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Relationship between sagittal plane kinematics, foot morphology and vertical forces applied to three regions of the foot

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ABSTRACT

Kinetic analysis of human motion with a multi-segment musculoskeletal foot model requires the distribution of loading applied to the modeled foot segments to be determined. This work thus examines the existence of any correlation between intersegmental foot kinematics, foot morphology, and the distribution of vertical loading in a multi-segment foot model. Gait analysis trials were performed by 20 healthy subjects at a self-selected speed with intersegmental foot joint angles and the distribution of vertical loading measured for a multi-segment foot model. A statistical relationship between the sagittal plane foot kinematics and loads applied to each foot sub-area was sought using multiple regression analyses. The sub-segmental loading of the normal and abnormal morphological groups was also compared. No meaningful relationships between sagittal plane foot kinematics and sub-segment foot loading were found (max. $R^2 = 0.36$). Statistically significant relationships between foot morphology classification and sub-area foot loading were however identified, particularly for feet exhibiting hallux valgus. Significant variation in inter-subject foot sub-segmental loading indicates that an appropriate technique for determining this load distribution must be determined before effective kinetic analyses are performed with multi-segment musculoskeletal foot models. The results of this study suggest that foot morphology is a better indicator of sub-area loading than sagittal plane kinematics and warrants further investigation.

Introduction

Commonly modelled as a single segment, the complexity of the foot's anatomy and a desire for a more complete description of foot motion has led to the development of a number of multi-segment musculoskeletal foot models (Carson et al. 2001; Baker & Robb 2006; Simon et al. 2006; Stebbins et al. 2006). Performing kinetic analyses with such models hence requires the loads acting on the sub-areas of the foot to first be determined. This is particularly problematic as intersegmental foot loading has been shown to be more variable than whole foot (WF) loading (Guiotto et al. 2013).

Several approaches have been presented in the literature to allow for direct experimental measurement of the loads applied to the sub-areas of the foot. These include a combined force platform and pressure mat (Abuzzahab et al. 1997; Boyd et al. 1997; MacWilliams et al. 2003; Sawacha et al. 2012), a piezo-dynamometric integrated

platform (Giacomozzi et al. 2000) and an array of fibre-optic sensors (Wang et al. 2005). Instrumented footwear capable of measuring footwear sub-area loading has also been described (Schepers et al. 2007; Liu et al. 2014). Whilst promising results have been reported for each of these methods, all require a pressure mat or alternative custom-made device not typically employed as part of a standard gait analysis protocol (Simon 2004).

Multi-segment foot kinetics have also been estimated from measured kinematics using foot-ground contact models (Meglan 1991; Gilchrist & Winter 1996; Peasgood et al. 2007; Jung et al. 2014). However, published contact models remain in an early stage of development and there is no single accepted method for modelling the foot–ground interaction (Pàmies-Vilà et al. 2014).

Limitations in the aforementioned approaches for determining the distribution of foot contact forces necessitate

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All authors confirm that they are in agreement to both proceed with the submission and have the corresponding author act as an agent on their behalf in matters pertaining to the publication of the manuscript.

the investigation of alternative methodologies. One such approach would be to identify a relationship between foot kinematics and sub-area kinetics and subsequently develop a predictive algorithm to determine the distribution of foot sub-segment loading from the captured motion data. Crucially, this approach could be achieved using only a motion capture system and force platform. As such, pressure mats and any other measurement devices not typically employed as part of a standard gait analysis protocol would not be required (Simon 2004; Cappozzo et al. 2005).

A small number of studies have been reported which investigated the connection between foot sub-segment loading and kinematics. These include studies of healthy adolescent gait (MacWilliams et al. 2003), juvenile subjects with and without cerebral palsy (Stebbins et al. 2005) and diabetic subjects (Hastings et al. 2010; Deschamps et al. 2011; Sawacha et al. 2012). The most comprehensive investigation of the correlates between sub-area foot loading and joint kinematics was performed by Giacomozzi et al. (2014), who found sagittal plane kinematics and baropodometric parameters to be well correlated in the temporal domain but reported only weak-to-moderate correlations between sub-segment pressures and intersegmental range of motion. Further exploration of such methods was encouraged.

