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## Foot posture is associated with kinematics of the foot during gait: A comparison of normal, planus and cavus feet

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### ABSTRACT

Variations in foot posture are associated with the development of some lower limb injuries. However, the mechanisms underlying this relationship are unclear. The objective of this study was to compare foot kinematics between normal, pes cavus and pes planus foot posture groups using a multi-segment foot model. Ninety-seven healthy adults, aged 18–47 were classified as either normal ( $n = 37$ ), pes cavus ( $n = 30$ ) or pes planus ( $n = 30$ ) based on normative data for the Foot Posture Index, Arch Index and normalised navicular height. A five segment foot model was used to measure tri-planar motion of the rearfoot, midfoot, medial forefoot, lateral forefoot and hallux during barefoot walking at a self-selected speed. Angle at heel contact, peak angle, time to peak angle and range of motion was measured for each segment. One way ANOVAs with post-hoc analyses of mean differences were used to compare foot posture groups. The pes cavus group demonstrated a distinctive pattern of motion compared to the normal and pes planus foot posture groups. Effect sizes of significant mean differences were large and comparable to similar studies. Three key differences in overall foot function were observed between the groups: (i) altered frontal and transverse plane angles of the rearfoot in the pes cavus foot; (ii) Less midfoot motion in the pes cavus foot during initial contact and midstance; and (iii) reduced midfoot frontal plane ROM in the pes planus foot during pre-swing. These findings indicate that foot posture does influence motion of the foot.

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## 1. Introduction

Prospective studies have found that variations in weightbearing foot posture are associated with an increased risk of medial tibial stress syndrome in military recruits [1] and overuse leg injuries in triathletes [2]. These findings suggest that pes cavus (high medial longitudinal arch) and pes planus (low medial longitudinal arch) may display abnormal biomechanical parameters that predispose an individual to injury. For example, planus feet demonstrate more motion compared to normal feet during gait [3] and as a consequence, may be susceptible to injuries in soft tissues that oppose this motion [4]. In contrast, cavus feet are thought to

exhibit less motion [5] compared to planus feet. Since less energy might be dissipated due to reduced motion, it is hypothesised that such feet are vulnerable to injuries related to impaired shock attenuation [6].

While the mechanisms that link variations in foot posture to injury remain unclear, studies of uninjured participants during walking have found systematic differences in plantar pressure [7] and muscle activity [8,9] in extremes of foot posture (i.e. planus and cavus) compared with normal feet. Thus, external loading and internal forces likely differ between foot types. More ambiguous is the association between foot posture and kinematics. Our recent systematic review [10] found that, compared to the normal feet, planus feet display significantly greater inversion and adduction excursion of the rearfoot (both components of foot supination) during the last 20% of stance phase (pre-swing). In addition, a positive association was found between pes planus and peak eversion of the rearfoot, which typically occurs in the first 50% of

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stance. However, our ability to make conclusions was limited due to the absence of a pes cavus group in all except one study. In addition, there was substantial variability in the methods used to classify foot posture, including many that did not have normative data for comparison.

Furthermore, inconsistencies in kinematic methods limit our ability to compare results between studies [10]. For example, one, two and three segment models have been used to represent the foot. Additionally, the protocol for recording static calibration reference trials varied among studies, including placing the participant in a relaxed standing, relaxed seated or a standardised neutral standing position. As such, discrepancies may exist in the zero position from which kinematic data were derived.

The aim of this study was to investigate foot kinematics during gait in people with a normal, cavus or planus foot posture, using validated foot classification methods to classify foot posture and a multi-segment foot modelling technique that adequately addresses the rigid body assumption [11]. Doing so will help us understand the typical motion associated with foot posture and the underlying mechanisms that may be responsible for lower limb overuse injury.

## 2. Methods

### 2.1. Participants

One hundred adults aged 18–47 years were recruited and assigned to one of the three groups based on clinical static foot posture measures. Thirty-seven participants (18 males, 19 females) were assigned to the normal group, 32 participants (16 males, 16 females) to the pes planus group, and 31 participants (13 males, 18 females) to the pes cavus group. The clinical measures included the 6-item Foot Posture Index (FPI) [12], the Arch Index (AI) [13] and normalised navicular height truncated (NNHt) [14]. To qualify for the normal group, static foot measurement needed to be within one standard deviation of the mean of normative data for the FPI [12], and either the AI or NNHt [15]. Participants were assigned to the pes cavus or pes planus group if static foot measurements were greater or less than one standard deviation of the mean of normative data for the FPI and either the AI or NNHt (Supplementary file).

