



DIFFERENCES IN TIBIOCALCANEAL KINEMATICS MEASURED WITH SKIN- AND SHOE-MOUNTED MARKERS

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ABSTRACT

Purpose. The aim of the current investigation was to compare the 3-D tibiocalcaneal kinematics between skin- and shoe-mounted markers. **Methods.** Eleven male participants ran at $4.0\text{m/s} \pm 5\%$ along a 22 m runway. Tibiocalcaneal kinematics were captured simultaneously using markers placed externally on the shoe and on the skin through windows cut in the shoe. Paired *t*-tests were used to compare the 3-D kinematic parameters, and intraclass correlations were employed to contrast the kinematic waveforms. **Results.** Strong correlations were observed between the waveforms at $R^2 \geq 0.85$. However, foot movements such as 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. **Conclusions.** The results indicate that shoe-mounted markers do not fully represent true foot movement.

Key words: tibiocalcaneal kinematics, shoe, skin, retroreflective markers

Introduction

During running, excessive motions of the ankle and tibia have been implicated in the aetiology of a number of overuse injuries [1–3]. Numerous investigations have been undertaken examining the 3-D kinematics of the foot relative to the tibia [4]. A number of studies have been conducted attempting to determine how these parameters are influenced by different running shoe properties [5, 6], quantify the coupling mechanism between eversion and tibial internal rotation and to investigate the potential relationship between kinematic parameters and running injuries [7, 8].

To quantify these movements, retro-reflective markers are typically attached through external palpation to the shoe. Whilst research suggests that this methodology may be accurate to an acceptable level in static situations (maximum error < 5 mm) [9], during dynamic movements such as running the foot may move inside the shoe resulting in larger inaccuracies in actual foot position measurements [4]. Consequently, measurement errors, typically referred to as movement artefact, may be introduced as a function of this relative movement. As a result, several techniques have been developed in order to overcome issues regarding the placement of markers on the shoe. For example, markers attached directly to bone via intercortical pins

can be used to accurately quantify skeletal motion [10, 11]. However, the application of this technique is limited due to its invasiveness. Therefore, the currently accepted ‘gold standard’ technique that is non-invasive is to place markers onto the foot itself through windows cut in the shoe [12].

Previous investigations have examined the kinematic differences between externally mounted markers and those placed inside such windows [4]. However, these studies have examined only limited discrete 3-D kinematic parameters and have not taken into account how the different techniques influence kinematic waveforms. Therefore the aim of the current investigation was to compare the 3-D tibiocalcaneal kinematics between skin- and shoe-mounted markers using both kinematic waveform (intra-class correlations) and discrete variable (paired *t*-tests) analyses.

Material and methods

Eleven male participants (age 23.4 ± 4.30 yrs; height 178.5 ± 8.23 cm; body mass 71.7 ± 9.26 kg) were recruited for this investigation. An ‘a priori’ power analysis was conducted using the Hopkins’ method based on a moderate effect size and a power measure of 80%, which suggested that 11 subjects were adequate for the design. All participants were free from lower extremity pathology and provided written informed consent in accordance with the Declaration of Helsinki. Ethical approval for this study was granted from a University School of Psychology ethical panel.

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Kinematic parameters were obtained at 250 Hz via an eight-camera motion analysis system (Qualisys Medical, Sweden) whilst participants ran at $4.0\text{m/s} \pm 5\%$ along a 20-m runway. Running velocity was monitored using Newtest 300 infrared light-cells (Newtest, Finland) spaced 5 m apart. Participants struck a Kistler 9281CA embedded force platform (Kistler Instruments, UK) sampling at 1000 Hz with their dominant limb in order to define the stance phase of running. Stance time was determined as the time over which a 20 N or greater vertical force was applied to the force platform [13].

The marker set used for the study was based on the calibrated anatomical systems technique (CAST) [14]. In order to define the anatomical and technical reference frames of the foot and shank, a static trial was captured allowing the anatomical frame to be referenced in relation to the technical frame. Markers that would not be used for tracking the segments during motion were then removed.

