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Differences in multi-segment foot kinematics measured using skin and shoe mounted markers

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Models with three segments have been implemented in order to represent the movement of the foot in a comprehensive way during walking and running, however the efficacy of mounting such a system of markers externally onto the shoe has not been explored. The aim of the current investigation was to determine whether 3-D three-segment foot kinematics differ between skin and shoe-mounted markers. Twelve male participants walked and ran at 1.25m/s and 4.0m/s along a 22 m runway. Multi-segment foot kinematics were captured simultaneously using markers placed externally on the shoe and on the skin through windows cut in the shoe. Wilcoxon tests were used to compare the 3-D kinematic parameters, and coefficients of multiple correlations (CMC) were employed to contrast the 3-D kinematic waveforms. Strong correlations were observed between the calcaneus-tibia waveforms $R^2 \geq 0.957$. However, at the more distal foot articulations lower correlations were found midfoot-calcaneus $R^2 \geq 0.484$, metatarsus-midfoot $R^2 \geq 0.538$ and metatarsus-calcaneus $R^2 \geq 0.335$. Significant differences between in discrete kinematic parameters were also observed between skin and shoe mounted markers, at the midfoot-calcaneus, forefoot-midfoot and forefoot-calcaneus articulations. The results indicate that shoe mounted markers do not fully represent true foot movement, and should therefore be interpreted with caution during examination of multiple-segment foot kinematics.

Keywords: Multi-segment foot, biomechanics, kinematics, overuse injury.

During three-dimensional (3-D) kinematic analyses of gait biomechanical models traditionally represent the foot as a single rigid segment [1]. However, more recently three-segment foot models have been implemented in order to represent the movement of the foot in a detailed manner during walking and running analyses [2].

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To quantify foot movements, retro-reflective markers were attached either to the skin or through external palpation to the shoe surface [3,4]. The accuracy of both techniques has been shown to be acceptable in clinical situations, with the majority of errors being <5mm [5]. The efficacy of the shoe mounted technique has been questioned during analyses using both single and multi-segment foot models [3,4]. During dynamic movements, such as walking and running, the foot may move inside the shoe resulting in larger inaccuracies in actual foot position measurements [3,4,6]. Therefore, inaccuracies typically referred to as movement artefact, may be introduced as a function of this movement [1].

Several procedures have been established in an attempt to overcome the potential inaccuracies associated with placing markers on the shoe. Markers attached directly to the underlying bone structures using Kirschner bone pins are utilized to accurately quantify underlying skeletal movement [7]. This technique is extremely limited due to its invasiveness and concerns regarding the ecological validity of gait patterns following the attachment of surgical equipment under local anaesthetic. The most utilized non-invasive technique is to position markers onto the foot through windows cut into the experimental footwear [6].

Previous investigations have examined the 3-D kinematic differences between shoe and skin mounted markers when using a single segment foot model. Sinclair et al examined the differences in stance phase kinematics between markers positioned onto the shoe and those positioned inside windows cut into the shoe [1]. The study documented that eversion range of motion, peak eversion, peak transverse plane range of motion, velocity of external rotation and peak eversion velocity were all significantly underestimated using shoe-mounted markers. However, there is clear paucity of studies that have examined these differences when using more complex multi-segment foot models. The aim of the current investigation was to compare the 3-D three-segment foot kinematics between skin- and shoe-mounted markers. This study tests the hypothesis that significant differences between skin and shoe mounted markers will be observed.

Methods

Participants

Twelve healthy male participants (age 24.23 SD 2.22 y, height 1.74 m SD 0.10, mass 75.78 SD 6.90 kg) were recruited for this study. All were free from musculoskeletal pathology at the time of data collection and provided informed consent in written form. Ethical approval was obtained from a University ethical committee in accordance with the declaration of Helsinki.

Procedure

Kinematic parameters were obtained at 250 Hz using an eight-camera motion analysis system (Qualisys Medical, Sweden) whilst participants walked and ran at 1.25m/s and 4.0m/s along a 22 m runway. Participants struck a Kistler 9281CA (Kistler Instruments, UK) embedded force platform [8] sampling at 1000 Hz with their dominant foot in order to define gait events of footstrike and toe-off. The stance phase was determined as the time over which a 20 N or greater vertical force was applied to the force platform [9].