If only one foot of a participant satisfied selection criteria for a group, then this foot was tested. There was one instance when this occurred and the participant was allocated to the normal group. If both feet qualified, one foot was randomly selected for testing (using the random number generator function in Microsoft Excel<sup>®</sup>, Microsoft Corporation, Redmond, WA). Participants were free from any current or recurring lower extremity injury that may have affected their ability to walk. Ethical approval was obtained from the La Trobe University Human Ethics Committee (ID number: HEC11-097).

### 2.2. Experimental protocol

Foot kinematics were recorded using ten 100 Hz Vicon cameras (8 MX2 and 2 MX40, Vicon motion system Ltd., Oxford, England) that detected 9 mm retro-reflective markers mounted on thermo-plastic plates heated and moulded to each participant's foot. A five segment foot model and marker set [16] was used as it has been found to most effectively fulfil the rigid body assumption [11]. Marker locations are displayed in Fig. 1 and documented in Supplementary files.

All participants completed a static calibration trial to define local coordinate frames for each segment and 0°. Participants stood in a relaxed position with the centre of the posterior calcaneus and second toe aligned with the global anterior/posterior axis. After a



Fig. 1. Marker placement and orientation of the foot for static reference trial.

period of acclimatisation, participants walked at a comfortable pace along a flat 12 m walkway. A minimum of five acceptable trials were recorded. A trial was deemed acceptable when the participant landed the whole of the tested foot on one force plate (Kistler, type 9865B, Winterthur, Switzerland), and the whole of the contralateral foot on a second force plate (AMTI, OR6, USA) without disrupting gait.

### 2.3. Kinematic evaluation

Five acceptable trials were processed for each participant. For each trial, heel contact and toe off were determined using vertical ground reaction force data. Walking speed was calculated using force plate data and trials that were within a range  $\pm 0.1$  m/s were processed. The segmental relationships of the foot were as follows:

- (i) Rearfoot relative to the lower leg.
- (ii) Midfoot relative to the rearfoot.
- (iii) Medial forefoot relative to the midfoot.
- (iv) Lateral forefoot relative to the midfoot.
- (v) Hallux relative to the medial forefoot.

Peak angle of dorsiflexion/plantarflexion, abduction/adduction and inversion/eversion were extracted for all segmental relationships between 0 and 70% of the gait cycle. This range was used as it captures kinematic variables during stance and early swing phases and ensures that the most relevant peak values for stance phase are recorded. The angle at heel contact was recorded, as was the range of motion (ROM) between the peak values. All angle parameters were expressed as absolute measures relative to the zero position from the static standing trial. Timing of peak angle was expressed as a percentage of the gait cycle.

### 2.4. Statistical analysis

The distribution of data was assessed for skewness, kurtosis and equality of variance (Levene's test). When the assumption of normality was met, a one-way analysis of variance (ANOVA) was performed with significance level set at  $<0.05$ . When Levene's test indicated significantly different variance between groups and the distribution of the total data set (all groups combined) was normal, one-way ANOVA was performed, with the significance level lowered to 0.01 [17]. Post hoc comparison of the mean differences (MD) between groups with Bonferroni adjustment was applied to all ANOVAs. Confidence intervals (CI) and effect sizes (ES) using Cohen's *d* were calculated for all significant mean differences.

When Levene's test indicated significantly different variance between groups and the total data set was not normally distributed, a non-parametric test (Kruskal–Wallis test) was performed. All statistical tests were calculated using SPSS version 21 for Windows (IBM Corporation, NY).

## 3. Results

### 3.1. Participant characteristics

Anthropometric, foot posture classification and spatio-temporal walking measurements are shown in Table 1. The only significant anthropometric difference was in height, with the planus group shorter than both the normal and cavus groups. As there was no related difference in foot length, stride length or walking speed, the difference in height was considered unlikely to cause a difference in foot kinematics and was not included as a covariate. As expected, significant differences were found between all groups for each static foot posture measurements ( $p < 0.05$ ). No significant differences were found in spatio-temporal measurements.