Windows were cut in the laboratory-supplied footwear (Pro Grid Guide 2, Saucony, USA) in accordance to pre-established guidelines on length and width [15] at the approximate positions of the 1st metatarsal, 5th metatarsal and calcaneus. To define the foot and tibial segment anatomical frame axes, retro-reflective markers were attached to the right foot and shank at the medial and lateral malleoli and the medial and lateral epicondyles of the femur (Fig. 1). The foot segment was simultaneously tracked using markers positioned on the 1st and 5th metatarsal heads and the calcaneus (Shoe) and also using markers positioned onto the skin within the shoe windows (Skin). The tibia was tracked via a cluster comprised of four 19 mm spherical reflective

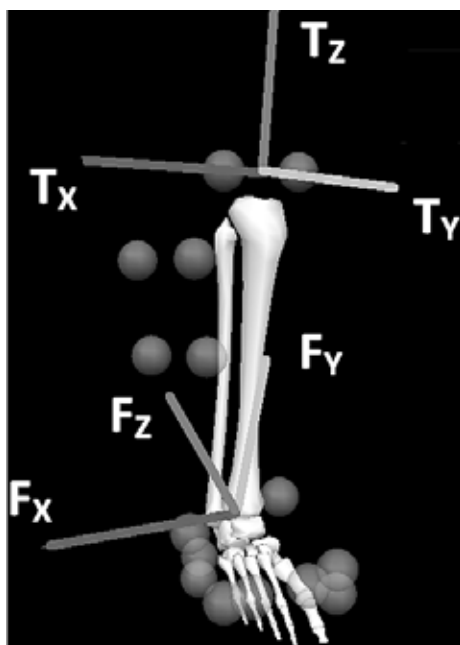


Figure 1. Tibial and foot segments (T – tibia and F – foot), with reference segment co-ordinate system axes: X – sagittal plane, Y – coronal plane and Z – transverse plane

markers mounted to a thin sheath of lightweight carbon fibre with a length-to-width ratio of 1.5:1, in accordance with previous recommendations [16].

The running trials were digitized using Qualisys Track Manager (Qualisys, Sweden) and then exported as C3D files. Kinematic parameters were quantified using Visual 3-D software (C-Motion, USA) after the marker data was smoothed using a low-pass Butterworth 4th order zero-lag filter at a cutoff frequency of 10 Hz. This frequency was quantified as that at which 95% of the signal power was maintained following a fast fourier transform (FFT). Three-dimensional kinematic parameters were calculated using an XYZ cardan sequence of rotations where X represents the sagittal plane, Y represents the coronal plane and Z represents the transverse plane rotations [17]. Trials were normalized to 100% of the stance phase then processed and averaged. In accordance with previous studies [18], the foot segment coordinate system was referenced to the tibial segment for ankle kinematics, whilst the tibial internal rotation was measured as a function of the tibial co-ordinate system in relation to the foot co-ordinate axes. The 3-D kinematic tibio-calcaneal measures which were extracted for statistical analysis were: (1) angle at footstrike, (2) angle at toe-off, (3) range of motion during stance, (4) peak angle during stance, (5) peak range of motion from footstrike to peak angle, (6) velocity at footstrike, (7) velocity at toe-off, (8) peak velocity and (9) eversion/tibial internal rotation (EV/TIR) ratio.

Descriptive statistics (mean \pm standard deviation) were calculated for the outcome measures. To compare differences between the 3-D tibio-calcaneal kinematic stance phase parameters of the skin- and shoe-mounted markers, paired *t*-tests were utilized with statistical significance accepted at the $p \leq 0.05$ level [19]. Intra-class correlations were also utilized to compare skin and shoe sagittal, coronal and transverse plane waveforms. The Shapiro-Wilk statistic for each condition confirmed that the data were normally distributed. All statistical procedures were conducted using SPSS 19.0 software (IBM, USA).