There is also a significant body of evidence to suggest that foot morphology plays an important role in determining plantar loading (Erdemir et al. 2005; Ledoux et al. 2005; Bus 2008; Guiotto et al. 2013). A second approach to determining foot sub-area loading would therefore be to similarly exploit any relationship identified between foot morphology and foot kinetics. Successful implementation of this approach would also allow the data required to effectively employ multi-segment musculoskeletal foot models to be determined as part of a typical gait assessment.

Using a previously published data set (Sawacha et al. 2012; Guiotto et al. 2013), the aim of this work was therefore to examine the strength of any correlates between intersegmental foot JAs, foot morphology and the distribution of vertical loading in a four-segment model of the foot and shank. The strength of all relationships was ascertained by statistical comparison to segmented GRFs, calculated using data simultaneously obtained from commercially available plantar pressure measurement devices (Sawacha, Gabriella et al., 2009; Sawacha, Guarneri et al. 2012). The possibility of inferring the sub-segment loading patterns required to effectively employ multi-segment foot models when plantar pressure measurement devices are not available could thus be evaluated.

Materials and methods

Subjects

The subject cohort was formed from a database of control subjects used in three previously published studies investigating the role of foot morphology in patients with diabetes (Sawacha, Gabriella, et al. 2009; Sawacha et al. 2012; Guiotto et al. 2013). Twenty healthy subjects (14males/6females, age: 58 ± 5 years, body mass: 74 ± 13 kg, height: 171 ± 9 cm) who did not have any metabolic, cardiovascular or neurological disease and no previous history of orthopaedic surgical treatment were randomly selected. The test protocol was approved by the local Ethics Committee of the University Clinic of Padova (Sawacha, Gabriella, et al. 2009) and all subjects provided informed ethical consent.

Foot morphology classifications were determined after clinical examination by an experienced foot and ankle surgeon (Ledoux et al. 2006; Cowley et al. 2008; Guiotto et al. 2013) with foot type (normal/cavus/planus), heel valgus/varus and the presence of hallux valgus all assessed according to accepted standards. A foot was classified as cavus if the middle third of the footprint covered less than the two thirds of the width of the forefoot (FF) print, and as planus if the width of the middle third of the footprint was greater than one third of the full foot width (Bourdiol 1980). Heel deviation was evaluated by comparing the Helbing line with the vertical. A valgus heel was identified as a deviation greater than 3° whilst any deviation towards the varus was classified as a varus heel (Bourdiol 1980). Hallux valgus was defined as a deviation of the great toe towards the lateral side of the foot with a prominence developed over the medial side of the first metatarsal head (Ledoux et al. 2005).

Using each of these three classification criteria independently, the 40 examined feet were then divided into morphological groups with the following results: 14 normal and 26 cavus feet, 18 normal and 22 valgus heels, 31 normal and 9 hallux valgus. No subjects presented planus foot or varus heel.