### 3.2. Kinematic variables

Kinematic variables found to have significant differences between the three foot posture groups are presented in Table 2, with all one-way ANOVA results and pairwise comparisons provided in Supplementary files. Graphical representations of the average angular position for all segmental comparisons in all planes are presented in Fig. 2. Comparisons between foot posture groups are described below, and to be concise, only statistically significant results are reported. Taking this into account, there were no significant differences between groups for the medial forefoot relative to the midfoot, so these findings are not reported below. There was one significant non-parametric finding for frontal plane angle of the hallux at heel contact.

Data from two participants in the planus group, one participant in the cavus group and from the midfoot and hallux from two participants in the normal group were excluded due to a technical issue (marker drop out).

#### 3.2.1. Pes cavus compared to normal foot posture

**3.2.1.1. Rearfoot relative to the leg.** In the transverse plane, the cavus group demonstrated greater abduction at heel contact, less peak adduction (i.e. lesser degree of adduction) during pre-swing (49–60% of the gait cycle) and less adduction/abduction ROM. In the frontal plane, the cavus group demonstrated greater eversion at heel contact and less peak inversion during pre-swing.

**3.2.1.2. Midfoot relative to the rearfoot.** In the transverse plane, the cavus group demonstrated greater abduction at heel contact, greater peak abduction during initial contact (0–10% of the gait cycle), and less abduction/adduction ROM during initial contact, midstance and terminal stance (10–48% of the gait cycle).

**3.2.1.3. Lateral forefoot relative to the midfoot.** In the transverse plane, the cavus group exhibited greater adduction at heel contact, less peak abduction (i.e. lesser degree of abduction) during midstance and greater peak adduction during pre-swing.

**3.2.1.4. Hallux relative to the medial forefoot.** In the frontal plane, the cavus group reached peak eversion earlier and exhibited less peak inversion during pre-swing.

#### 3.2.2. Pes planus compared to normal foot posture

**3.2.2.1. Rearfoot relative to the leg.** In the transverse plane, the pes planus group demonstrated earlier peak abduction.

**Table 1**

Participant characteristics. All values are mean (SD) unless otherwise noted.

Variable	Normal ( $n=37$ )	Pes planus ( $n=30$ )	Pes cavus ( $n=30$ )
<i>Anthropometric measurements</i>			
Gender (M/F) – $n$	18/19	15/15	13/17
Age (years)	25.1 (4.9)	24.2 (5.4)	27.2 (7.8)
Height (cm) <sup>*</sup>	173.3 (9.4)	166.6 (10.1)	174.0 (10.3)
Body mass (kg)	70.1 (13.6)	66.7 (14.9)	73.4 (14.6)
Body mass index (kg/m <sup>2</sup> )	23.3 (3.2)	23.7 (3.0)	24.0 (2.9)
Foot length (mm)	255.8 (19.5)	249.4 (21.9)	249.9 (21.9)
Left/right foot – $n$	20/17	15/15	17/13
<i>Clinical measurements</i>			
FPI <sup>*</sup>	3.9 (1.1) range: 1–6	9.0 (1.0) range: 7–12	–1.41 (1.1) range: –3–0
AI <sup>*</sup>	0.22 (0.02) range: 0.15–0.29	0.29 (0.05) range: 0.23–0.40	0.15 (0.06) range: 0.04–0.24
NNHt <sup>*</sup>	0.25 (0.02) range: 0.20–0.32	0.19 (0.03) range: 0.11–0.24	0.32 (0.02) range: 0.29–0.37
<i>Spatio-temporal measurements</i>			
Walking speed (m/s)	1.35 (0.1)	1.32 (0.2)	1.33 (0.1)
Stride length (m)	0.68 (0.1)	0.66 (0.1)	0.68 (0.1)

FPI, Foot Posture Index; AI, Arch Index; NNHt, normalised navicular height truncated.

<sup>\*</sup> Significant difference between groups with one-way ANOVA ( $p < 0.05$ ).

**Table 2**  
Statistically significant mean differences between foot posture groups with 95% confidence intervals (CI) and effect sizes (ES).<sup>a</sup>

