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## Invasive in vivo measurement of rear-, mid- and forefoot motion during walking<sup>☆</sup>

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### Abstract

The aim of this work was to use bone anchored external markers to describe the kinematics of the tibia, fibula, talus, calcaneus, navicular, cuboid, medial cuneiform, first and fifth metatarsals during gait. Data were collected from six subjects. There was motion at all the joints studied. Movement between the talus and the tibia showed the expected predominance of sagittal plane motion, but the talocalcaneal joint displayed greater variability than expected in its motion. Movement at the talonavicular joint was greater than at the talocalcaneal joint and motion between the medial cuneiform and navicular was far greater than expected. Motion between the first metatarsal and the medial cuneiform was less than motion between the fifth metatarsal and cuboid. Overall the data demonstrated the complexity of the foot and the importance of the joints distal to the rearfoot in its overall dynamic function.

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### 1. Introduction

The kinematics of the foot and ankle during walking are a topic of great interest both from the biomechanical and clinical aspect. Previous clinical experimental research has provided descriptions of calcaneal motion relative to the leg, tibial rotation relative to the foot, and the motion of various definitions of ‘forefoot’ or ‘midfoot’ segments relative to the heel [1–4]. These studies have utilised skin-mounted markers to derive information on the motion of bones or assumed rigid segments during walking. There are several difficulties with describing the foot and ankle in this way. Firstly, there is good evidence that skin movement artefacts

are likely to reduce the validity of the kinematic data [5–7], although it is not clear how they affect different parts of the foot. Secondly, in dividing the foot into several separate segments, an assumption is made that several of the individual bones of the foot do not move relatively to each other, and there is evidence that this is unlikely [8]. Measurements based on this assumption either miss important kinematics between bones, or attribute motion to one joint when it actually occurs at another, which has not been measured. Finally, descriptions of foot and ankle kinematics may be incomplete because not all foot bones are included in the measurements. This is particularly the case for the talus, which is inaccessible in vivo without an invasive approach.

To avoid some of these pitfalls an invasive in vivo approach has been used in several studies [6,9–14]. However, these data have been limited to assessment of the tibia, talus and calcaneus during walking/running and have not assessed the mid or forefoot. Cadaver models are an

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alternative [8,15–19] but these inevitably involve some compromise in the extent to which *in vivo* gait can be replicated. The aim of this work, therefore, was to provide high quality *in vivo* kinematic data to describe rear, mid and forefoot kinematics during walking. The following bones were studied: tibia, fibula, talus, calcaneus, navicular, cuboid, medial cuneiform, first and fifth metatarsal.

## 2. Method

The study was approved by the ethical committee of the University Hospital and six male volunteers (mean age 38 years, range 28–55, mean weight 85 kg, range 71–110, mean height 180.5 cm, range 176–183) gave informed consent to participate.

Prior to the experimental procedure, the subjects were acquainted with the laboratory and 9.5 m walking track. They performed barefoot walking trials to determine their starting position, self-selected speed and preferred cadence. Walking consistency was assisted during all subsequent trials by a metronome.

Subsequently, each subject was taken to the operating room for insertion of the intracortical pins. Self-drilling, 1.6 mm diameter pins (Synthes, Bettlach, Switzerland) were inserted under local anaesthetic infiltration (Xylocain and Marcain, AstraZeneca, Södertälje, Sweden) into nine bones (tibia, fibula, calcaneus, talus, navicular, cuboid, medial cuneiform and metatarsals one and five) using fluoroscopy guidance. This was conducted under sterile surgical conditions. Insertion sites and intracortical pin orientation were chosen to avoid nerves and blood vessels, as well as to minimise the risk of skin impingement or marker arrays touching each other. After sterile dressing of the insertion sites, custom marker arrays were attached to the ends of the pins. Each array was equipped with three arms with reflective markers attached and the orientation of each arm was adjusted to minimise the risk of inter-array interference (Fig. 1).

After performing enough practice walks to ensure they had acclimatised to walking with the pins, subjects performed 10 walking trials at self-selected cadence, determined prior to pin insertion. The trials were immediately preceded by a relaxed standing reference trial with the long axis of the foot aligned with the  $x$  axis of the global coordinate system (posterior–anterior). A second standing trial was collected after the walking trials to enable any deformation of the pins or movement of the markers during the walking trials to be detected. The 10 camera motion capture system (Qualisys, ProReflex, Göteborg, Sweden) was synchronised with a force platform (Kistler, Winterthur, Switzerland). Kinematic data were collected at 240 Hz, ground reaction forces at 960 Hz.

