Australia. Twenty-four participants (mean age of 22.4 yrs (SD = 4.8 yrs), height of 1.79 m (SD = 0.10 m) and body mass of 75.8 kg (SD = 13.4 kg)) were recruited to the study. An weight bearing anterior-posterior and lateral-medial x-ray were taken of a marker set (seven x 10 mm markers [Figure 1]) affixed to each participant in two experimental conditions: barefoot [A] and shod [B]. A basic structured shoe (Mexico 66, ACICS Corporation, Japan) consisting of an outsole, midsole and upper was used. A Shimadzu **Computer Radiography** (CR) machine (Shimadzu, Japan) was used to take all x-rays.

To take the weight-bearing A-P view, the participant stood on the floor with their feet on the CR x-ray plate. The x-ray tube was angled at 20° to the perpendicular line coming from the floor. The source-image distance (SID) used was 1.0 m. To take the lateral-medial view, the participant stood on a raised platform, with the CR cassette mounted between the two feet. This ensured even distribution of the centre of mass over the base of support. The x-ray beam was (perpendicular) to the foot sagittal plane. The source-image distance used was 100 cm. The data was automatically digitised by computational software (Voyager PACS digitization software, 3.2 Release 7 Build 3, Voyager Imaging, Australia) and provided for analysis as raw, unidentified, digital imaging and communications in medicine (DICOM) files. The exposure settings used (A-P View – 5 mAs and 55 kVp and lateral-medial view – 5 mAs and

59 kVp) ensured the correct contrast and density of image was obtained. The two x-ray images were calibrated with a standard reference object. The 2D positions of each marker and corresponding anatomical landmark were manually digitised in Matlab (Matlab 2010b, Mathworks, USA) following custom guidelines (Appendix 1). This was repeated for each experimental condition on both the A-P and lateral-medial x-ray images.

To assess the accuracy of marker placement, the vector magnitude between the underlying anatomical landmark and each of the skin (d_1) and shoe mounted (d_2) markers was calculated. The vector magnitude between the skin and shoe mounted markers was also calculated (d_3), which was assumed to be a measure of shoe thickness. The adjusted measure of shoe mounted marker displacement (d_4) was defined as the vector magnitude between the anatomical landmark and shoe mounted marker minus the vector magnitude between the two markers. The mean shoe marker offset (MMO) was calculated as the adjusted shoe mounted marker displacement minus the vector magnitude between the anatomical landmark and skin mounted marker (Figure 2). The MMO was considered a medial-lateral offset on the A-P x-ray image and a superior-inferior offset on the lateral-medial image. The MMO was assumed to be a direct measure of shoe mounted marker placement accuracy.

Two independent researchers with a minimum of five years expertise working with foot and ankle radiography identified the coordinates of markers separately, one week apart to analyse both intra- and inter-rater reliability. Rater 1 re-identified marker positions one week later to assess intra-rater reliability. Intra-class correlation coefficients were used as measures of reliability of the method (Landis and Koch, 1977).

Results

The results of the accuracy assessment indicate that shoe mounted markers were placed further away from the anatomical landmarks compared to the equivalent skin mounted markers (Table 1). On the A-P view, the greatest displacement of a shoe mounted marker from an anatomical landmark was the styloid process (MMO = 6.9 mm). The mean marker offset between all other markers was < 5 mm, which was equivalent to the radius of the markers. On the lateral-medial view, the greatest displacement of a shoe mounted marker from an anatomical landmark was the apex of the 2nd toe (MMO = 9.2 mm). Four markers resulted in mean marker offsets of < 1 mm. The calculated mean marker offset also provides a method to compensate for shoe thickness in an in-shoe model, with medial-lateral and superior-inferior offset projections provided for each shoe mounted marker (Table 2).

In respect to the reliability of the method, the application of markers on the anterior-posterior x-ray view resulted in strong to excellent intra-rater reliability (ICC = 0.61 – 0.96). The application of markers on the lateral-medial x-ray view resulted in strong to excellent intra-rater reliability (ICC = 0.73 – 0.96). Inter-rater reliability ranged from moderate to excellent on both the A-P view (ICC = 0.44 – 0.96) and the lateral-medial view (ICC = 0.45 – 0.83).