Results

The results indicate that the kinematic waveforms measured using the shoe- and skin-mounted markers were quantitatively similar, although significant differences were found to exist in discrete kinematic parameters. Figure 2 presents the 3-D tibio-calcaneal angular motions from the stance phase. Tables 1 and 2 present the results of the statistical analysis conducted on the joint angle measures.

In the coronal plane, the skin-mounted markers produced a significantly greater peak range of motion ($t[10] = 3.16, p \leq 0.05$) and peak eversion magnitude ($t[10] = 2.30, p \leq 0.05$). In the transverse plane, the skin-mounted markers once again produced a significantly

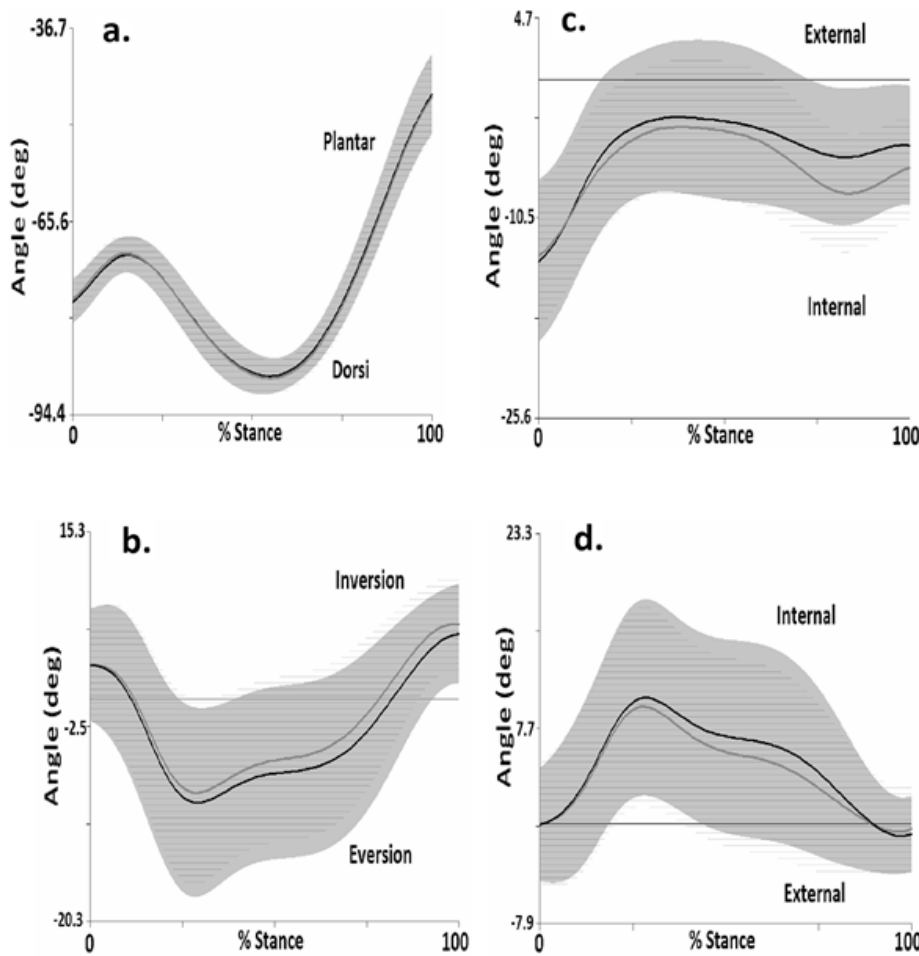


Figure 2. Mean and standard deviation kinematic parameters representing (a.) sagittal, (b.) coronal, (c.) transverse and (d.) tibial internal rotation movements for shoe- (grey line) and skin-mounted (black line) markers (shaded area is $1 \pm SD$: shoe – grey shade; skin – horizontal bars)

Table 1. Ankle joint kinematics (mean \pm standard deviation) in the sagittal, coronal and transverse planes as a function of the different foot tracking techniques