A maximum of 2 h elapsed between commencing the laboratory experiment and removal of the pins. After pin removal, the insertion sites were cleaned and covered with new sterile dressings. Subjects were provided with antibiotic (Heracillin, AstraZeneca, Södertälje, Sweden) and pain relief medication (Citodon, AstraZeneca, Södertälje, Sweden), the latter to be taken only if required. All subjects reported some pain for approximately one week after the experiment, but no clinical complications occurred.

To describe the individual bone kinematics, local coordinate frames for each bone were defined using the three markers attached to each pin. The local coordinate frame was set such that in the relaxed standing trial the  $x$  (anterior/posterior),  $y$  (medial/lateral) and  $z$  (vertical) axes were parallel to those of the global reference

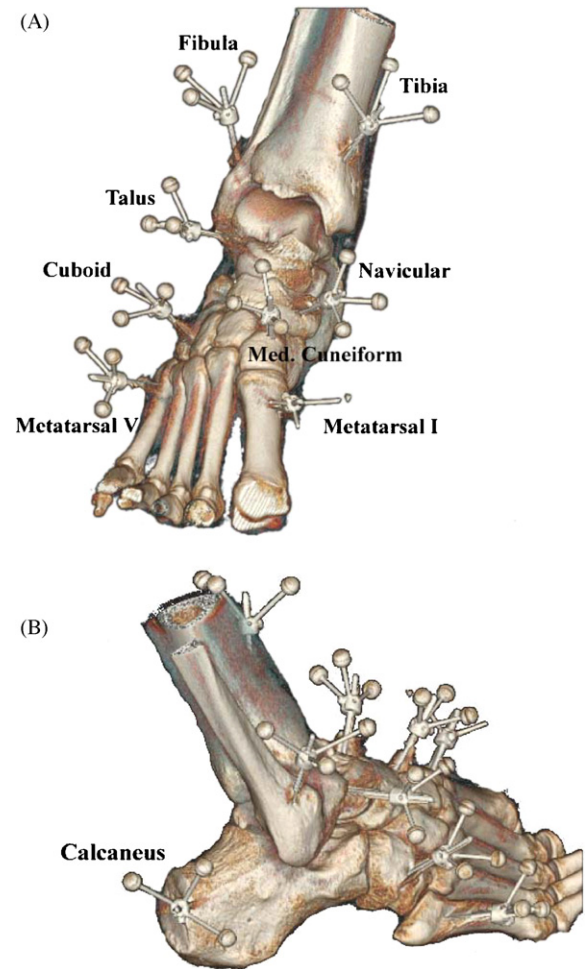


Fig. 1. Computed tomography image of the inserted intracortical pins and the attached marker arrays. (A) Frontal view, (B) lateral view to show the calcaneal markers.

frame. Joint rotations were calculated using Euler angles (sequence sagittal ( $y$ ), frontal ( $x$ ) and transverse ( $z$ ) plane motion). Data were normalised to 0–100% of stance phase and  $0^\circ$  was the position of the joint in the relaxed standing trial. Kinematic data from the 10 walking trials were averaged for each subject.

## 3. Results

The stance times for subjects was between 0.62 and 0.73 s (S.D. all  $<0.024$ ). The intra-subject coefficients of multiple correlations (CMC) for the vertical ground reaction forces were 0.90–0.99. The CMC is used to reflect the extent to which the pattern of the data was consistent across the ten trials. These CMC values are evidence that the subjects walked in repeatable manner.

The mean total range of motion at each of the 11 joints for each participant, and the corresponding standard deviation and intra- and inter-subject CMC, are reported in Table 1. The kinematic pattern for each joint and each subject is illustrated in Figs. 2 (rearfoot), 3 (midfoot) and 4 (forefoot).

Table 1

The mean total range of motion (°) at each of the 11 joints for each participant, with the corresponding intra-subject CMC and standard deviation for each