Discussion

This study presents a method to determine the accuracy of markers placed on either the skin or shoe surface in relation to the underlying anatomical landmark they are purported to represent. We present data pertaining to the measured accuracy of markers from the underlying anatomical landmark as well as the reliability of the measurement protocol proposed. The mean difference in displacement of the shoe mounted marker, accounting for shoe thickness, was less than 10 mm for all markers studied. Previously proposed methods to assess reliability focus on static marker placement, indicating that reliable marker placement can result in consistent joint kinematics. However, this paper presents a novel method using radiology designed to quantify the accuracy of motion capture marker placement on palpable anatomical landmarks through a shoe.

This study has established that when using the developed guidelines (Appendix 1), the method is reliable. In the participants used in this study, the method identified that the application of markers was accurate to < 10 mm with respect to the underlying anatomical landmark.

When accounting for shoe thickness, the application of shoe mounted markers resulted in sub-millimetre accuracy in 43% of cases. The recorded accuracy was < 5mm in 78% of cases. The large mean marker offsets demonstrated in respect to the forefoot markers on the lateral-medial x-ray image can be explained by the presence of the shoe toe box, whereby the dorsal surface of the shoe does not directly articulate with the dorsal aspect of the toes. Despite this, the high accuracy demonstrated in this study is testament to the strength and transparency of the guidelines and methods proposed to assess the accuracy of marker placement on the shoe overlying anatomical landmarks.

Although the development of this method is novel and provides a significant step forward in footwear research, it does have its limitations. The proposed method may prove to be more difficult in the presence of a more structured shoe (i.e. heel counters), especially given the likelihood of increased difficultly in palpating anatomical landmarks through rigid shoe componentry. Furthermore, this method managed the accuracy individually in the sagittal and coronal planes. The lack of measured accuracy in the transverse plane limits the interpretation and consequent validation of the dynamic displacement of markers in 3-D space. Future research utilising computer tomography (CT scans) will aid in the 3-D interpretation of marker placement accuracy. Despite this limitation, the results presented can still inform future development of in-shoe kinematic models, whereby the shoe thickness is accounted for as either a medial-lateral or superior-inferior offset for true estimation of in-shoe foot segment geometry and coordinate systems.

Conclusion

We have developed a reliable radiologic method that is capable of describing the accuracy of markers placed on the surface of the shoe with reference to an underlying anatomical landmark. As expected, all shoe mounted marker were placed further away from the referenced anatomical landmark than their skin-mounted counterparts, yet when accounting for shoe thickness, the mean marker offset of shoe mounted markers was less than 10 mm for all markers. Based on the results of this study, the protocol described serves as an additional tool for footwear researchers given its ability to determine the accuracy of markers placed on either the skin or shoe surface in reference to the underlying anatomical landmark they are intended to represent.

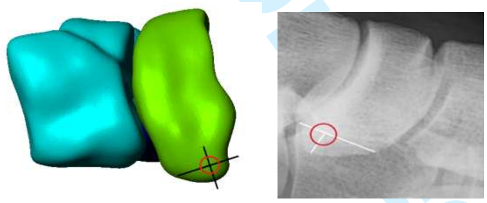
Acknowledgements

We would like to acknowledge ASICS Oceania for supplying the footwear used in this study and the Medical Radiation Department, University of South Australia providing access to the radiology suite. Ergolab is supported by AutoCRC and the South Australian Government.