Segmental relationship	Plane	Kinematic variable <sup>b</sup>	Mean angle (SD)		Mean difference <sup>c</sup> (CI) <sup>d</sup>	ES																																																																																																																											
			Cavus	Normal																																																																																																																													
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Rearfoot/leg	Transverse	Heel contact	-0.2 (3.3)	-2.8 (3.4)	2.6 (0.7 to 4.5)	0.77																																																																																																																											
		Peak adduction	-7.1 (3.7)	-10.8 (3.6)	3.7 (1.5 to 5.9)	1.01																																																																																																																											
		Range of motion	12.4 (2.2)	14.4 (2.6)	-1.9 (-4.3 to 0.4) <sup>e</sup>	0.83																																																																																																																											
	Frontal	Heel contact	5.1 (3.2)	3.2 (3.0)	1.9 (0.1 to 3.8)	0.61																																																																																																																											
		Peak inversion	0.4 (2.6)	-1.8 (2.9)	2.3 (0.6 to 4.0)	0.79																																																																																																																											
Midfoot/rearfoot	Transverse	Heel contact	1.2 (1.7)	0.7 (1.7)	2.0 (0.8 to 3.1)	1.10																																																																																																																											
		Peak adduction	0.4 (1.7)	-1.8 (1.7)	2.2 (1.1 to 3.3)	1.30																																																																																																																											
		Range of motion	4.2 (1.2)	5.5 (1.7)	-1.2 (-2.2 to -0.2)	0.88																																																																																																																											
Lateral forefoot/midfoot	Transverse	Heel contact	0.7 (3.7)	3.9 (5.1)	-3.1 (-6.1 to -0.2)	0.71																																																																																																																											
		Peak abduction	7.3 (3.6)	10.6 (3.5)	-2.8 (-5.5 to -0.1)	0.92																																																																																																																											
		Peak adduction	-6.3 (4.2)	-2.3 (4.0)	-4.0 (-6.7 to -1.3)	0.97																																																																																																																											
Hallux/medial forefoot	Frontal	Time to peak eversion	36.7 (8.7)	44.9 (8.1)	-8.2 (-16.0 to -0.4) <sup>e</sup>	0.97																																																																																																																											
		Peak inversion	1.8 (8.1)	9.5 (11.2)	-7.7 (-13.1 to -2.1)	0.78																																																																																																																											
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<table border="1"> <thead> <tr> <th rowspan="2">Segmental relationship</th> <th rowspan="2">Plane</th> <th rowspan="2">Kinematic variable<sup>b</sup></th> <th colspan="2">Mean angle (SD)</th> <th rowspan="2">Mean difference<sup>c</sup> (CI)<sup>d</sup></th> <th rowspan="2">ES</th> </tr> <tr> <th>Cavus</th> <th>Planus</th> </tr> </thead> <tbody> <tr> <td colspan="7"><i>Pes cavus compared to pes planus</i></td> </tr> <tr> <td rowspan="10">Rearfoot/leg</td> <td rowspan="5">Transverse</td> <td>Heel contact</td> <td>-0.2 (3.3)</td> <td>-3.3 (2.5)</td> <td>3.1 (1.2 to 5.1)</td> <td>1.05</td> </tr> <tr> <td>Peak abduction</td> <td>5.3 (3.3)</td> <td>3.0 (2.3)</td> <td>2.3 (0.3 to 4.2)<sup>e</sup></td> <td>0.80</td> </tr> <tr> <td>Time to peak abduction</td> <td>28.8 (7.3)</td> <td>21.6 (8.2)</td> <td>7.1 (2.3 to 11.9)</td> <td>0.92</td> </tr> <tr> <td>Peak adduction</td> <td>-7.1 (3.7)</td> <td>-12.2 (3.5)</td> <td>5.1 (2.8 to 7.4)</td> <td>1.40</td> </tr> <tr> <td>Range of motion</td> <td>12.4 (2.2)</td> <td>15.2 (4.2)</td> <td>-2.8 (-5.3 to -0.4)<sup>e</sup></td> <td>0.83</td> </tr> <tr> <td rowspan="5">Frontal</td> <td>Heel contact</td> <td>5.1 (3.2)</td> <td>2.4 (2.9)</td> <td>2.7 (0.8 to 4.7)</td> <td>0.88</td> </tr> <tr> <td>Peak inversion</td> <td>0.4 (2.6)</td> <td>-2.6 (3.1)</td> <td>3.0 (1.2 to 4.8)</td> <td>1.04</td> </tr> <tr> <td rowspan="3">Midfoot/rearfoot</td> <td>Sagittal</td> <td>Peak dorsiflexion</td> <td>1.2 (1.9)</td> <td>2.9 (2.4)</td> <td>-1.6 (-3.0 to -0.3)</td> <td>0.78</td> </tr> <tr> <td rowspan="2">Transverse</td> <td>Heel contact</td> <td>1.2 (1.7)</td> <td>-1.2 (2.1)</td> <td>2.5 (1.3 to 3.6)</td> <td>1.25</td> </tr> <tr> <td>Peak adduction</td> <td>0.4 (1.7)</td> <td>-1.9 (2.0)</td> <td>2.4 (1.2 to 3.5)</td> <td>1.23</td> </tr> <tr> <td rowspan="3">Frontal</td> <td>Range of motion</td> <td>4.2 (1.2)</td> <td>6.1 (2.0)</td> <td>-1.8 (-2.9 to -0.8)</td> <td>1.15</td> </tr> <tr> <td>Range of motion</td> <td>6.1 (2.2)</td> <td>4.5 (1.7)</td> <td>1.5 (0.2 to 2.8)</td> <td>0.81</td> </tr> <tr> <td rowspan="5">Lateral forefoot/midfoot</td> <td rowspan="3">Transverse</td> <td>Heel contact</td> <td>0.7 (3.7)</td> <td>7.0 (5.8)</td> <td>-6.2 (-9.3 to -3.1)</td> <td>1.29</td> </tr> <tr> <td>Peak abduction</td> <td>7.3 (6.3)</td> <td>11.7 (5.0)</td> <td>-4.4 (-7.2 to -1.6)</td> <td>0.77</td> </tr> <tr> <td>Peak adduction</td> <td>-6.3 (4.2)</td> <td>-1.0 (5.3)</td> <td>-5.3 (-8.2 to -2.5)</td> <td>1.10</td> </tr> <tr> <td rowspan="2">Frontal</td> <td>Time to peak eversion</td> <td>29.9 (7.0)</td> <td>35.3 (9.5)</td> <td>-5.4 (-10.6 to -0.2)</td> <td>0.64</td> </tr> <tr> <td>Time to peak inversion</td> <td>60.0 (4.8)</td> <td>62.8 (4.2)</td> <td>-2.8 (-5.5 to -0.1)</td> <td>0.62</td> </tr> <tr> <td rowspan="2">Hallux/medial forefoot</td> <td rowspan="2">Frontal</td> <td>Peak inversion</td> <td>1.8 (8.1)</td> <td>9.2 (7.1)</td> <td>-7.3 (-13.1 to -1.6)</td> <td>0.95</td> </tr> <tr> <td>Range of motion</td> <td>14.9 (7.3)</td> <td>9.7 (5.5)</td> <td>5.1 (1.5 to 8.8)</td> <td>0.80</td> </tr> </tbody> </table>							Segmental relationship	Plane	Kinematic variable <sup>b</sup>	Mean angle (SD)		Mean difference <sup>c</sup> (CI) <sup>d</sup>	ES	Cavus	Planus	<i>Pes cavus compared to pes planus</i>							Rearfoot/leg	Transverse	Heel contact	-0.2 (3.3)	-3.3 (2.5)	3.1 (1.2 to 5.1)	1.05	Peak abduction	5.3 (3.3)	3.0 (2.3)	2.3 (0.3 to 4.2) <sup>e</sup>	0.80	Time to peak abduction	28.8 (7.3)	21.6 (8.2)	7.1 (2.3 to 11.9)	0.92	Peak adduction	-7.1 (3.7)	-12.2 (3.5)	5.1 (2.8 to 7.4)	1.40	Range of motion	12.4 (2.2)	15.2 (4.2)	-2.8 (-5.3 to -0.4) <sup>e</sup>	0.83	Frontal	Heel contact	5.1 (3.2)	2.4 (2.9)	2.7 (0.8 to 4.7)	0.88	Peak inversion	0.4 (2.6)	-2.6 (3.1)	3.0 (1.2 to 4.8)	1.04	Midfoot/rearfoot	Sagittal	Peak dorsiflexion	1.2 (1.9)	2.9 (2.4)	-1.6 (-3.0 to -0.3)	0.78	Transverse	Heel contact	1.2 (1.7)	-1.2 (2.1)	2.5 (1.3 to 3.6)	1.25	Peak adduction	0.4 (1.7)	-1.9 (2.0)	2.4 (1.2 to 3.5)	1.23	Frontal	Range of motion	4.2 (1.2)	6.1 (2.0)	-1.8 (-2.9 to -0.8)	1.15	Range of motion	6.1 (2.2)	4.5 (1.7)	1.5 (0.2 to 2.8)	0.81	Lateral forefoot/midfoot	Transverse	Heel contact	0.7 (3.7)	7.0 (5.8)	-6.2 (-9.3 to -3.1)	1.29	Peak abduction	7.3 (6.3)	11.7 (5.0)	-4.4 (-7.2 to -1.6)	0.77	Peak adduction	-6.3 (4.2)	-1.0 (5.3)	-5.3 (-8.2 to -2.5)	1.10	Frontal	Time to peak eversion	29.9 (7.0)	35.3 (9.5)	-5.4 (-10.6 to -0.2)	0.64	Time to peak inversion	60.0 (4.8)	62.8 (4.2)	-2.8 (-5.5 to -0.1)	0.62	Hallux/medial forefoot	Frontal	Peak inversion	1.8 (8.1)	9.2 (7.1)	-7.3 (-13.1 to -1.6)	0.95	Range of motion	14.9 (7.3)	9.7 (5.5)	5.1 (1.5 to 8.8)	0.80
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<sup>a</sup> Significant result for non-parametric (Kruskal–Wallis) test not included in table.  
<sup>b</sup> Angle values expressed in degrees. Timing values expressed as percentage of gait cycle.  
<sup>c</sup> Mean differences expressed as comparison of absolute angle measures and not an expression of kinematic variables.  
<sup>d</sup> 95% Confidence intervals unless otherwise signified.  
<sup>e</sup> 99% Confidence intervals. Significantly different variance between groups but normal distribution of total (groups combined) data set.