Experimental set-up

Gait analysis was completed using a six-camera stereophotogrammetric system (60–120 Hz, BTS S.r.l, Padova) and dual force platforms (FP 4060, Bertec Corporation, U.S.A), each with a plantar pressure mat (Imagortesi, Piacenza) placed on top. In accordance with Sawacha, Gabriella et al. (2009), a four-segment kinematic model was employed allowing for the characterisation of shank, hindfoot (HF), midfoot (MF), FF and WF kinematics (see Figure 1). The loading measured with the plantar pressure mats was also sub-divided into HF, MF and FF areas by projecting
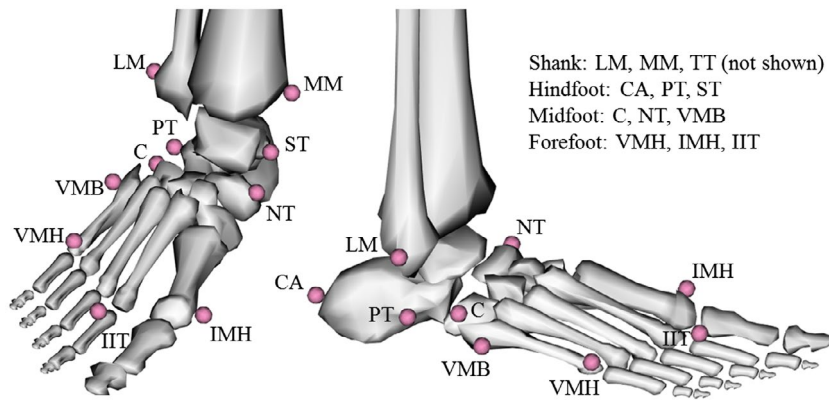
Figure 1. Details of the four segment 3-D kinematic model used.
Notes: Definition of anatomical landmarks; tibial tuberosity (TT), medial (MM) and lateral malleoli (LM), sustentaculum talii (ST), throclea peronealis (PT), calcaneus (CA), navicular tuberosity (NT), cuboid (C), fifth metatarsal base (VMB), first (IMH) and fifth (VMH) metatarsal heads, proximal epiphysis of second toe phalanx (IIT). Visualised in OpenSim (Delp et al. 2007).
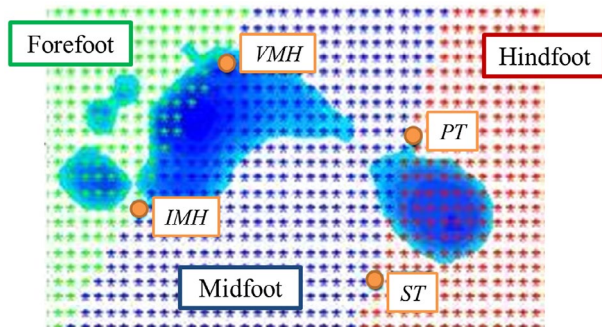

Figure 2. Segmentation of plantar pressure load into hindfoot, midfoot and forefoot sub-areas.
Notes: Hindfoot and midfoot loading areas demarcated by the line connecting both the vertical projection of the sustentaculum talii (ST) and the throclea peronealis (PT). Midfoot and forefoot loading areas demarcated by the line connecting both the vertical projection of the first metatarsal head (IMH) and fifth metatarsal head (VMH). Adapted from Sawacha et al. (2012).

Figure 3. Illustration of additional kinematic variables calculated. (A) Sole angle (θ_{sole}). (B) Longitudinal arch angle (θ_{arch}).
Note: Visualised in OpenSim (Delp et al. 2007).

segmenting lines formed from the location of key gait markers onto the mat surface (see Figure 2), as in Sawacha et al. (2012). Each patient performed multiple barefoot walking trials at a self-selected speed, from which three trials were selected for further processing based on the condition that a contemporary left and right foot strike were acquired on both the force and the plantar pressure systems. This resulted in a total of 120 foot strikes measured.

Data processing

Intersegmental JAs (HF–shank, MF–HF, FF–MF, WF–shank) and sub-area loading means and standard deviations were calculated as in Sawacha, Cristoferi et al. (2009) after the stance phase had been divided into four discrete intervals: initial stance (0-17%), midstance (17–50%), terminal stance (50–83%) and pre-swing (83–100%) (Perry 1992). As
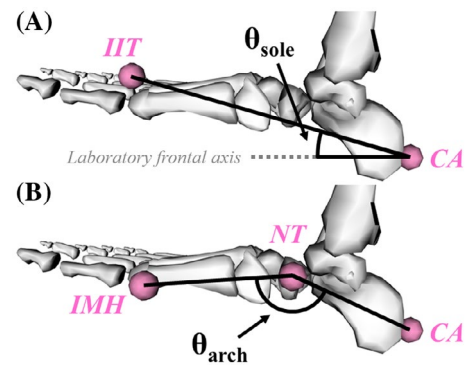
illustrated in Figure 3, two additional kinematic variables were also calculated (Matlab, The Mathworks Inc.):

(a) Sole angle (θ_{sole}): The intersection of an imaginary line between markers on the calcaneus and second phalanx with the laboratory frontal axis.
(b) Longitudinal arch angle (θ_{arch}): The angle formed in the sagittal plane by linking the navicular tuberosity to markers on the calcaneus and first metatarsal head.

