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In vitro study of foot kinematics using a dynamic walking cadaver model

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Abstract

There is a dearth of information on navicular, cuboid, cuneiform and metatarsal kinematics during walking and our objective was to study the kinematic contributions these bones might make to foot function. A dynamic cadaver model of walking was used to apply forces to cadaver feet and mobilise them in a manner similar to in vivo. Kinematic data were recorded from 13 cadaver feet. Given limitations to the simulation, the data describe what the cadaver feet were capable of in response to the forces applied, rather than exactly how they performed in vivo. The talonavicular joint was more mobile than the calcaneocuboid joint. The range of motion between cuneiforms and navicular was similar to that between talus and navicular. Metatarsals four and five were more mobile relative to the cuboid than metatarsals one, two and three relative to the cuneiforms. This work has confirmed the complexity of rear, mid and forefoot kinematics. The data demonstrate the potential for often-ignored foot joints to contribute significantly to the overall kinematic function of the foot. Previous emphasis on the ankle and sub talar joints as the principal articulating components of the foot has neglected more distal articulations. The results also demonstrate the extent to which the rigid segment assumptions of previous foot kinematics research have over simplified the foot.
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Keywords: Foot kinematics; Walking simulator; Cadaver; Mid foot; Forefoot

1. Introduction

Previous descriptions of foot and ankle kinematics are 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 (Carson et al., 2001; Hunt et al., 2001; Kidder et al., 1996; Rattanaprasert et al., 1999). In reality these segments are not rigid and these measures either miss important kinematics between bones, or attribute motion to one joint when it actually occurs at another which has not been measured. Further errors are inherent due to skin movement artefacts.

Invasive in vivo research avoids these issues but has either been restricted to non-walking conditions (Lundberg et al., 1989a–c; Lundberg and Svensson, 1993; Ouzounian and Shereff, 1989; Van Langelaan, 1983) or limited to assessment of the tibia, talus and calcaneus during walking/running (Arndt et al., 2004; Reinschmidt et al., 1997; Stacoff et al., 2000). There is a dearth of information on navicular, cuboid, cuneiform and metatarsal kinematics during walking and our objective was to study the kinematic contributions these bones might make to foot function. Since in vivo access to these bones is very limited we sought to use a dynamic ‘walking’ cadaver model to describe the kinematics of the tibia, talus, calcaneus, navicular, cuboid, three cuneiforms, five metatarsals and proximal phalanx of the hallux.

2. Materials and methods

The dynamic cadaver model (walking simulator) consists of a metal frame on four wheels, pulled along a track by a motor and cable (Fig. 1). A pneumatic cylinder applies a vertical load to the cadaver foot through a

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passive hinged "knee" joint. The sagittal plane motion of the tibia is dictated by the forward progression of the simulator along tracks. Although there is no control over frontal and transverse plane tibial motion, approximately 10° of motion is available in either plane.

Artificial muscle forces are generated by eight motors connected to nine tendons (Tib. Posterior (TP), Tib. Anterior (TA), Flex. Hallucis longus (FHL), Flex. Digitorum longus (FDL), Achilles (AT), Per. Brevis (PB), Per. Longus (PL), Ext. Digitorum longus (EDL) and Ext. hallucis longus (EHL)) (EDL and EHL were tied together), via eight steel cables, an in-series load cell and braided line. Timing of tendon actuation was fixed and set to match EMG temporal characteristics (Perry, 1995). Tendon force is determined by motor size and pre-tensioning. Sections of elastic rubber tubing connected to the motor arm were used to resist the motor action and determine the rate of load application. The tendon actuators were open loop controlled. Pre-tensioning of each individual tendon was adjusted manually in three functional tendon groups: anterior group (TA, EDL, EHL); posterior group (TB, FHL, FDL, AT); lateral group (PB, PL). Adjustments to the pre-tensioning were made in response to visual inspection of foot kinematics during repeated trial 'walks' and sought to meet qualitative criteria of an acceptable simulation of rearfoot kinematics. Whilst there are quantitative data which could have used as 'target' kinematic data (Reinschmidt et al., 1997; Leardini et al., 1999; Rattanaprasert et al., 1999; Hunt et al., 2001; Stacoff et al., 2000; Arndt et al., 2004), these data are typically from small samples (<20), show wide inter subject variation and involved different methodologies. Data from different studies do not agree on the exact range and timing of rearfoot motion. Thus, it was not felt appropriate to use data from any single study, nor attempt to average data across previous studies. The criteria for acceptable simulation of foot kinematics were the characteristics common to the results of all quantitative studies. This was a qualitative description of the gross pattern of foot kinematics that the cadaver should exhibit, namely: heel strike on the lateral calcaneus; gradual forefoot loading; and gradual heel lift accompanied by inversion of the heel. All trials in which the cadaver specimens met this criterion were used.