3.2.2.2. *Midfoot relative to the rearfoot.* In the frontal plane, the planus group exhibited less inversion/eversion ROM.

3.2.2.3. *Lateral forefoot relative to the midfoot.* In the transverse plane, the planus group exhibited greater abduction at heel contact.

3.2.2.4. *Hallux relative to the medial forefoot.* In the sagittal plane, the planus group exhibited less peak plantarflexion during midstance.

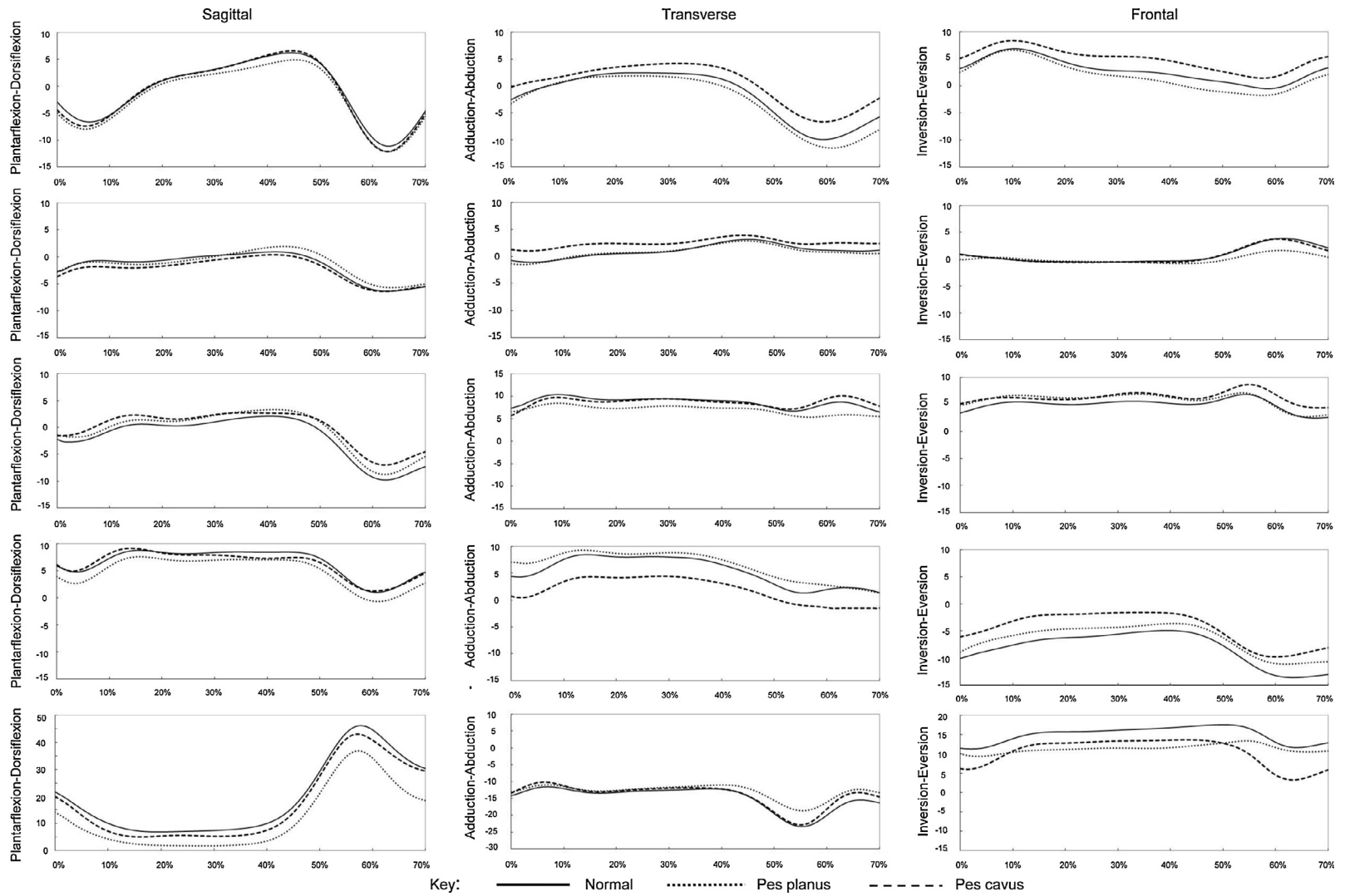
3.2.3. *Pes cavus compared to pes planus foot posture*