Finally, after visual inspection of sub-segment plantar loading data, three further variables considered to be characteristic of the loading curves were also identified: the time that HF loading fell below 2% of total loading (t_{LowHF}), the maximum MF load proportion (F_{MaxMF}) and the time of F_{MaxMF} (t_{MaxMF}) (see Figure 4(B)).

Statistical analysis

Backward step multiple regression analyses were performed to ascertain the strength of relationship between
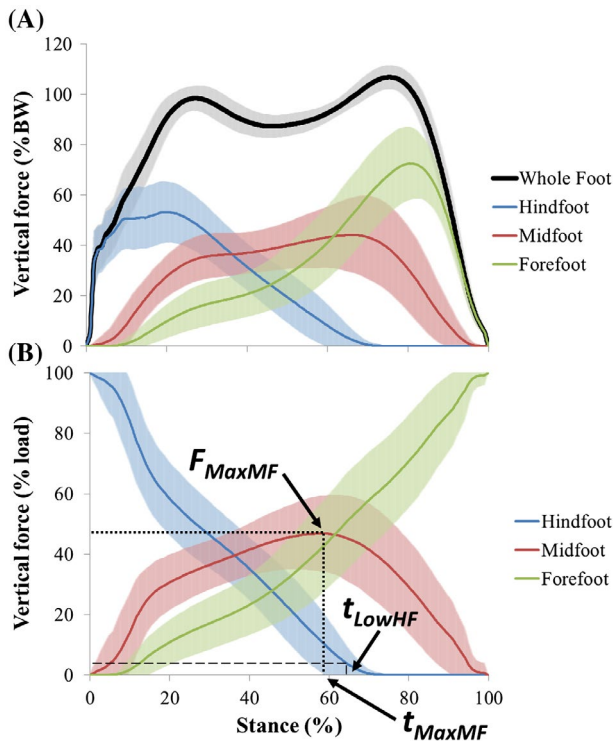
Figure 4. Distribution of vertical loading between foot segments. Mean ± 1 SD for all trials shown. (A) Normalised to subject body weight (BW). (B) Proportion of total load. Mean t_{LowHF}, F_{MaxMF}, t_{MaxMF} values also indicated.

Table 1. Results of backward step multiple regression analyses with the mean kinetic variables shown as dependent variables ($n = 120$).

Independent variables (kinematic)	Dependent variable (kinetic)	% stance	R^2
HF - shank JA	HF load	0-17	0.19
		17-50	0.08
MF - HF JA		50-83	0.36
		83-100	0.09
FF - MF JA	MF load	0-17	0.19
		17-50	0.10
		50-83	0.13
WF - shank JA		83-100	0.09
θ_{sole}	FF load	0-17	0.22
		17-50	0.07
		50-83	0.15
		83-100	0.09
	t_{LowHF}	0-100	0.15
θ_{arch}	F_{MaxMF}	0-100	0.12
	t_{MaxMF}	0-100	0.18

Notes: Mean kinematic parameters calculated for the corresponding phase of stance served as independent variables: HF – shank JA, MF – HF JA, FF – MF JA, WF – shank JA, sole angle (θ_{sole}), longitudinal arch angle (θ_{arch}).

the joint kinematics and plantar sub-area loading. As seen in Table 1, kinematic variables served as the independent

Table 2. Results of inter-group comparisons for foot type, valgus heel and hallux valgus foot morphology classifications.