Markers were placed on anatomical landmarks in accordance with the Leardini et al [2] foot model protocol allowing the anatomical frames of the calcaneus, midfoot and forefoot to be defined. The calibrated anatomical systems technique (CAST) procedure for modelling and tracking segments was adhered to [10]. Windows were cut in the laboratory-supplied experimental footwear (Pro Grid Guide 2, Saucony, USA) at the approximate locations of those outlined by Leardini et al [2]. The pre-established guidelines for length and width outlined by Shultz & Jenkyn were adhered to [11]. The three foot segments were simultaneously tracked using markers positioned on the shoe and also those on the skin within the shoe windows. Additional markers were positioned on the medial and lateral femoral epicondyles to allow the anatomical frame of the tibia to be delineated and a rigid tracking cluster was also positioned on the tibia.

Data processing

Data were digitized using Qualisys track manager and exported to Visual 3D (C-motion, Germantown USA). Marker trajectory data were filtered at 6 and 12 Hz for walking and running trials [12]. Stance phase joint angles were computed using and XYZ sequence of rotations between the calcaneus-tibia (Cal-Tib), midfoot-calcaneus (Mid-Cal), forefoot-midfoot (Fore-Mid) and forefoot-calcaneus (Fore-Cal).

Statistical analysis

Descriptive statistics for the stance phase peak angles (PK) and range of motion (ROM) for both skin and shoe mounted markers were computed, including the mean differences between the two techniques. The similarity of stance phase waveforms was examined using coefficient of multiple correlations (CMC) in accordance with the procedure outlined by Ferrari et al [13]. Based on predominant non-normality of the dataset differences in stance phase kinematic parameters were examined using Wilcoxon rank tests with the alpha criterion for statistical significance