Ankle	Shoe	Skin
Sagittal plane – plantar (+) / dorsi (-)		
Angle at footstrike (deg)	-77.01 \pm 2.73	-77.51 \pm 2.92
Angle at toe-off (deg)	-47.07 \pm 5.48	-46.67 \pm 5.38
Range of motion (deg)	29.94 \pm 3.88	30.84 \pm 3.68
Peak range of motion (deg)	11.99 \pm 2.46	11.24 \pm 3.04
Peak dorsi-flexion (deg)	-89.01 \pm 2.25	-88.75 \pm 2.36
Coronal plane – inversion (+) / eversion (-)		
Angle at footstrike (deg)	2.33 \pm 5.01	2.31 \pm 4.92
Angle at toe-off (deg)	6.15 \pm 4.15	5.30 \pm 4.15
Range of motion (deg)	4.19 \pm 2.33	3.36 \pm 2.13
Peak range of motion (deg)	12.61 \pm 3.70	13.46 \pm 4.14 *
Peak eversion (deg)	-10.28 \pm 8.18	-11.15 \pm 8.39 *
Transverse plane – external (+) / internal (-)		
Angle at footstrike (deg)	-13.58 \pm 5.55	-13.88 \pm 6.56
Angle at toe-off (deg)	-6.82 \pm 4.08	-4.99 \pm 4.65
Range of motion (deg)	6.76 \pm 3.10	8.89 \pm 3.39 *
Peak range of motion (deg)	10.45 \pm 1.19	12.12 \pm 2.27 *
Peak angle (deg)	-3.13 \pm 4.74	-1.76 \pm 5.22 *

* significant differences accepted at $p \leq 0.05$

Table 2. Tibial internal rotation parameters (mean \pm standard deviation) in the sagittal, coronal and transverse planes as a function of the different foot tracking techniques

Tibial internal rotation	Shoe	Skin
Transverse plane – internal (+) / external (-)		
Angle at footstrike (deg)	0.84 \pm 4.96	0.72 \pm 4.55
Angle at toe-off (deg)	0.13 \pm 3.68	-0.40 \pm 3.24
Range of motion (deg)	2.17 \pm 1.39	2.52 \pm 2.09
Peak range of motion (deg)	10.34 \pm 3.74	11.13 \pm 4.09 *
Peak tibial internal rotation (deg)	11.17 \pm 7.91	11.85 \pm 7.89
EV/TIR ratio	1.27 \pm 0.16	1.26 \pm 0.20

* significant differences accepted at $p \leq 0.05$

greater range of motion ($t[10] = 7.06, p \leq 0.050$, peak range of motion ($t[10] = 3.27, p \leq 0.05$) and peak angle ($t[10] = 2.46, p \leq 0.05$). It was further observed that the skin-mounted markers produced a significantly greater peak range of motion for tibial internal rotation ($t[10] = 3.32, p \leq 0.05$). Comparisons between the shoe and

skin angular kinematic waveforms for the ankle joint revealed strong correlations for the sagittal ($R^2 = 0.99$), coronal ($R^2 = 0.92$) and transverse ($R^2 = 0.97$) planes. Comparisons between the tibial internal rotation waveforms also revealed strong correlations ($R^2 = 0.85$).

Figure 3 presents the 3-D tibiocalcaneal angular velocities from the stance phase, while Tables 3 and 4 pre-