Appendix 1– Identification of Anatomical Landmarks on X-ray

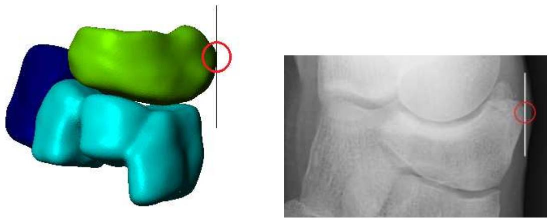
Navicular Tuberosity

Lateral-Medial View



The navicular tuberosity on the lateral-medial x-ray view is located in the inferior-posterior corner of the navicular bone

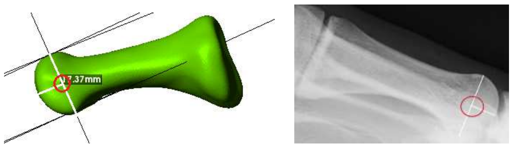
A-P View



The navicular tuberosity on the A-P x-ray view is located at the most medial point of the navicular bone.

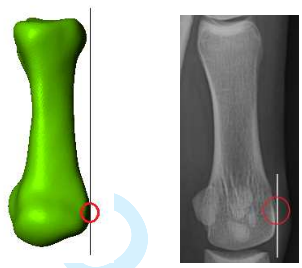
1st Metatarsal head

Lateral-Medial View



The 1st metatarsal landmark on the lateral-medial x-ray view is identified as the median point on a line connecting the two widest points of the 1st metatarsal head.

A-P View

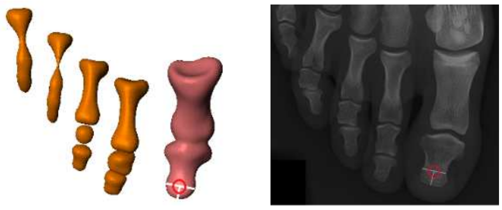


The 1st metatarsal landmark on the A-P x-ray view is identified as the most medial point of the 1st metatarsal head.

Identification of Apex of 1st Toe (hallux)

Lateral-Medial View

A-P View

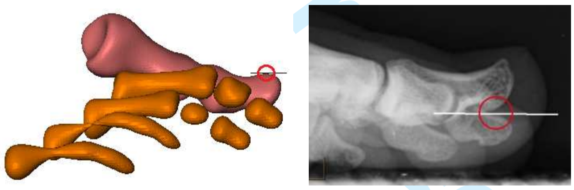


The Apex of the 1st toe landmark on the lateral-medial x-ray view is identified as the most dorsal point of the distal 1st phalanx.

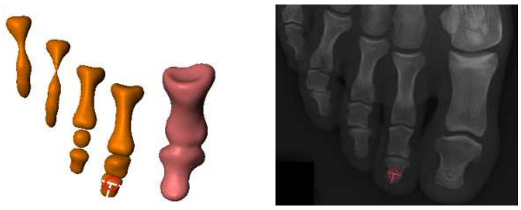
The Apex of the 1st toe landmark on the A-P x-ray view is identified as the median point on a line connecting the two widest points of the distal 1st phalanx.

Identification of Apex of 2nd Toe

Lateral-Medial View



A-P View

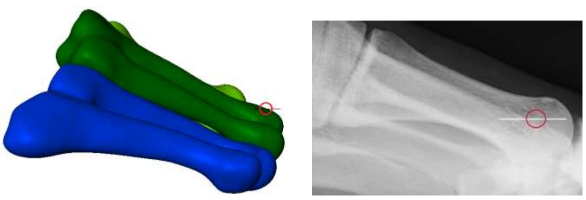


The Apex of the 2nd toe landmark on the lateral-medial x-ray view is identified as the most dorsal point of the distal 2nd phalanx.

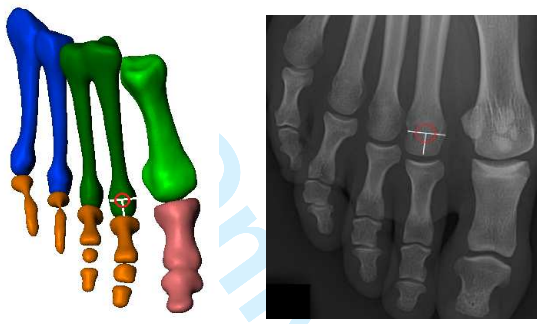
The Apex of the 2nd toe landmark on the A-P x-ray view is identified as the median point on a line connecting the two widest points of the distal 2nd phalanx.