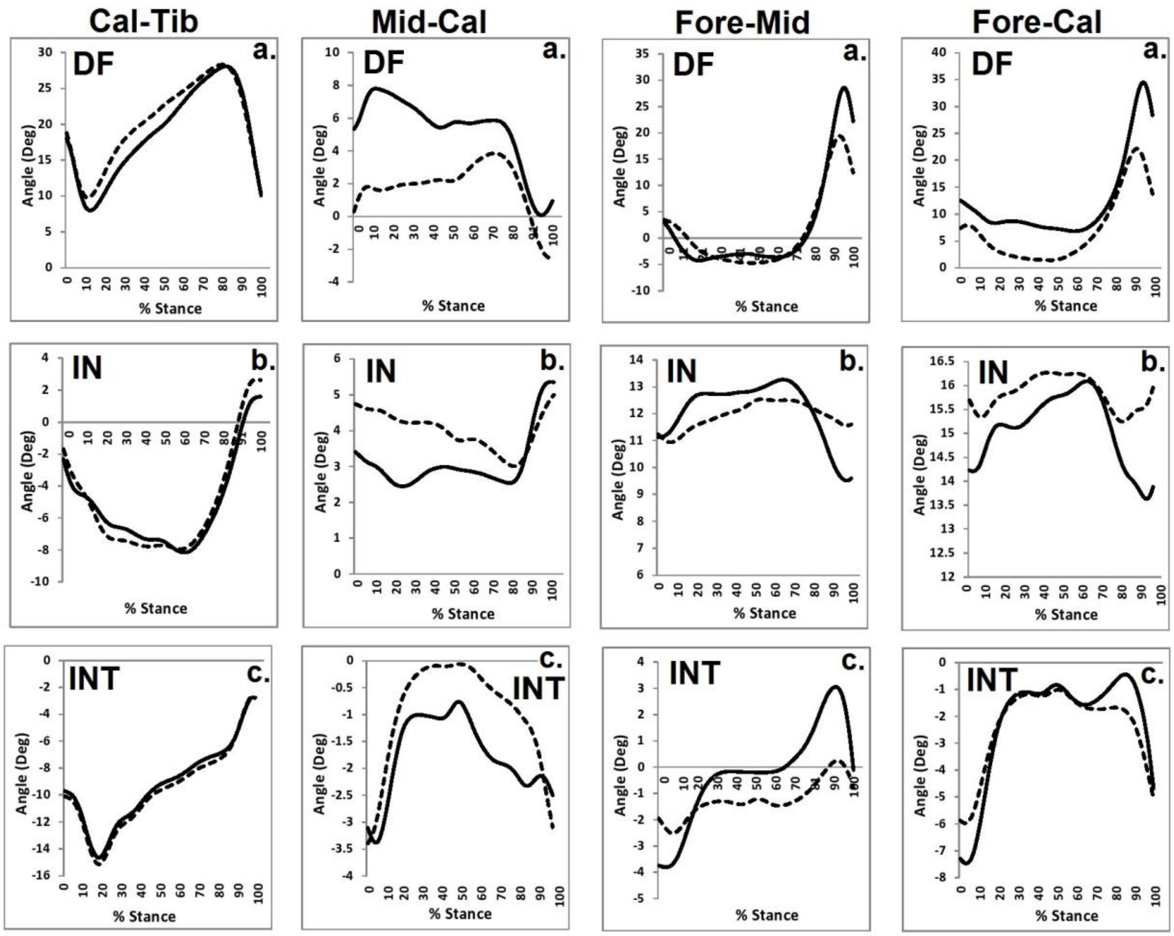

Figure 1 Multi-segment foot kinematics during running in the *a.* sagittal, *b.* coronal and *c.* transverse planes as a function of skin and shoe mounted markers (Black = shoe and Dot = skin).

adjusted to p=0.002 based on the number of comparisons to control type I error. Statistical procedures were undertaken using SPSS v21 (IBS, SPSS INC USA).

Results

The results indicate that the 3-D kinematic curves measured using the shoe and skin-mounted markers were in the main quantitatively similar, although significant differences were found to exist in discrete kinematic parameters. Figures 1-2 present the 3-D angular motions of the multi-segment foot during the stance phase of both running and walking. Table 1 presents the results of the statistical analysis conducted on the joint angle measures and Table 2 shows the similarity between skin and shoe mounted waveforms measured using CMC.

Discussion

The aim of the current investigation was to compare the 3-D three-segment foot kinematics between skin and shoe-mounted markers. This study represents the first to statistically examine the differences in stance phase waveforms and discrete kinematic parameters. The 3-D kinematics of the foot segments during walking and running are of great interest in both biomechanical and clinical examinations of patients [1,14,15]. 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 [1].