Kinetic Variable	% stance	Normal vs cavus	Normal vs valgus heel	Normal vs hallux valgus
HF load	0-17	NS	$p = 0.01$ ($d = 0.21$)	$p = 0.03$ ($d = 0.16$)
	17-50	NS	NS	NS
	50-83	NS	NS	NS
	83-100	NS	NS	NS
MF load	0-17	NS	$p = 0.002$ ($d = 0.21$)	NS
	17-50	NS	NS	$p = 0.008$ ($d = 0.72$)
	50-83	NS	NS	$p < 0.001$ ($d = 0.96$)
	83-100	NS	NS	$p < 0.001$ ($d = 1.05$)
FF load	0-17	NS	NS	NS
	17-50	NS	NS	$p = 0.028$ ($d = 0.54$)
	50-83	NS	NS	$p = 0.001$ ($d = 0.85$)
	83-100	NS	NS	$p < 0.001$ ($d = 1.05$)
t_{LowHF}	0-100	NS	NS	NS
F_{MaxMF}	0-100	NS	NS	$p = 0.004$ ($d = 0.80$)
t_{MaxMF}	0-100	NS	NS	$p = 0.01$ ($d = 0.65$)

Notes: Statistically significant differences between the groups have been highlighted ($p < 0.05$) with absolute values for effect size also shown. NS = Not statistically significant.

predictor variables, whilst the kinetic measures were defined as the dependent variables. Comparisons between the kinetic variables calculated for subjects with normal and abnormal foot morphology classifications were performed by means of independent samples *t*-test after evidence of normality (Shapiro–Wilk Test) or alternatively Kruskal Wallis Test (SPSS, IBM Corp.). The Cohen's *d* effect sizes (Cohen 1988) were calculated for all statistically significant relationships with the level of significance set to be $p < 0.05$.

Results

Figure 4(A) shows that inter-subject variation in load was higher for the three segmented force curves than for the WF vertical load (mean standard deviation: WF = 6.3 ± 2.7% body weight vs. 8.6 ± 4.0%, 10.0 ± 4.3% and 10.0 ± 4.3% for HF, MF and FF, respectively). Figure 4(B) presents the same data relative to total load applied with the characteristic curve variables t_{LowHF}, F_{MaxMF} and t_{MaxMF} also illustrated.

Results of regression analyses between the dependent mean foot sub-area loads recorded for each gait interval and independent mean kinematic parameters measured over the same period are reported in Table 1. Negligible to low coefficients of determination were found in all cases with a maximum R^2 value of 0.36. However, Table 2 indicates that there are a number of statistically significant relationships between subject foot morphology and the proportion of vertical loading applied to each sub-area of the foot. Subjects presenting valgus heel partnered greater proportional loading to the HF ($p = 0.01$, $d = 0.21$) with reduced loading to the MF ($p = 0.002$, $d = 0.21$) during

initial stance, although the effect sizes of $d \approx 0.2$ can be considered small (Cohen 1988).

In contrast, feet identified as having hallux valgus applied a reduced proportion of loading to the HF during initial stance ($p = 0.03$, $d = 0.16$). The presence of hallux valgus was also found to be significant during all subsequent phases of gait with a greater share of total loading applied to the MF during the midstance ($p = 0.008$, $d = 0.72$), terminal stance ($p < 0.001$, $d = 0.96$) and pre-swing ($p < 0.001$, $d = 1.05$) stance intervals. There was a corresponding reduction in FF loading during the midstance ($p = 0.028$, $d = 0.54$), terminal stance ($p = 0.001$, $d = 0.85$) and pre-swing ($p < 0.001$, $d = 1.05$) stance periods. Finally, hallux valgus was also associated with an increased maximum MF load proportion ($p = 0.004$, $d = 0.80$) which typically occurred later in stance ($p = 0.01$, $d = 0.65$). Cohen's d effect sizes of 0.5 represent a medium effect size whilst those equalling 0.8 can be considered large (Cohen 1988). This indicates that the differences in sub-segment loading observed for hallux valgus feet are substantial and certainly non-trivial. Finally, foot type (normal/cavus) was not found to have any significant effects.