3.2.3.1. *Rearfoot relative to the leg.* In the transverse plane, the cavus group demonstrated greater abduction at heel contact, later and greater peak abduction during midstance, less peak adduction during pre-swing and less abduction/adduction ROM. In the frontal plane, the cavus group demonstrated greater eversion at heel contact, and less peak inversion and greater eversion during pre-swing.

3.2.3.2. *Midfoot relative to the rearfoot.* In the sagittal plane, the cavus group demonstrated less peak dorsiflexion during midstance. In the transverse plane, the cavus group demonstrated greater abduction at heel contact, greater peak abduction during initial contact and less abduction/adduction ROM. In the frontal plane, the cavus group demonstrated greater inversion/eversion ROM.

3.2.3.3. *Lateral forefoot relative to the midfoot.* In the transverse plane, the cavus group demonstrated greater adduction at heel contact less peak adduction during midstance and greater peak abduction during pre-swing. In the frontal plane, the cavus group reached peak eversion and peak inversion earlier than the pes planus group.

3.2.3.4. *Hallux relative to the medial forefoot.* In the frontal plane, the cavus group displayed greater peak inversion during pre-swing and greater inversion/eversion ROM.



**Fig. 2.** Average motion (degrees) of all segmental relationships for the three foot posture groups from heel contact to 70% of the gait cycle. Positive values indicate dorsiflexion, abduction and eversion. Negative values indicate plantarflexion, adduction and inversion. (a) Scale on vertical axis for transverse plane motion is altered compared to other graphs. (b) Scale on vertical axes for sagittal, transverse and frontal plane motion is altered compared to other graphs.

#### 4. Discussion

This study provides a novel comparison of foot kinematics between normal, planus and cavus foot posture groups. Further strengths compared to previous work include the use of valid foot posture classification measures based on normative data and the use of a multi-segment foot model that seeks to minimise violation of the rigid body assumption and demonstrates motion of functional foot segments that were identified in invasive bone pin and cadaver research [11,18]. The findings indicate that cavus feet have a distinct pattern of motion compared to both normal and planus feet. Three key differences in overall function between the foot posture groups were: (i) altered frontal and transverse plane angles of the rearfoot in the cavus group; (ii) less motion of the midfoot in the sagittal and transverse planes during initial contact and midstance in the cavus group; and (iii) reduced midfoot frontal plane ROM during pre-swing in the planus group.

Before discussing our findings in detail, it is important to consider that all kinematic parameters were calculated relative to the position of the foot in a relaxed standing reference position rather than an examiner-determined 'neutral' reference position. This approach was taken due to the questionable reliability and validity of placing participants in a neutral position, and because this position may not be reached during gait [19,20]. Although we believe that this approach is preferable, the use of a relaxed reference position can result in apparently counter-intuitive findings compared to studies that have used a neutral reference position. For example, a planus foot may demonstrate greater rearfoot eversion than a normal foot when a subtalar neutral position reference position is used [21], but such a finding may not be present when using the relaxed reference position approach as the rearfoot is already more everted to begin with in the reference position. Arguably, therefore, the comparison of absolute angular values between foot posture groups is actually a comparison of the extent to which the feet move away from their position during relaxed standing. However, ROM data is independent of this issue and can be directly compared between groups.