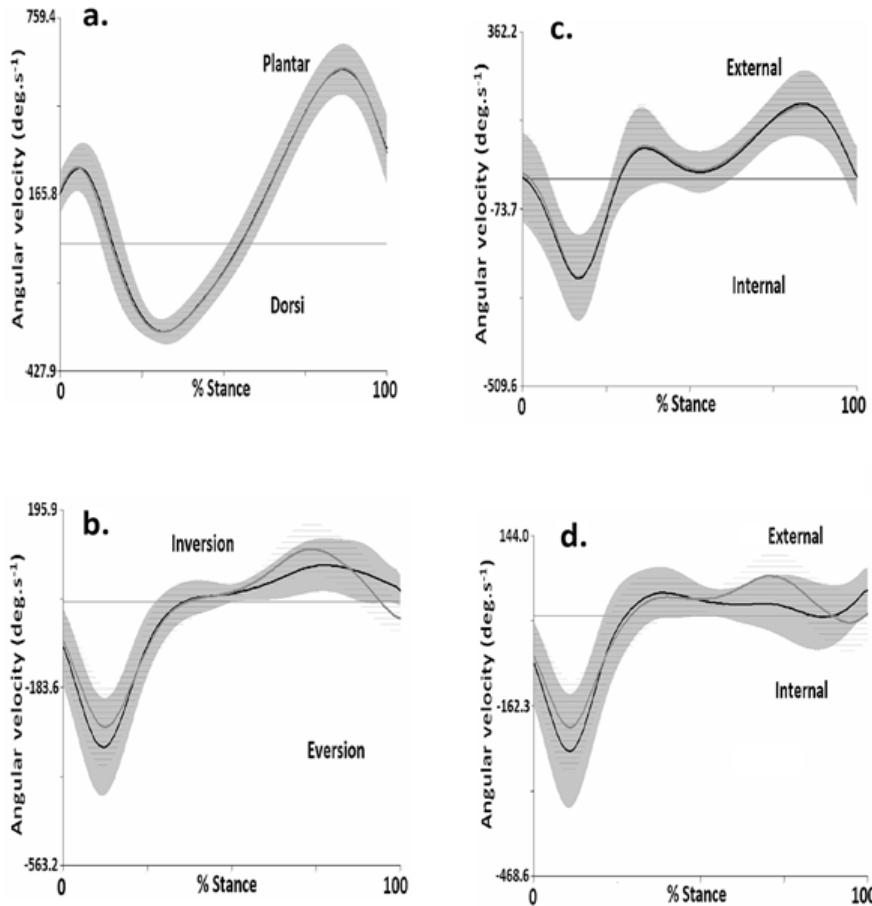


Figure 3. Mean and standard deviation velocities representing (a.) sagittal, (b.) coronal, (c.) transverse and (d.) tibial internal rotation velocity for shoe- (grey line) and skin-mounted (black line) markers (shaded area is $1 \pm SD$: shoe – grey shade; skin – horizontal bar

Table 3. Ankle joint velocities (mean \pm standard deviation) in the sagittal, coronal and transverse planes as a function of the different foot tracking techniques

Ankle	Shoe	Skin
X – plantar (+) / dorsi (-)		
Velocity at footstrike ($\text{deg} \cdot \text{s}^{-1}$)	189.55 \pm 57.38	181.50 \pm 76.27
Velocity at toe-off ($\text{deg} \cdot \text{s}^{-1}$)	313.12 \pm 76.62	322.03 \pm 85.37
Peak plantar flexion velocity ($\text{deg} \cdot \text{s}^{-1}$)	603.52 \pm 79.74	604.03 \pm 89.51
Peak dorsi-flexion velocity ($\text{deg} \cdot \text{s}^{-1}$)	-314.22 \pm 28.08	-318.47 \pm 44.22
Y– inversion (+) / eversion (-)		
Velocity at footStrike ($\text{deg} \cdot \text{s}^{-1}$)	-90.35 \pm 63.05	-107.11 \pm 83.10
Velocity at toe-off ($\text{deg} \cdot \text{s}^{-1}$)	-36.34 \pm 12.70	-26.04 \pm 25.50
Peak inversion velocity ($\text{deg} \cdot \text{s}^{-1}$)	130.61 \pm 51.54	107.90 \pm 45.72
Peak eversion velocity ($\text{deg} \cdot \text{s}^{-1}$)	-294.56 \pm 65.96	-338.37 \pm 85.50 *
Z – external (+) / internal (-)		
Velocity at footstrike ($\text{deg} \cdot \text{s}^{-1}$)	-5.12 \pm 114.74	-15.41 \pm 117.05 *
Velocity at toe-off ($\text{deg} \cdot \text{s}^{-1}$)	6.89 \pm 83.15	-0.78 \pm 55.39
Peak internal rotation velocity ($\text{deg} \cdot \text{s}^{-1}$)	219.32 \pm 28.08	219.48 \pm 83.58
Peak external rotation velocity ($\text{deg} \cdot \text{s}^{-1}$)	-247.78 \pm 99.13	-255.01 \pm 99.52