Participant		Fib-Tib			Talus-Tib			Calc-Tib			Calc-Tal			Nav-Talus			Cub-Calc			Cub-Nav			Mcun-Nav			1st Met-Mcun			5th Met-Cub			1st Met-Talus					
		ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC			
1	Sag	2.8	0.7	0.10	14.3	1.7	0.97	15.5	2.9	0.87	8.8	3.5	0.93	8.0	2.3	0.92	19.5	2.9	0.69	9.7	1.6	0.87	9.3	2.3	0.92	8.6	2.4	0.83	13.6	2.3	0.93	16.7	2.3	0.97			
	Front	2.0	0.5	0.00	10.0	1.7	0.80	17.2	3.8	0.88	11.7	1.4	0.60	21.0	2.6	0.95	16.8	5.6	0.91	15.6	2.4	0.88	22.8	1.7	0.95	6.9	1.6	0.95	15.3	3.2	0.80	6.5	1.2	0.86			
	Trans	3.1	0.7	0.87	7.2	2.4	0.93	4.8	0.8	0.94	6.3	2.9	0.72	21.0	2.7	0.99	8.5	0.9	0.95	17.6	1.2	0.99	14.5	2.5	0.99	7.5	1.4	0.95	13.0	2.7	0.94	10.1	1.9	0.97			
2	Sag	2.9	0.8	0.56	17.2	2.6	0.95	15.5	2.1	0.96	7.6	2.4	0.75	8.1	2.0	0.95	6.7	1.8	0.83	6.1	1.2	0.82	10.8	1.2	0.94	4.0	0.9	0.89	12.4	2.0	0.90	13.7	2.1	0.94			
	Front	2.4	0.4	0.59	13.9	1.3	0.96	7.4	1.3	0.94	8.3	1.9	0.91	5.2	1.5	0.95	7.8	1.5	0.86	4.0	0.5	0.69	5.8	1.1	0.73	5.4	1.2	0.71	7.6	1.2	0.94	9.4	2.8	0.88			
	Trans	2.5	0.3	0.87	11.4	1.6	0.96	5.7	0.8	0.98	6.5	1.8	0.83	6.0	1.5	0.70	6.7	0.8	0.65	6.5	1.5	0.70	3.4	1.2	0.95	4.4	0.8	0.85	10.9	2.3	0.94	9.4	2.1	0.83			
3	Sag	5.0	2.3	0.77	17.4	2.2	0.94	20.5	3.0	0.96	6.5	1.0	0.92	10.3	1.3	0.92	11.3	0.7	0.77	10.6	2.4	0.84	12.6	1.5	0.92	6.5	2.2	0.74	10.8	2.3	0.71	21.2	2.4	0.91			
	Front	4.9	0.9	0.94	5.5	1.2	0.76	8.8	1.7	0.89	10.1	1.7	0.90	13.6	1.5	0.98	9.7	2.3	0.84	9.2	0.8	0.77	10.9	1.0	0.95	4.9	1.3	0.74	14.4	5.0	0.45	6.6	1.7	0.89			
	Trans	5.7	1.2	0.90	7.5	1.4	0.84	11.6	1.1	0.96	10.5	0.3	0.93	21.3	1.5	0.97	11.1	0.7	0.73	7.2	2.0	0.64	5.7	1.1	0.71	6.3	0.8	0.48	8.6	1.3	0.78	20.4	1.3	0.95			
4	Sag	7.1	1.1	0.77	15.1	1.8	0.98	16.4	2.3	0.95	5.8	1.2	0.97	7.4	1.3	0.97	7.8	2.0	0.76	6.5	2.4	0.80	11.0	0.5	0.94	4.2	1.4	0.81	14.3	3.2	0.82	18.2	2.5	0.98			
	Front	2.7	0.8	0.93	5.7	1.7	0.79	12.4	1.6	0.99	7.6	1.6	0.96	15.8	1.8	0.98	14.2	2.9	0.84	11.6	3.6	0.87	7.0	1.5	0.85	5.1	1.9	0.77	10.9	4.0	0.52	8.9	1.5	0.97			
	Trans	3.4	1.0	0.79	8.8	1.5	0.93	6.8	0.8	0.96	5.7	1.0	0.93	13.6	1.7	0.96	5.2	1.2	0.55	8.3	1.7	0.68	5.6	1.2	0.83	5.6	1.2	0.86	10.3	1.5	0.83	13.4	2.4	0.96			
5	Sag	4.9	2.0	0.92	12.6	2.9	0.92	15.6	2.0	0.94	5.4	1.1	0.47	8.1	1.4	0.70	5.8	1.8	0.71	5.1	1.0	0.63	10.8	1.0	0.91	5.5	0.8	0.84	14.4	2.8	0.83	18.1	0.9	0.95			
	Front	3.5	0.5	0.82	5.5	1.3	0.86	12.0	1.9	0.92	11.2	3.1	0.84	18.8	3.7	0.95	6.6	2.5	0.59	7.9	2.1	0.93	9.0	2.2	0.87	4.2	1.0	0.69	7.3	2.0	0.40	16.7	3.0	0.94			
	Trans	2.4	0.5	0.94	4.0	0.7	0.71	8.0	1.5	0.97	8.6	1.2	0.96	19.5	3.5	0.95	9.2	1.0	0.80	7.0	0.9	0.64	4.1	1.2	0.88	5.7	0.9	0.91	8.9	0.3	0.92	20.1	2.6	0.95			
6	Sag	5.5	1.2	0.90	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	18.6	2.1	0.98	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	6.9	0.5	0.71	5.2	1.6	0.95	14.5	0.3	0.98	3.1	1.3	0.89	14.1	1.1	0.65	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>			
	Front	4.3	1.1	0.77	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	9.8	2.8	0.87	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	12.7	1.5	0.90	4.7	0.8	0.88	7.1	1.5	0.71	6.2	1.4	0.79	7.0	1.2	0.81	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>			
	Trans	3.7	1.2	0.70	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	7.2	0.7	0.90	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	7.7	1.0	0.83	6.6	0.9	0.97	4.1	0.6	0.99	6.8	0.8	0.77	7.1	1.4	0.89	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>			
		ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC	ROM	S.D.	CMC
Data for sample																																					
Sag		4.7	1.6	<0.2	15.3	2.0	0.6	17.0	2.1	0.7	6.8	1.4	<0.2	8.4	1.1	0.3	9.7	5.2	0.5	7.2	2.4	<0.2	11.5	1.8	0.3	5.3	2.0	<0.2	13.3	1.4	0.6	17.6	2.7	0.7			
Front		3.3	1.2	<0.2	8.1	3.8	0.7	11.3	3.5	<0.2	9.8	1.8	<0.2	14.9	6.1	0.4	11.3	3.9	<0.2	8.8	4.4	<0.2	10.4	6.3	<0.2	5.4	1.0	<0.2	10.4	3.7	<0.2	9.6	4.2	<0.2			
Trans		3.5	1.2	<0.2	7.8	2.7	0.4	7.3	2.4	0.6	7.5	2.0	<0.2	16.3	6.5	0.3	8.1	2.0	0.5	8.9	4.3	<0.2	6.2	4.2	<0.2	6.1	1.1	0.3	9.8	2.1	0.6	14.7	5.3	0.6			
n=		6			5			6			5			5			6			6			6			6			6								