The first of three key findings in this study was that the cavus group, compared to the normal and planus groups, demonstrated greater peak eversion and abduction of the rearfoot. There are only two other studies that are suitable for direct comparison, as they used the same reference position and a cavus group [22,23]. Findlow and colleagues [22] used the same multi-segment foot model and found a similar everted and abducted position of the rearfoot for cavus compared to planus feet. Similar findings have also been reported in studies that compared planus with normal foot posture, in which planus feet maintained a less everted position throughout gait [21,24]. As cavus feet display only slightly higher peak plantar pressure in the lateral heel compared to planus feet [25], it is possible that the rearfoot positioning found in our study is indicative of a strategy to centralise plantar pressure and reduce force applied to lateral structures of the foot. In contrast, Powell and colleagues [23] reported that planus feet exhibit greater peak eversion compared to cavus feet. However, this difference was due to greater eversion excursion during initial contact rather than during midstance or propulsion as in our study. Other studies that used different reference positions to ours report inconsistent results, with two finding greater peak eversion in pes planus [3,21] compared to three that found no significant differences [8,26,27].

The second key finding was that the midfoot of the cavus group exhibited less peak dorsiflexion and transverse plane ROM during initial contact and midstance. This is indicative of reduced deformation of the medial longitudinal arch, which is thought to contribute to shock attenuation [5]. As increased vertical loading rates and tibial shock (peak positive acceleration) are associated with injuries such as stress fractures [28], this finding could be of

clinical importance. However, impact force data measured concurrently are needed to confirm the proposed relationship between medial longitudinal arch deformation and shock attenuation during gait.

The third key finding was that the midfoot of the planus group showed less ROM in the frontal plane, which is associated with reduced eversion of the midfoot on the rearfoot during pre-swing. Two comparative studies that investigated midfoot frontal plane motion found little difference in this variable between foot types [22,23]. However, our finding is consistent with biomechanical theory, which suggests that planus feet are comparatively less capable of undertaking the coordinated supinatory motion of the foot that occurs during terminal stance and pre-swing [29]. This supinatory motion, in anatomical terms, has been reported to result in important realignment of the calcaneo-cuboid joint [30]. This, along with tensile forces in plantar tissues due to toe flexion is thought to increase the stiffness of the midfoot and forefoot during the propulsive phase of gait [31]. In planus feet, it is possible that muscles such as tibialis posterior are unable to exert the necessary force to produce eversion of the midfoot on the rearfoot during propulsion. This theory is supported by EMG studies that have reported increased intensity of tibialis posterior muscle activity during propulsion in planus feet [9].

The majority of significant kinematic differences (31 out of a total of 36) were found in the cavus group compared to both the normal and planus groups. In real terms, the sizes of these significant differences were small, with all angular variations less than 7.7°. However, the magnitude of effect sizes are classified as medium or large [32] and were typical of those found in other kinematic studies of foot posture, which we summarised in our recent systematic review [10]. It is possible that small angular differences are clinically meaningful in the development of lower limb overuse injury when performing highly repetitive tasks such as jogging and running, although further research is needed to confirm this.

The findings of this study need to be considered in the context of two limitations. Firstly, we examined kinematic data in isolation and hence conclusions about the influence of foot posture on overall biomechanics are difficult without concurrent biomechanical information, such as kinetics and EMG. Secondly, a homogeneous cohort of young, healthy participants was recruited, so our findings may not be generalisable to a symptomatic population.

#### 5. Conclusion

The findings of this study confirm that different foot postures are associated with differences in movement of the foot when walking. Specifically, the cavus feet displayed less motion during initial contact and midstance, while planus feet exhibited less midfoot ROM during pre-swing.

#### Authors' contribution

Study concept and design: AKB, GSM, HBM, KBL. Acquisition of data: AKB, PL, CJN. Analysis and interpretation of data: AKB, PL, GSM, HBM, KBL. Drafting of manuscript: AKB, PL, GSM, HBM, CJN, KBL.

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**Conflict of interest:** The authors declare that there are no conflicts of interest.

## 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.2015.03.004>.

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