Discussion

The aim of this study was to determine if any correlations exist between intersegmental foot kinematics, foot morphology and the distribution of sub-segment foot loading. The inter-subject vertical forces acting under each sub-segment of the foot were found to vary more greatly than those acting on the foot as a whole. This is in agreement with previous literature (Guiotto et al. 2013) and indicative that foot sub-segment loading is highly subject-specific. As such, an effective technique for their determination, either through modelling or direct measurement, is essential for the effective use of multi-segment foot models.

No meaningful correlation between intersegmental JAs and foot sub-area loading could be observed indicating that they would serve as a poor predictor of foot segment kinetics. The maximum recorded R^2 value of 0.36 compares favourably with the findings of Giacomozzi et al. (2014), who also reported weak correlations ($R^2 < 0.15$) between all intersegmental sagittal plane foot JAs and maximum sub-segment vertical forces, with the exception of the calcaneus–MF joint. This particular relationship was however only found for loading in the medial MF region, an area that is not typically loaded in high or normal arched feet (Giacomozzi et al. 2014), as considered here.

Conversely, a number of significant relationships between foot morphology and the distribution of sub-segment loading were observed. This is in agreement with several sources that have stated that, even without the presence of a specific pathology, foot kinetics are largely determined by the structure and morphology of the foot (Bevans & Bowker 1999; Ledoux et al. 2005; Guiotto et al. 2013). Further investigation of these relationships and their potential to be exploited in the prediction of foot sub-area load distributions is therefore warranted. It should however be noted that only barefoot gait was considered in this study and that the significance of foot morphology may be diminished when shod gait is investigated (Bishop et al. 2013). Additionally, foot morphological classifications were relatively broad and, whilst the potential for confounding variables is considered limited, no efforts to control for their occurrence were made.

A likely explanation for the low correlation found between intersegmental JAs and sub-segmental vertical loading is that robust studies evaluating the repeatability of 3-D multi-segment kinematic foot models are yet to be reported (Deschamps et al. 2011; Di Marco et al. Forthcoming). This would suggest that any correlations that do exist between intersegmental kinematics and sub-segment loading would be obscured by the errors inherent in the measurement method. It therefore follows that improved correlations may be achievable with more advanced measurement techniques or after correcting for the effects of soft tissue artefact (Leardini et al. 2005; Bonci et al. 2014; Camomilla et al. 2015).

A limitation of the reported methodology is that the data sets recorded for each of the 40 feet involved in the study were all considered to be independent samples. However, in order to increase the sample size available, these feet came from only 20 patients. The results recorded for each individual foot were therefore affected by the contralateral foot, meaning that each sample should not be considered to be strictly independent. This was not reflected in the statistical methods employed and all results should be considered with an understanding of this limitation.

Furthermore, neither sub-segment COPs nor shear loads has been considered, both measures which are required for a full kinetic analysis to be performed with a multi-segment foot model. Only sagittal plane kinematics was considered with no relationship between vertical loading and frontal or transverse plane kinematics sought. This neglects the important role played by shear stresses and 3-D foot kinematics in determining foot kinetics (Uccioli et al. 2001; Sawacha et al. 2012; Stucke et al. 2012) and thus implies that they should be considered in the development of future models (Bruening et al. 2010).

This study has shown that the variability of foot sub-segmental loading is greater than that of the foot as a whole and highlights the necessity in determining the appropriate distribution of loading when employing multi-segment musculoskeletal foot models. The intersegmental sagittal plane foot kinematics obtained with the reported

methodology was found to be a poor indicator of sub-segment loading. However, stronger relationships were found to foot morphology and further investigation is encouraged. The development of a method for determining an appropriate distribution of sub-segment loading without plantar pressure data would allow multi-segment musculoskeletal foot models to be used for a far greater number of subjects and datasets. This could lead to a better understanding of foot sub-segmental loading and ultimately, improved clinical outcomes. Future studies could include a wider subject cohort such that a full analysis on the influence of arch height, varus/valgus heel and different foot deformities could be performed.

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