The CMC listed next to the mean kinematic data for the sample is the inter-subject CMC, reflecting the consistency of the kinematic patterns across the subjects.

<sup>a</sup> Indicates data not collected as talus pin was not inserted.

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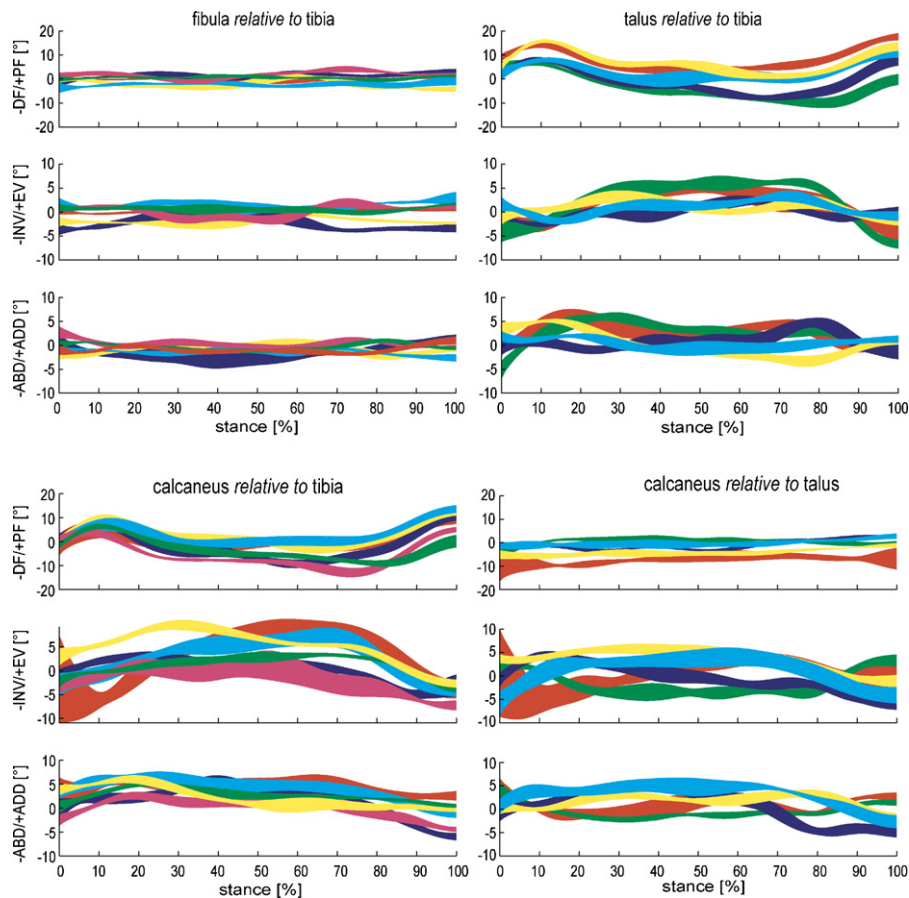


Fig. 2. Rearfoot kinematics for each subject during stance (0–100%). Each band describes the mean  $\pm$  1 S.D. for each subject. Data are the mean and S.D. of 10 trials.  $n = 6$  except for talus relative to the tibia and calcaneus relative to the talus, in these cases  $n = 5$ .