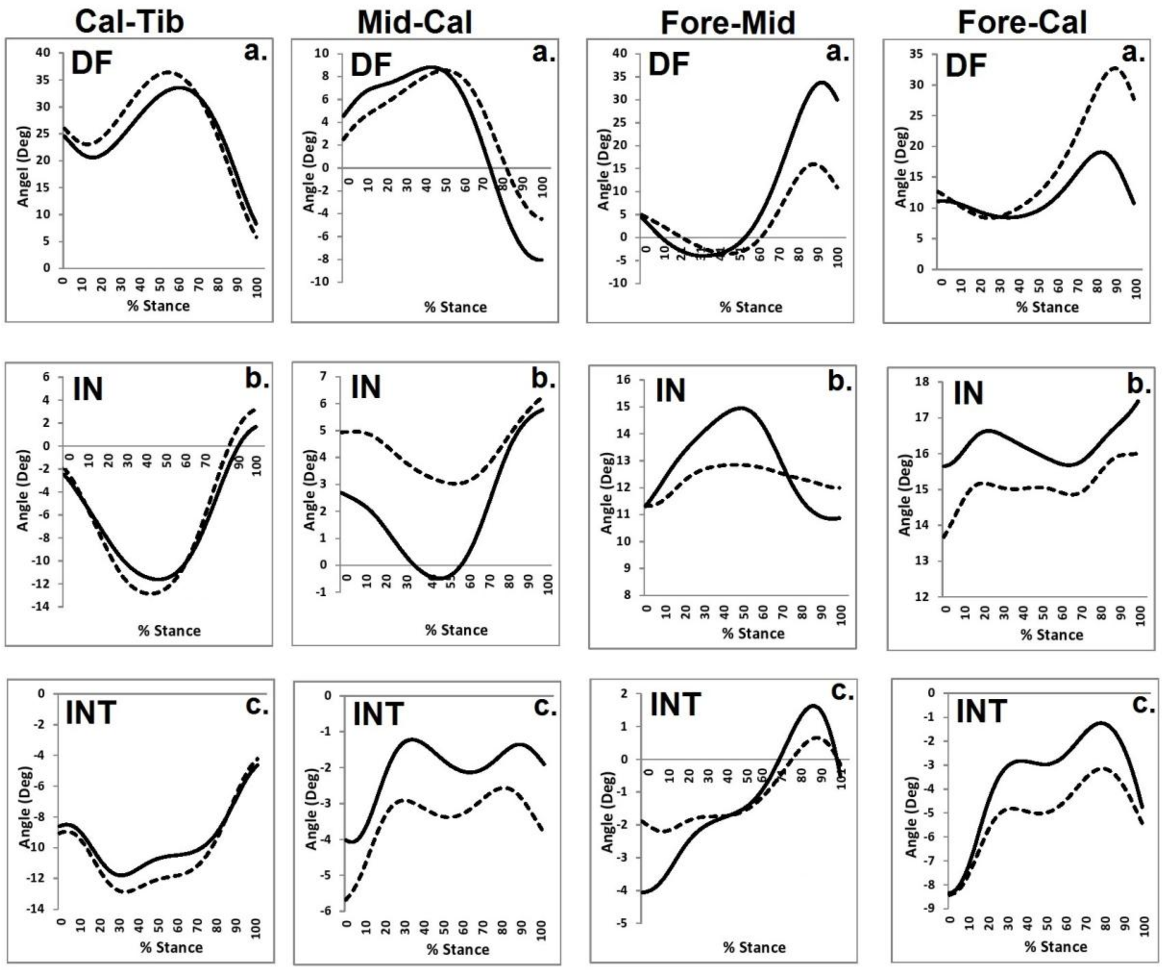

Figure 2 Multi-segment foot kinematics during walking in the *a.* sagittal, *b.* coronal and *c.* transverse planes as a function of skin and shoe mounted markers (Black = shoe and Dot = skin).

In support of the hypothesis, the results of the current investigation show that significant differences in discrete three-segment foot kinematic parameters were observed between shoe and skin mounted markers during both running and walking. It is important to note that there were significant differences between the two marker configurations in all three planes of rotation. These differences were observed primarily at the more distal articulations with the largest deviations being noted at the Fore-Mid complex. Notably, the findings of the current study oppose the single segment foot investigation of Sinclair et al, who showed that the shoe mounted markers served to underestimate foot movements, whilst in the current investigation there was a trend towards overestimation [1]. It was hypothesized that that this divergence may relate to the errors in experimental kinematic data due to violation of the rigid body in single segment foot analyses, which would be proliferated when quantifying multi-segment foot kinematics.

The greatest similarity between 3-D kinematic curves was demonstrated at the Cal-Tib complex. However, for the relative Fore-Cal and Mid-Cal rotations there was generally a low level of similarity between the two tracking techniques. It was hypothesized that these observations may relate to the poorer fit of footwear that has been observed in the more distal aspects of the foot due to its natural curvature [16]. As the fit is poorer in these regions the relative foot-shoe movement is likely to be larger thus resulting in a lack of agreement when these regions of the foot are quantified simultaneously using shoe and skin mounted markers.