Identification of 2nd Metatarsal Head

Lateral-Medial View



A-P View



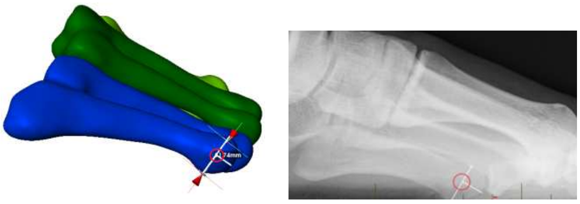
The 2nd metatarsal head landmark on the lateral-medial x-ray view is identified as the most dorsal point of the 2nd metatarsal head.

The Apex of the 2nd toe landmark on the A-P x-ray view is identified as the median point on a line connecting the two widest points of the 2nd metatarsal head.

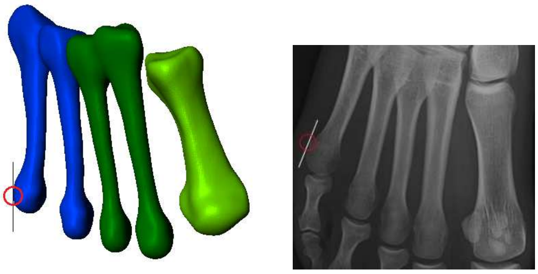
Identification of 5th Metatarsal Head

Lateral-Medial View

A-P View



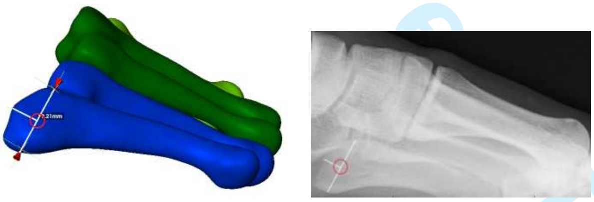
The 5th metatarsal head landmark on the lateral x-ray view is identified as the most lateral point of the 5th metatarsal head.



The 5th metatarsal head landmark on the A-P x-ray view is identified as the median point on a line connecting the two widest points of the 5th metatarsal head.

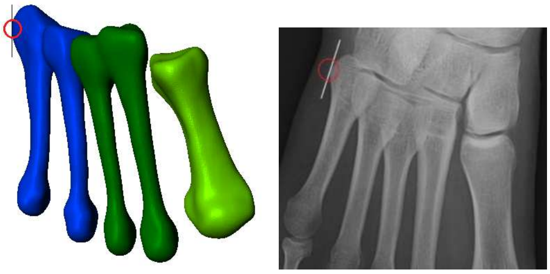
Identification of Styloid Process

Lateral-Medial View



The styloid process landmark on the lateral-medial x-ray view is identified as the most lateral point of the styloid process (5th metatarsal base).

A-P View



The styloid process landmark on the A-P x-ray view is identified as the median point on a line connecting the two widest points of the styloid process (5th metatarsal base).

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Table 1 – Skin & Shoe Marker Displacement from Anatomical Landmark

Markers	**A-P View**				**Lateral-Medial View**			
	Skin-mounted		*Shoe-mounted*		*Skin-mounted*		*Shoe-mounted*	
	Mean (mm)	95% CI (mm)	Mean (mm)	95% CI (mm)	Mean (mm)	95% CI (mm)	Mean (mm)	95% CI (mm)
Navicular tub.	5.3	4.2 - 6.3	9.9	8.4 - 11.3	2.6	1.7 - 3.4	3.5	2.3 - 4.8
1st met. head	5.0	4.3 - 5.7	7.4	6.5 - 8.2	2.0	1.4 - 2.5	1.8	1.0 - 2.6
Apex 1st toe	2.1	1.2 - 2.9	2.2	0.6 - 3.9	3.8	2.7 - 5.0	9.6	8.1 - 11.1
Apex 2nd toe	4.1	3.3 - 4.9	4.0	2.4 - 5.6	5.6	4.1 - 7.2	14.5	12.2 - 16.7
2nd met. head	2.4	1.5 - 3.3	2.5	1.1 - 3.9	7.6	6.4 - 8.8	16.7	14.4 - 19.0
5th met. head	4.5	3.5 - 5.5	9.2	7.8 - 10.7	2.3	1.5 - 3.1	3.0	1.4 - 4.5
Styloid process	5.5	4.9 - 6.1	12.4	11.2 - 13.5	1.8	1.0 - 2.5	4.1	2.9 - 5.3