### 3.1. Rearfoot

The mean (S.D.) total range of motion between fibula and tibia was  $4.7^\circ$  ( $1.6^\circ$ ),  $3.3^\circ$  ( $1.2^\circ$ ) and  $3.5^\circ$  ( $1.2^\circ$ ) in the sagittal, frontal and transverse planes, respectively. Intra-subject CMC were  $>0.7$  in 78% of cases (inter-subject CMC were all  $<0.2$ ). At the talo-tibia joint, the mean (S.D.) total range of motion was  $15.3^\circ$  ( $2.0^\circ$ ),  $8.1^\circ$  ( $3.8^\circ$ ) and  $7.8^\circ$  ( $2.7^\circ$ ) in the sagittal, frontal and transverse planes, respectively. Intra-subject CMC were  $>0.7$  in 100% of cases, and inter-subject CMC were 0.64 and 0.71 for the sagittal and frontal planes (CMC for transverse plane was  $<0.4$ ). For the calcaneo-tibia complex, the mean (S.D.) total range of motion was  $17.0^\circ$  ( $2.1^\circ$ ),  $11.3^\circ$  ( $3.5^\circ$ ) and  $7.3^\circ$  ( $2.4^\circ$ ) in the sagittal, frontal and transverse planes, respectively. Intra-subject CMC were  $>0.87$  in 100% of cases and inter-subject CMC were 0.69 and 0.60 for the sagittal and transverse planes (CMC for frontal plane was  $<0.2$ ). At the talocalcaneal joint, the mean (S.D.) total range of motion was  $6.8^\circ$  ( $1.4^\circ$ ),  $9.8^\circ$  ( $1.8^\circ$ ) and  $7.5^\circ$  ( $2.0^\circ$ ) in the sagittal, frontal and transverse planes, respectively. Intra-subject CMC were  $>0.7$  in 96% of cases (inter-subject CMC were all  $<0.2$ ).

### 3.2. Midfoot

The mean (S.D.) total range of motion between the navicular and talus was  $8.4^\circ$  ( $1.1^\circ$ ),  $14.9^\circ$  ( $6.1^\circ$ ) and  $16.3^\circ$  ( $6.5^\circ$ ) in the sagittal, frontal and transverse planes, respectively, and intra-subject CMC were  $>0.7$  in 100% of cases. Inter-subject CMC were all  $\leq 0.4$ . At the calcaneo-cuboid joint, the mean (S.D.) total range of motion was  $9.7^\circ$  ( $5.2^\circ$ ),  $11.3^\circ$  ( $3.9^\circ$ ) and  $8.1^\circ$  ( $2.0^\circ$ ) the sagittal, frontal and transverse planes. Intra-subject CMC were  $>0.7$  in 78% of cases and  $>0.55$  in all cases. Inter-subject CMC was 0.52 for sagittal and transverse planes (CMC for frontal plane was  $<0.2$ ). Between the cuboid and the navicular, the mean (S.D.) total range of motion was  $7.2^\circ$  ( $2.4^\circ$ ),  $8.8^\circ$  ( $4.4^\circ$ ) and  $8.9^\circ$  ( $4.3^\circ$ ) in the sagittal, frontal and transverse planes. Intra-subject CMC was  $>0.7$  in over 70% of cases, and  $>0.63$  in all cases (inter-subject CMC were all  $<0.2$ ). At the medial cuneiform–navicular joint, the mean (S.D.) total range of motion was  $11.5^\circ$  ( $1.8^\circ$ ),  $10.4^\circ$  ( $6.3^\circ$ ) and  $6.2^\circ$  ( $4.2^\circ$ ) in the sagittal, frontal and transverse planes, respectively. Intra-subject CMC were  $>0.7$  in 100% of cases, and inter-subject CMC were all  $<0.32$ .



### 3.3. Forefoot

The mean (S.D.) total range of motion between the first metatarsal and the medial cuneiform was  $5.3^\circ$  (2.0°),  $5.4^\circ$  (1.0°) and  $6.1^\circ$  (1.1°) in the sagittal, frontal and transverse planes respectively and intra-subject CMC were  $>0.7$  in 89% of cases, and  $>0.48$  in all cases. Inter-subject CMC were all  $<0.3$ . Between the fifth metatarsal and cuboid, the mean (S.D.) total range of motion was  $13.3^\circ$  (1.4°),  $10.4^\circ$  (3.7°) and  $9.8^\circ$  (2.1°) in the sagittal, frontal and transverse planes. Intra-subject CMC were  $>0.7$  in 78% of cases, and inter-subject CMC were 0.63 and 0.64 for the sagittal and transverse planes (CMC for frontal plane was  $<0.2$ ).

