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Invasive in vivo measurement of rear-, mid- and forefoot motion during walking☆

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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.

Keywords: Foot; Kinematics; Gait; In vivo

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 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° was the position of the joint in the relaxed standing trial. Kinematic data from the 10 walking trials were averaged for each subject.

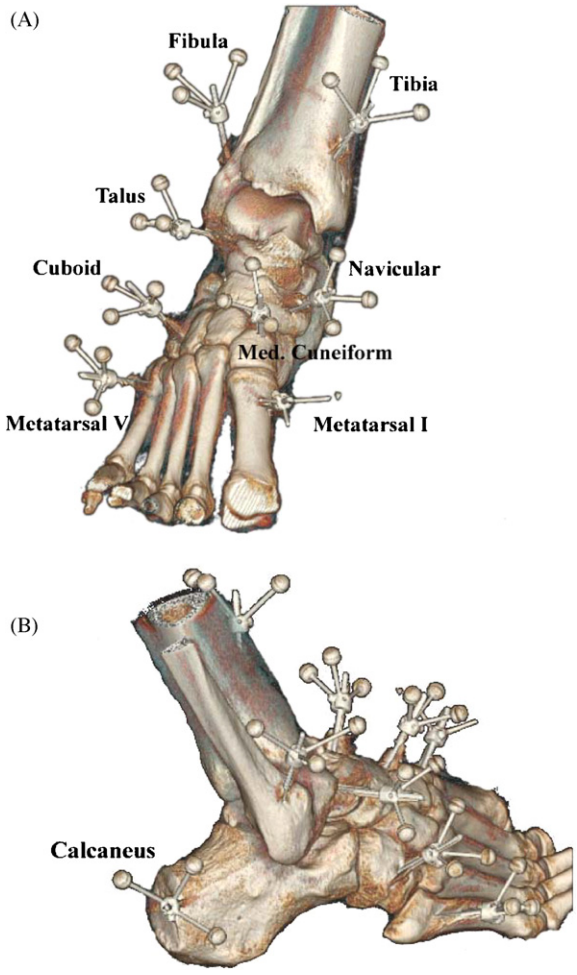

Fig. 1. Computed tomography image of the inserted intracortical pins and the attached marker arrays. (A) Frontal view, (B) lateral view to show the calcaneal markers.

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).