315 **Table 2** - Compensation for Shoe Thickness (Mean Marker Offset)

Marker	Marker Offset	
	medial-lateral axis (mm)	*Dorsal-plantar axis (mm)*
Navicular Tub.	5.4	3.9
1st met. head	2.7	2.5
Apex 1st toe	3.8	4.4
Apex 2nd toe	4.3	5.3
2nd met. head	7.3	3.8
5th met. head	10.7	4.5
Styloid process	11.1	5.6

Table 3 – Reliability of Identification of Marker Placement

X-Ray View	Marker	Intra-rater		Inter-Rater	
		ICC	Abs Diff (mm)	ICC	Abs Diff (mm)
Anterior-Posterior					
	Navicular tub.	0.73	0.91	0.66	1.40
	1st met. head	0.86	0.52	0.58	1.06
	Apex 1st toe	0.74	0.62	0.88	0.38
	Apex 2nd toe	0.61	0.23	0.44	0.85
	2nd met. head	0.93	0.29	0.96	0.52
	5th met. head	0.77	0.18	0.86	0.42
	Styloid process	0.96	0.08	0.92	0.02
Lateral-Medial					
	Navicular tub.	0.96	0.12	0.8	1.63
	1st met. head	0.78	0.17	0.63	0.49
	Apex 1st toe	0.78	0.21	0.5	1.18
	Apex 2nd toe	0.79	0.69	0.6	1.13
	2nd met. head	0.88	0.25	0.45	1.63
	5th met. head	0.92	0.13	0.83	0.09
	Styloid process	0.73	0.37	0.49	0.14

Abs Diff – Absolute difference between shoe and skin mounted marker displacement.

Figure Lists

Figure 1 – Foot-shoe complex markers : A – Navicular tuberosity, B – 1st Metatarsal head, C – Apex 1st Toe, D – Apex 2nd Toe, E – 2nd Metatarsal head, F – 5th Metatarsal head and G – Styloid process

Figure 2 – Calculation of Marker Placement Accuracy. Point A- Anatomical landmark, Point B – Skin mounted marker and Point C – Shoe mounted marker.