Finally, the motion of the first metatarsal relative to the talus is reported as an indicator of the overall kinematics of the medial arch. The mean (S.D.) total range of motion was  $17.6^\circ$  (2.7°),  $9.6^\circ$  (4.2) and  $14.7^\circ$  (5.3°) in the sagittal, frontal and transverse planes. Intra-subject CMC were  $>0.83$  in 100% of cases, and inter-subject CMC 0.74 and 0.61 for the sagittal and transverse planes (CMC for frontal plane was  $<0.2$ ).

## 4. Discussion

One obvious but important observation is the fact that there was motion in all the studied joints during walking,

thus all the joints contributed to the motion of the foot in walking. This is reflected in the combined motion at the three joints of the medial arch (mean motion between metatarsal one and the talus was  $17.6^\circ$ ,  $9.6^\circ$  and  $14.7^\circ$  in the sagittal, frontal and transverse planes, Table 1). The ankle is often assumed to be the primary source of sagittal plane motion within the foot, but in four of five relevant subjects (1, 3, 4 and 5) the sagittal plane motion in the medial arch was greater than that at the tibio-talar joint. A recent cadaver study [8] led to similar conclusions. The medial arch motion reported here was larger than previous in vivo studies have indicated [10,11] although these studied the foot on a tilting platform rather than during walking.

The motion between the fibula and the tibia was small and inconsistent between subjects. Whilst the highest rotation (subject 4) was  $7.1^\circ$  (sagittal plane), mean rotations were less than  $5^\circ$  in most cases. There was evidence of consistent subject specific patterns of motion but not of a sample wise kinematic pattern.

The range of movement between the talus and the tibia showed the expected predominance of sagittal plane motion (mean  $15.3^\circ$ ) compared to frontal and transverse planes ( $8.1^\circ$  and  $7.8^\circ$ , respectively). The pattern of sagittal and frontal plane motion showed some consistency across subjects (CMC of 0.64 and 0.71, respectively), but less consistency in

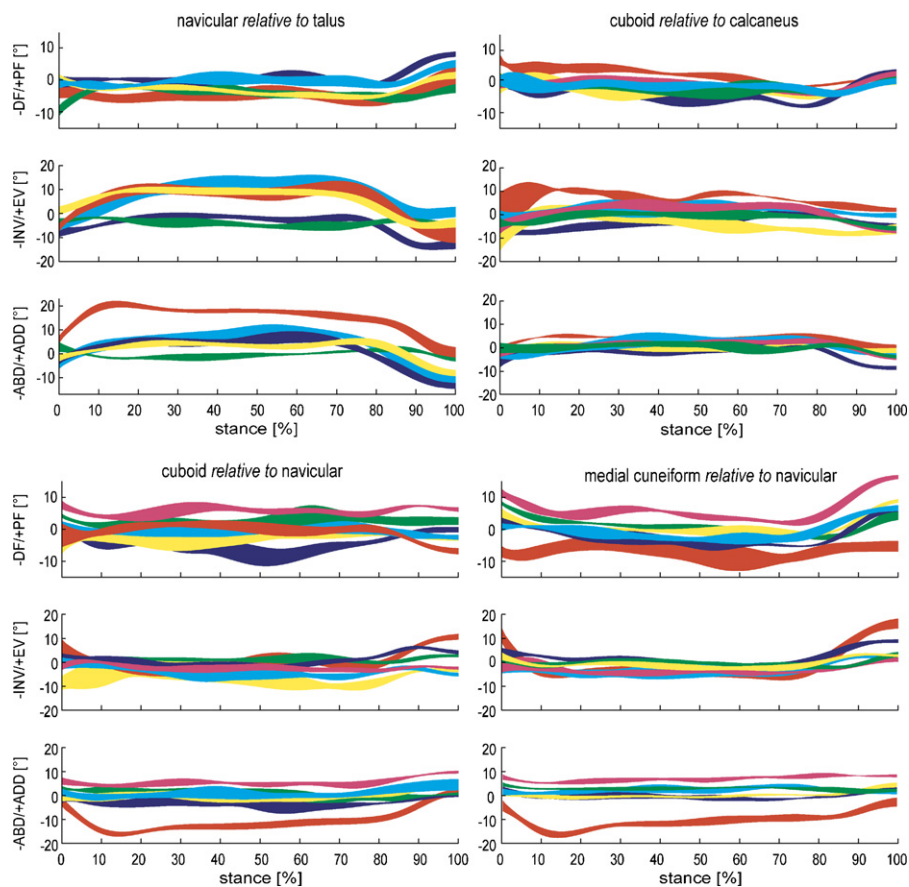


Fig. 3. Midfoot kinematics for each subject during stance (0–100%). Each band describes the mean  $\pm$ 1 S.D. for each subject. Data are the mean and S.D. of 10 trials.  $n = 6$  except for navicular relative to the talus ( $n = 5$ ).

