"How do the mid and forefoot bones move? results from bone pin studies in living subjects"

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The work is collaboration between:

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Background

Descriptions of foot and ankle kinematics in the literature are generally incomplete because they are selective in their location of measurement devices on the foot. Non-invasive in vivo studies of foot and ankle kinematics have been limited to descriptions of the calcaneus relative to the leg, or various definitions of 'forefoot' or 'mid foot' segment relative to the heel. 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 researching 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, although how it affects different parts of the foot is not clear. 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 relative to each other, and there is evidence that this is unlikely. Measurements made 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 might 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.

Invasive in vivo research which directly measures the movements of bones by placing beads or pins into the bones avoids these issues, but has either been restricted to non-walking conditions (standing or single plane movements of the foot) or limited to assessment of the tibia, talus and calcaneus during walking/running.

The aim of this work 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.

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.

For each subject self drilling, 1.6 mm intracortical 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) with fluoroscopy guidance (figure 1). This was conducted under sterile surgical conditions. Insertion locations and intracortical pin orientation were chosen to avoid nerves and blood vessels, as well as minimising the risk of skin impingent or marker arrays touching each other. Each array was equipped with three arms with reflective markers.

After as many practice walks as were required subjects performed 10 walking trials at self selected cadence determined prior to pin insertion. 3D kinematic data for the reflective markers were derived from 10 camera motion capture cameras (Qualisys, ProReflex, Göteborg, Sweden) at 240 Hz.

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 frame. Data were normalised to 0-100% of stance phase and 0º was the position of the joint in the relaxed standing trial. Kinematic data from the 10 walking trials were averaged for each subject.

Figure 1. Photo of one foot with bone pins in situ.

Results.
Data showed that subjects walked at normal cadence, the motion of the calcaneus relative to the tibia and the ground reaction forces were as described in non invasive studies in the literature, and intra subject coefficient of multiple correlation was >0.9 in all cases. This indicates that subjects walked normally and repeatably despite the presence of the bone pins. Table 1 shows the mean total range of motion at each of the joints for which bone pins were inserted. Data for individual subjects and kinematic data during stance will also be presented.

	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	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*	ROM	*SD*
Sag	4.7	*1.6*	15.3	*2.0*	17.0	*2.1*	6.8	*1.4*	8.4	*1.1*	9.7	*5.2*	7.2	*2.4*	11.5	*1.8*	5.3	*2.0*	13.3	*1.4*	17.6	*2.7*
Front	3.3	*1.2*	8.1	*3.8*	11.3	*3.5*	9.8	*1.8*	14.9	*6.1*	11.3	*3.9*	8.8	*4.4*	10.4	*6.3*	5.4	*1.0*	10.4	*3.7*	9.6	*4.2*
Trans	3.5	*1.2*	7.8	*2.7*	7.3	*2.4*	7.5	*2.0*	16.3	*6.5*	8.1	*2.0*	8.9	*4.3*	6.2	*4.2*	6.1	*1.1*	9.8	*2.1*	14.7	*5.3*
n=	*6*		*5*		*6*		*5*		*5*		*6*		*6*		*6*		*6*		*6*		*5*	

Table 1. Mean total range of motion (ROM) during stance for each of 11 articulations. Sag, Front, Trans are the three planes of motion. Data are mean of 5 or 6 feet, n = number of feet used.

Discussion
One obvious but important observation is the fact that there was motion in all the studied joints during walking, thus all the joints contribute 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 17.6º, 9.6º and 14.7º in the sagittal, frontal and transverse planes).

The ankle is often assumed to be the primary source of sagittal plane motion within the foot, but in four of five relevant subjects the sagittal plane motion in the medial arch was greater than that at the tibio-talar joint.

The range of movement between the talus and the tibia showed the expected predominance of sagittal plane motion (mean 15.3º) compared to frontal and transverse planes (8.1º and 7.8º respectively). Transverse plane ankle motion was considerable, with a high of 11.4º for subject 2. Movement in the frontal plane was larger than expected, with a high of 13.9º for subject 2. The data also suggest that the extent to which the ankle needs to move in the frontal and transverse planes might 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.

As previously reported the talocalcaneal joint displayed least motion in the sagittal plane and a predominance of frontal plane motion. Except for subject 2, frontal plane motion was always more than that at the ankle, and in all cases sagittal plane motion was less than both frontal and transverse plane motion. The pattern of frontal plane motion at the talocalcaneal joint varied between the subjects (inter subject CMC was <0.2).

The motion between the navicular and talus confirms that movement in the talonavicular joint is far greater than at the talocalcaneal joint. In some cases frontal and transverse plane motion was observed to be twice that at the talocalcaneal joint. The high standard deviations for the sample mean (frontal and transverse planes, table 1) and low inter subject CMC (<0.4) reflect the wide variation between subjects. With only occasional exception, the range of motion between the cuboid and calcaneus was less than that of the talonavicular joint. However, it was greater than that of the talocalcaneal joint, further confirming the importance of this mid foot articulation.

The motion between the medial cuneiform and navicular was shown to be larger than expected, with around 10 degrees achieved in the sagittal and transverse planes. This is comparable to motion at the calcaneocuboid and talocalcaneal joints and demonstrates that this often ignored joint, which is perhaps assumed to be relatively immobile, is likely to have important contribution to foot function.

The average motion between metatarsal one and the medial cuneiform was far less than the motion between the fifth metatarsal and cuboid (mean data was 5.3º, 5.4º and 6.1º, compared to 13.3º, 10.4º and 9.8º) 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 calceneus. 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. This might also question our over emphasis on the medial arch of the foot being the principle functional unit reflecting overall foot function.

Conclusion.

The in vivo work is the first to describe mid and forefoot kinematics in actual walking. Mid and forefoot motion was found to be in the same order of magnitude as for the rearfoot confirming the functional role of these joints. The data collected show the potential for often ignored foot joints to contribute significantly to the overall kinematic function of the foot. The challenge is now how to best interpret these data in the context of improved experimental models of the foot and clinical surgical and orthosis practice.