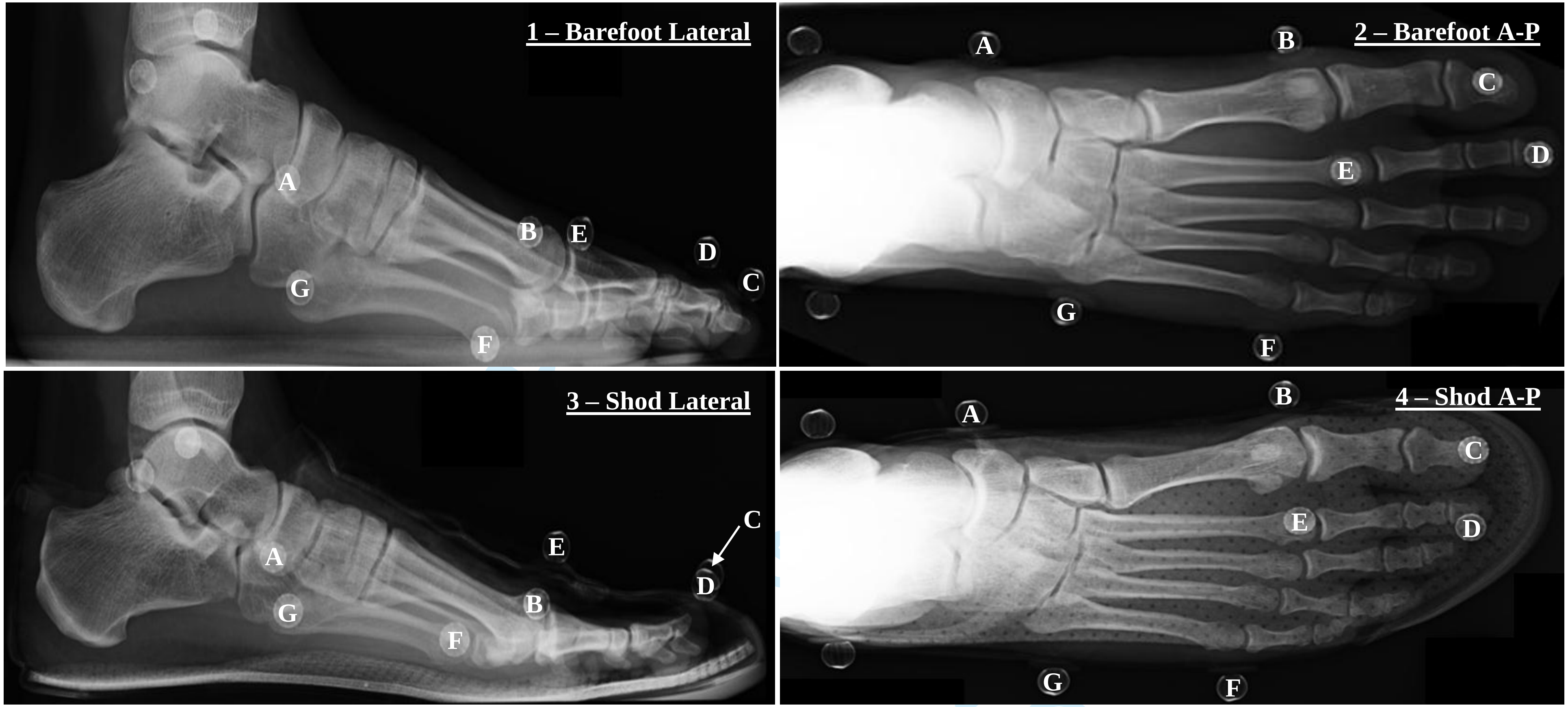

Figure 1 – Foot-shoe complex marker set (static reference markers): A – Navicular Tuberosity, B – 1st Metatarsal Head, C – Apex 1st Toe, D – Apex 2nd Toe, E – 2nd Met Head, F – 5th Met Head and G – Styloid Process

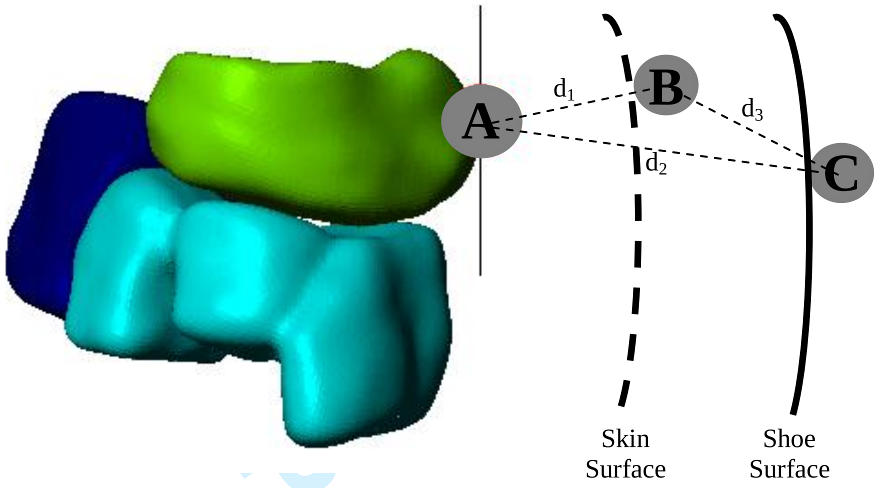

Figure 2 – Calculation of Marker Placement Accuracy. Point A- Anatomical landmark, Point B – Skin mounted marker and Point C – Shoe mounted marker.