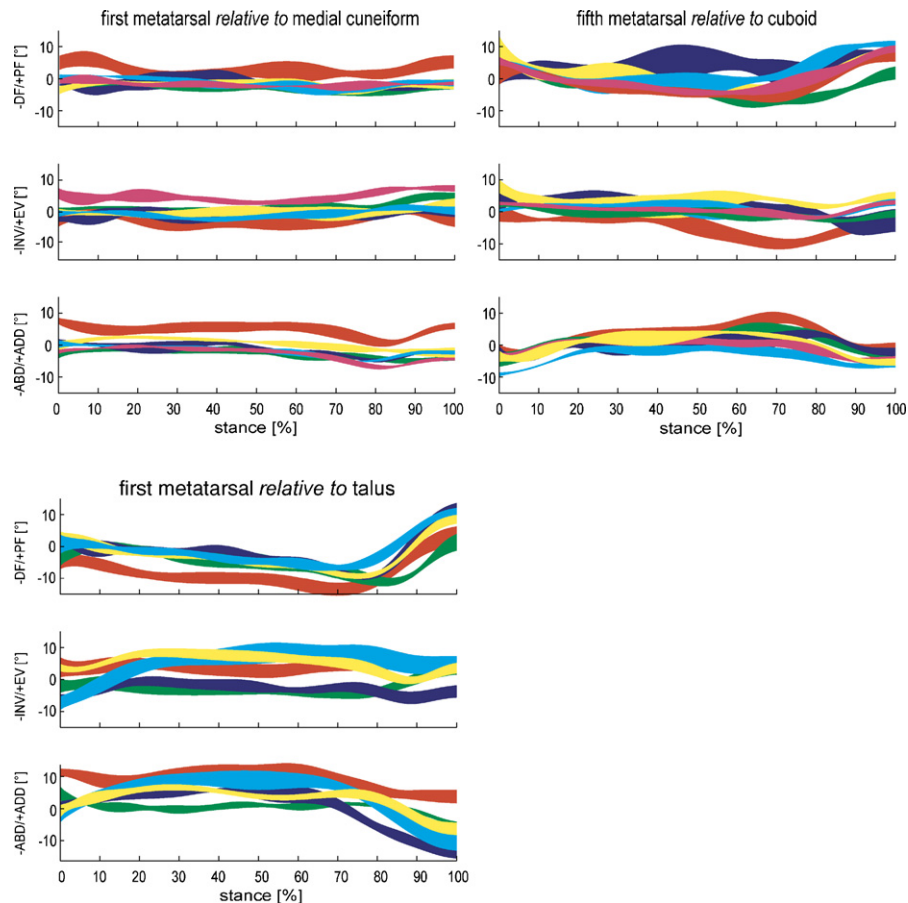


Fig. 4. Forefoot kinematics for each subject during stance (0–100%). Each band describes the mean  $\pm$ 1S.D. for each subject. Data are the mean and S.D. of 10 trials.  $n = 6$  except for fifth metatarsal relative to the talus ( $n = 5$ ).

the transverse plane (0.38). The range of sagittal plane motion is in line with previously presented data [14]. Transverse plane ankle motion was considerable, with a high of  $11.4^\circ$  for subject 2, but consistent with previous studies [11,14]. Movement in the frontal plane was larger than expected, with a high of  $13.9^\circ$  for subject 2. Interestingly, subjects 4 and 3 who displayed smaller frontal and transverse plane talus–tibia motion displayed relatively large frontal plane and transverse plane talocalcaneal motion. However, subject 5, who had the smallest range of frontal and transverse plane talus–tibia motion displayed relatively average talocalcaneal motion in these planes. Arguably the complex natural interlocking orientation of the three separate talocalcaneal facets and the short sinus tarsi ligament provide a high degree of constraint on the ability of the talocalcaneal joint to vary its kinematics. In contrast, and considering its anatomy in a similar context, the ankle most likely has a greater ability to modify its kinematics in response to functional demands. Thus, the extent to which the ankle needs to move in the frontal and transverse planes may in some cases depend upon the ability of the talocalcaneal joint to move in these planes. There is perhaps interdependency between these joints which is often ignored in the allocation of simple roles of dorsiflexor/plantar flexor to the ankle, and ‘torque converter’ to the talocalcaneal joint.