	Run				Walk			
	Shoe		Skin		Shoe		Skin	
	M	SD	M	SD	M	SD	M	SD
Cal-Tib								
PK X	32.56	8.23	35.61	6.57	27.58	9.89	27.86	8.26
PK Y	-12.39	3.94	-13.46	4.30	-8.91	2.74	-8.45	2.22
PK Z	-12.80	7.32	-13.84	7.23	-15.65	8.97	-16.08	9.41
ROM X	15.79	4.90	19.60	4.26	8.22	4.18	8.80	3.74
ROM Y	4.09	1.80	5.09	2.31	4.01	1.95	4.50	2.08
ROM Z	4.26	3.72	5.02	3.64	7.21	3.50	7.56	3.59
Mid-Cal								
PK X	10.86	11.36	8.97	3.30	9.64	5.38	4.38	1.90
PK Y	-4.87	2.75	-2.92 ¥	2.18	-4.73	1.15	-4.34	1.94
PK Z	2.30	2.28	2.57	0.76	3.13	2.66	2.56	2.15
ROM X	12.46	4.16	6.92 ¥	1.66	5.03	2.71	2.81 ¥	2.00
ROM Y	2.91	1.58	1.60	0.95	2.99	2.02	1.64	1.24
ROM Z	3.21	1.59	1.51	0.72	2.15	1.03	0.51	0.29
Fore-Mid								
PK X	36.72	22.96	16.61	7.71	29.10	12.49	19.96	6.52
PK Y	16.08	4.22	13.05	4.96	13.92	4.27	13.01	4.40
PK Z	3.15	3.41	0.71	2.46	4.14	2.79	0.50 ¥	1.43
ROM X	26.52	13.49	6.80 ¥	2.00	19.50	5.42	9.05	2.05
ROM Y	4.43	3.38	1.03	0.95	1.79	1.22	0.64	0.38
ROM Z	4.33	2.36	1.74	1.25	4.08	2.45	1.27	0.79
Fore-Cal								
PK X	2.66	2.95	1.96	3.25	35.83	11.73	22.94	3.54
PK Y	-6.62	3.83	-3.53 ¥	2.81	1.65	2.00	0.43	2.32
PK Z	-5.50	3.56	-2.45	2.46	1.68	1.58	2.29	2.74
ROM X	15.91	11.01	3.05	1.26	16.19	6.10	6.56	2.49
ROM Y	4.12	1.81	2.30	1.31	3.35	4.02	1.98	2.03
ROM Z	4.03	2.73	2.22	1.35	2.09	1.01	0.87	0.81

Notes: ¥ = Significantly different from shoe $p \leq 0.002$. X = Sagittal, Y = Coronal and Z = Transverse plane.

Table 1 Multi-segment foot kinematics obtained as a function of skin and shoe mounted markers.

	CMC Skin/ Shoe	
	Run	Walk
Cal-Tib		
X	0.957	0.974
Y	0.985	0.987
Z	0.956	0.996
Mid-Cal		
X	0.813	0.855
Y	0.484	0.523
Z	0.545	0.753
Fore-Mid		
X	0.816	0.962
Y	0.538	0.578
Z	0.859	0.863
Fore-Cal		
X	0.669	0.831
Y	0.335	0.500
Z	0.809	0.944

Notes: X = Sagittal, Y = Coronal and Z = Transverse plane.

Table 2 Coefficient of multiple correlations for 3-D joint waveforms.

The current investigation also shows that during running there was lower similarity between skin and shoe mounted markers. The mean differences in discrete kinematic parameters between shoe and skin mounted markers were also larger during running than when walking. It is likely that this relates to the increased relative motion in all three planes of rotation during running in comparison to walking [17]. The increased motion of the foot segments relative to one another during running is likely to increase the propensity for relative foot-shoe movement, decreasing the similarity between foot kinematics quantified using markers placed on the shoe and those positioned onto the foot itself.

The current study further substantiates the notion that markers positioned on the shoe do not represent true foot movement when contrasted against markers placed onto the skin. The observations from this study may have clinical significance as malalignment and dysfunction of the foot articulations have been associated with an increased incidence of overuse and traumatic injury in athletes [18,19,20]. As such, misrepresentation may serve to confound the efficacy of epidemiological analyses.

Conclusions

Although previous studies have compared shoe to skin-mounted markers, current knowledge is still limited in terms of the parameters that have been taken under consideration. This study adds to the literature by providing a comprehensive 3-D kinematic and waveform comparison between skin and shoe-mounted foot models. Given that significant differences were observed between skin and shoe-mounted markers in key coronal and transverse plane parameters, it can be concluded that the results of studies using shoe-mounted markers should be interpreted with caution, particularly when performing clinical analyses. Future analyses may consider placing markers onto the skin surface through appropriately sized holes in experimental footwear.

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