* significant differences accepted at $p \leq 0.05$

Table 4. Tibial internal rotation velocities (mean \pm standard deviation) in the sagittal, coronal and transverse planes as a function of the different foot tracking techniques

Tibial internal rotation	Shoe	Skin
Z – internal (+) / external (–)		
Velocity at foot strike (deg · s ⁻¹)	-78.09 \pm 57.51	-95.35 \pm 75.98
Velocity at toe-off (deg · s ⁻¹)	0.49 \pm 45.30	47.99 \pm 29.12
Peak internal rotation velocity (deg · s ⁻¹)	91.04 \pm 27.72	90.68 \pm 17.26

sent the results of the statistical analysis of the joint angular velocity measures.

In the coronal plane, the skin-mounted markers produced significantly greater peak eversion velocity ($t[10] = 5.11, p \leq 0.05$). In the transverse plane, the skin-mounted markers once again produced a significantly greater velocity of external rotation ($t[10] = 2.65, p \leq 0.05$). Comparisons between shoe- and skin-mounted kinematic angular velocity waveforms for the ankle joint revealed strong correlations for the sagittal ($R^2 = 0.99$), coronal ($R^2 = 0.96$) and transverse ($R^2 = 0.99$) planes. Comparisons between the tibial internal rotation waveforms also revealed strong correlations ($R^2 = 0.90$).

Discussion

The aim of the current investigation was to determine the kinematic differences 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 results indicate that the different foot tracking mechanisms employed have no significant influence on sagittal plane kinematic parameters. This is further substantiated by intra-class correlation analyses, which show very high agreement ($R^2 \geq 0.99$) between the shoe- and skin-mounted marker waveforms. This concurs with the findings of Reinschmidt et al. [11], who despite reporting an observable increase in dorsi-flexion in shoe-mounted conditions also found that sagittal plane kinematics were minimally affected by the different methods of tracking the foot segment.

However, when quantifying tibiocalcaneal motions in the coronal and transverse planes, significant differences between the discrete kinematic parameters were identified. It was observed that placing markers on the running shoe lead to a significant underestimation of coronal and transverse plane rotations. This opposes the findings of Reinschmidt et al. [11], who found that the shoe-mounted foot tracking technique overestimates the motions of the ankle and tibia in the coronal and transverse planes. This may potentially be attributable to the fact that Reinschmidt et al. removed the heel cap

from their experimental footwear thus greatly increasing the potential for relative shoe-to-foot movement.

Whilst the findings of the current investigation disagree with previous observations, the current study provides further evidence that shoe-mounted markers are not representative of true foot movement compared with markers placed directly onto the skin. The findings of the current investigation have potential clinical significance as lower extremity movements of excessive ankle eversion and tibial internal rotation are implicated in the aetiology of a number of lower extremity pathologies [20]. Therefore, any mis-representation of these parameters may serve to confound the efficacy of epidemiological analyses.

Although skin-mounted markers provide a better representation of the underlying bone than do shoe-mounted markers [4], the data obtained using skin-mounted markers should also be treated with some caution due to skin motion occurring between the markers and the underlying bone.

Clinical gait analyses such as the current investigation have typically considered the foot as a single rigid segment [12]. However, this technique may not allow for 3-D kinematics to be collected for joints within the foot, which are also susceptible to injury and dysfunction [21]. Therefore, whilst this study provides important information regarding the differences between skin- and shoe-mounted markers for a single segment foot model, future work should be conducted examining the differences between the two tracking mechanisms when using a multiple segment foot model.

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 is concluded that the results of studies using shoe-mounted markers should be interpreted with caution, particularly when performing clinical analyses.

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