The talocalcaneal joint is generally considered to show mainly frontal and transverse plane motion. In this study, whilst subjects 3 and 5 did conform to this notion, subjects 1 and 2 showed more sagittal plane motion than transverse. Except for subject 2, frontal plane motion was always more than that at the ankle. The pattern of frontal plane motion at the talocalcaneal joint showed some variation between the subjects (inter-subject CMC was  $<0.2$ ). One subject showed little or no heel motion after heel strike and throughout 0–80% of stance. One other showed little motion immediately after heel strike, but movement only after 0–10% of stance (Fig. 2). Two others showed the expected talocalcaneal eversion immediately after heel strike. Similar variation was also reported by Arndt et al. [14]. In their study of three subjects, one subject displayed only  $\sim 1^\circ$  of sub-talar eversion after heel strike and no further motion up to 80% of stance. The other subjects displayed  $\sim 4^\circ$  of talocalcaneal eversion after heel strike and gradual inversion throughout stance.

The motion measured between the navicular and talus confirmed that movement in the talonavicular joint was greater than at the talocalcaneal joint [8,9–11,15]. In some cases frontal and transverse plane motion was observed to be twice that at the talocalcaneal joint (subjects 1, 3, 4 and 5). The high standard deviations for the sample mean (frontal and transverse planes, Table 1) and low inter-subject CMC

(<0.4) reflected the wide variation between subjects. The nature of the joint anatomy, particularly the curvature of the talar head and corresponding navicular facet, provides little osseous constraint, and the joint is likely to have considerable freedom of movement and thus is highly adaptable to functional demands. As others have reported [15] the range of motion between the cuboid and calcaneus was often less than that of the talonavicular joint, although there were some exceptions to this, mainly in the sagittal plane. However, it was greater than that of the talocalcaneal joint, further confirming the importance of this midfoot articulation. The motion of the cuboid relative to the navicular was less than the motion of either relative to the talus and calcaneus, but was not inconsiderable. The motion measured between these two bones contradicts concepts in which these bones act as a rigid unit.

The motion between the medial cuneiform and navicular was shown to be larger than expected, reaching 10° in the sagittal and frontal planes. This is comparable to the sagittal and frontal plane motion at the calcaneo-cuboid and talocalcaneal joints. This joint, which is commonly assumed to be relatively immobile, is likely to have important contribution to foot function. Our data contradict Lundberg et al. [9–11] who reported motion at the cuneiform–navicular joint between 2° and 5°, but this can be attributed to the fact that they studied the foot on a tilting platform rather than during walking. Motion of a similar range has been described in a cadaver study by Nester et al. [8] under a simulation of walking kinematics.

The average motion between the first metatarsal and the medial cuneiform was far less than the motion between the fifth metatarsal and the cuboid (mean data were 5.3°, 5.4° and 6.1°, compared to 13.3°, 10.4° and 9.8°) and roughly half that between the navicular and the medial cuneiform. This mobility on the lateral side of the forefoot is in addition to the considerable motion between cuboid and calcaneus. This demonstrates a considerable capacity for motion on the lateral arch of the foot as well as that already reported for the medial arch of the foot.

Intracortical pins are currently the only means of measuring individual bone kinematics under natural dynamic conditions. Alternative techniques, such as radio-stereometric analysis, magnetic resonance imaging and computed tomography, only permit static or semi-static analysis. Also, the in vivo nature of the study enables a higher degree of validity than in cadaver studies. However, one possible criticism is that use of intracortical pins may alter the walking pattern of subjects. In defence of this method, the stance times and ground reaction forces were all within the normal range, and the low standard deviation for the stance times, and high CMC for the vertical ground reaction forces, indicates that subjects walked in a repeatable pattern across their ten trials. Likewise for the kinematic data, intra-subject CMC were high (72% >0.8, 88% were >0.7). We assume walking in a repeatable manner is a key characteristic of a subject adopting their normal

walking pattern. A further comparison of walking with bone pins and walking with markers attached to the skin has recently been reported [20]. A further potential limitation is our choice not to use anatomical reference frames to describe bone position and orientation. Anatomical reference frames are extremely difficult to define for many foot bones because, unlike long bones, their complex surface anatomy does not offer any landmarks from which to reliably orientate the cardinal planes. The use of coordinate frames defined in reference to the global frame when the subject was stood relaxed means there is potential for a difference between subjects in the relationship between the anatomical position of the bones and the planes of motion in which we describe motion. Finally, our use of six subjects limits the extent to which results are generalisable, although we have derived conclusions which are common to all or most of the six subjects.

This study has provided, for the first time, a comprehensive description of in vivo rear, mid and forefoot kinematics during walking. The data show the complexity of the foot and the importance of the less obvious joints distal to the rearfoot in its overall dynamic function. The results indicate the need to study in more detail the intricate function of the many small structures in the foot so that their importance in relation to clinical practice can be better understood. An improved understanding would have relevance to surgical practice, foot implant prosthesis designs, and the design of footwear and other foot related assistive devices.

## Conflicts of interest

There are no conflicts of interest regarding this work and the authors.

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