The simulation starts at heel contact and stops with only the toes on the ground and the metatarsal phalangeal joints close to maximal dorsiflexion (toe off is not simulated). The last few instances of stance and toe off could not be replicated due to the mechanical design of the simulator and lack of electronic control. The simulation takes 2 s, which is 3–4 times slower than in vivo but faster than other simulators (12–60 s) (Hurschler et al., 2003; Kim et al., 2001; Sharkey and Hamel, 1998). This faster walking speed is achieved by our use of open loop control rather than closed loop electronic control. However, this compromises the ability to exactly match in vivo muscle and ground reaction forces, and subtle adjustment of muscle forces and tibial angle are more difficult. However, a faster walking speed enables dynamic effects to be incorporated.

The use of cadaver material was approved by the Institutional Review Board. Data were collected on 13 right-sided specimens, 4 male, (age 32–80, mixed death histories). None had evidence of prior surgery. Specimens were fresh frozen, allowed to defrost over 48 h in a refrigerator (<4 °C) and then room temperature (no more than 4 h). Specimens were dissected to provide access to the leg tendons but all structures below the malleoli remained intact.

The tibia, talus, calcaneus, navicular, cuboid, three cuneiforms, five metatarsals and the proximal phalanx of the hallux were drilled with 1.6 mm *K* wires. A cluster of four reflective markers was screwed and glued onto each *K* wire (Fig. 2). A combination of the real markers and virtual markers (generated from static 'standing' trial) were used to define the x (anterior/posterior), z (medial/lateral) and y-axis (vertical axis) of the local co-ordinate frames for each bone. The local frames for each bone were co-incident with the axes of the global frame when the foot was weight bearing, the mid line of the foot was aligned parallel to the x (anterior/posterior) axis of the global co-ordinate system, and the tibia vertical.

Kinematic data were recorded (120 Hz) using 6 cameras (Vicon Motion Systems, UK) positioned close to the specimens. The measurement volume was 70 cm (l) × 40 cm (w) × 30 cm (h). A range of 3–6 trials were collected for each foot. Ground reaction forces were measured using an AMTI force platform. Euler angles were computed for 22 anatomical joints using the

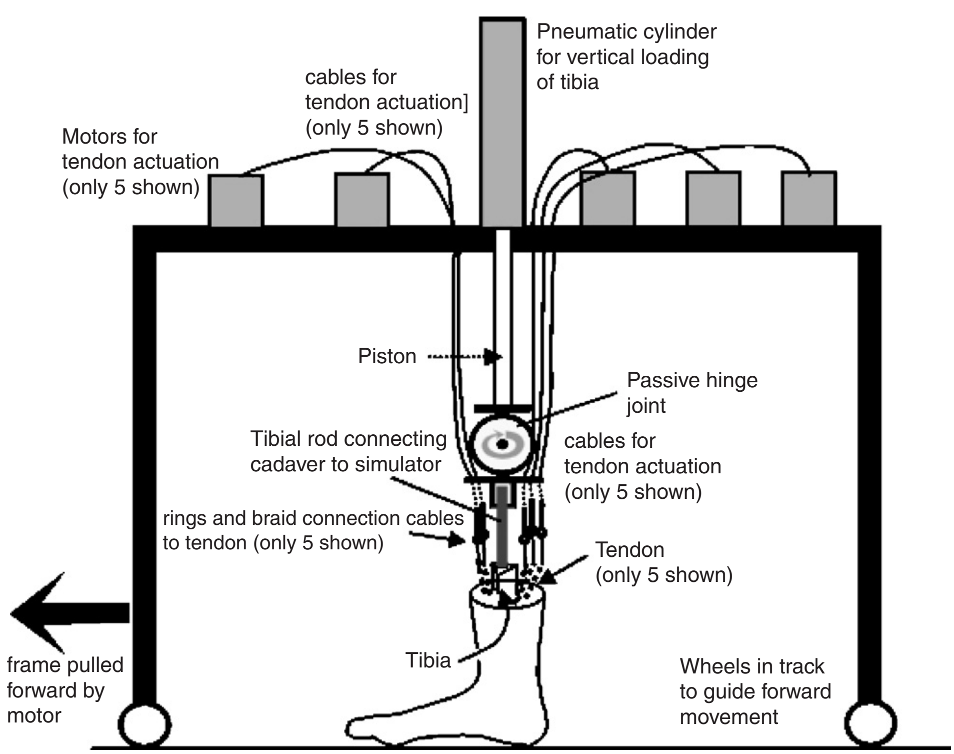

Fig. 1. Diagram of the walking simulator, consisting of the aluminium trolley running on four wheels in a track. A hinged joint is mounted at the base of the pneumatic piston and allows sagittal plane motion of the tibia. Cadaver specimen is mounted at base of the hinge joint via an aluminium rod. Only 5 tendons and motors are shown for purposes of illustration, simulator applied forces through 9 tendons in total.

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