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Short communication

An ultrasound based non-invasive method for the measurement of intrinsic foot kinematics during gait

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ABSTRACT

Soft tissue artefact (STA) and marker placement variability are sources of error when measuring the intrinsic kinematics of the foot. This study aims to demonstrate a non-invasive, combined ultrasound and motion capture (US/MC) technique to directly measure foot skeletal motion. The novel approach is compared to a standard motion capture protocol. Fourteen participants underwent instrumented barefoot analysis of foot motion during gait. Markers were attached to foot allowing medial longitudinal arch angle and navicular height to be determined. For the US/MC technique, the navicular marker was replaced by an ultrasound transducer which was secured to the foot allowing the skeletal landmark to be imaged. Ultrasound cineloops showing the location of the navicular tuberosity during the walking trials were synchronised with motion capture measurements and markers mounted on the probe allowed the true position of the bony landmark to be determined throughout stance phase. Two discrete variables, minimum navicular height and maximum MLA angle, were compared between the standard and US/MC protocols. Significant differences between minimum navicular height ($P=0.004$, 95% CI (1.57, 6.54)) and maximum medial longitudinal arch angle ($P=0.0034$, 95% CI (13.8, 3.4)) were found between the measurement methods. The individual effects of STA and marker placement error were also assessed. US/MC is a non-invasive technique which may help to provide more accurate measurements of intrinsic foot kinematics.

1. Introduction

The intrinsic kinematics of the foot are of interest for a number of clinical conditions, and this has been reflected in the large number of multi-segment foot models for motion analysis reported in the literature over the past two decades (Bishop et al., 2012). These models tend to be based on skin mounted marker sets, however studies using bone pins have demonstrated significant differences between the true motion of the foot bones and the motion measured using skin mounted markers (Nester et al., 2007). This error is due in part to movement of the surrounding soft tissue relative to the underlying bony landmarks. In addition, the accuracy of marker placement over the chosen landmark has also been shown to be a potential source of error when measuring foot kinematics (Telfer et al., 2010).

There are primarily two reported methods that allow the direct measurement of bone positions when assessing the intrinsic motion of the foot during dynamic activity: bone pins (Nester, 2009) and fluoroscopy (Shultz et al., 2011). These methods however require invasive surgery or exposure of the patient to ionising radiation respectively, potentially limiting their utility for clinical and large scale research applications.

The aim of this study is to demonstrate a non-invasive method which combines ultrasound and motion capture (US/MC) to directly measure skeletal motion during gait and therefore negate STA and marker placement error when measuring selected foot kinematic parameters, and to compare this method to measurements made using a standard protocol with skin mounted markers.

2. Materials and methods

2.1. Participants

Fourteen healthy participants, 7♀, age 37.9 years (SD 12.4), height 1.74 m (SD 0.08) and weight 75 kg (SD 11.3) gave informed, written consent to participate in this study. Ethical approval was obtained from the institutional review board prior to the study commencing (reference HLS12/43).

2.2. Equipment

Using sampling frequencies of 120 Hz, an 8 camera motion capture system (Opus 3; Qualisys, Gothenburg, Sweden) was used to track retroreflective markers

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and a force plate embedded in the walkway (Type 9286B; Kistler Winterthur, Switzerland) allowed stance phase to be defined. An intraoperative 13 MHz linear array US probe was used (IOE 323; Esaote, Genoa, Italy) for the US/MC trials. This probe was chosen because of its relatively small size (40 mm length and 9 mm diameter) and light weight (~10 g). US measurements were recorded at 47 Hz using a MyLab 70 US machine (Esaote, Genoa, Italy) with one preset optimised focal zone (depth 1 cm) giving an image resolution of approximately 0.1 mm.

2.3. Protocol

In all cases, the right foot of the participant was tested. With the foot semi-weight bearing, retroreflective markers were attached to the medial portion of the distal 1st metatarsal head, the sustentaculum tali and, in the case of the standard surface marker protocol, the navicular tuberosity (NT). For the US/MC technique, the NT marker was replaced by the US probe which was taped securely to the foot, orientated vertically over the NT allowing clear visualisation of the landmark (Fig. 1). Three markers arrayed in a plane perpendicular to the scan plane were attached directly to the probe.

For both the standard and US/MC techniques, five walking trials were recorded using a two step protocol at a self selected but controlled speed. Trials with speeds $> \pm 5\%$ of the initial trial were rejected and the measurement repeated. US cineloops showing the location of the NT during the US/MC trials were simultaneously recorded and synchronised with the motion capture measurements. Synchronisation was achieved by a researcher manually performing three vertical perturbations of the probe on the foot at the start of each trial prior to the participant beginning walking. These perturbations appeared as distinct movements of the NT on the US cineloop, and as vertical oscillations of the probe mounted markers. The minimum vertical height of the probe for each perturbation were defined as events and used to synchronise the motion capture and ultrasound measurements. Static trials were also recorded for both techniques, with an US image captured simultaneously with the marker data during the static trial for the US/MC technique.

2.4. Data processing and analysis

US cineloops were processed using Kinovea (V0.8.15; Kinovea open source project, www.kinovea.org) and all further data analysis was carried out in *R* (V3.0.0; www.r-project.org). Marker data was low pass filtered at 6 Hz using a fourth order Butterworth filter. The position of the most medial point of the NT relative to the scan plane on the US image (see Fig. 2) was determined for the static US image and for each frame of the US cineloop through stance phase. The position of the three US probe mounted markers and the position of the NT relative to the probe were combined to determine the US-derived position of the NT (full code and description of the calculations used to obtain the US derived position of the NT have been included as supplementary materials). Linear interpolation was used to resample all dynamic measurements to 101 points covering stance phase.

For the purpose of this study, the medial longitudinal arch (MLA) angle was defined as the angle between the 1st metatarsal head, the NT and the sustentaculum tali. Navicular height was defined as the vertical height (z-coordinate) of the NT. To determine the MLA using the US/MC protocol, the vertical height of the NT throughout stance was replaced in the standard trials by the z-coordinate of the US-derived NT. For the dynamic data, two discrete variables, minimum NT height and maximum MLA angle, were compared between the standard and US/MC protocols.

To isolate the contributions of STA and marker placement error, navicular height during the static trials was determined for both techniques. The differences were determined and compared. These values found were offset from the results from the standard protocol in order to present the isolated effect of STA throughout stance phase.

Between technique comparisons were carried out using paired t-tests or non-parametric equivalent depending on distribution of the data. A Bonferroni corrected $\alpha = 0.013$ was used to define statistical significance.

3. Results

Motion/time curves for MLA angle and navicular height determined using the two methods are presented in Fig. 3. Significant differences were found between minimum navicular height determined via the two methods, with the standard protocol estimating the height to be 49.1 mm compared to 45.1 mm for the US/MC technique ($P = 0.004$, 95% CI (1.57, 6.54)). Maximum MLA during stance was significantly different between methods ($P = 0.0034$, 95% CI (13.8, 3.4)) with the standard protocol estimating this angle to be 164.1° compared to 172.3° for the US/MC technique.

The assessment of marker placement error showed the standard protocol tended to overestimate the navicular height by a mean value of 2.1 mm, although this was not statistically significant ($P = 0.07$, 95% CI (−4.4, 0.2)). The isolated error associated with STA (i.e. individual marker placement error offsets removed) is presented in Fig. 4.

An example of an US cineloop of NT movement recorded during treadmill walking (to allow a number of consecutive steps to be viewed) has been included in the supplementary materials for demonstration purposes.

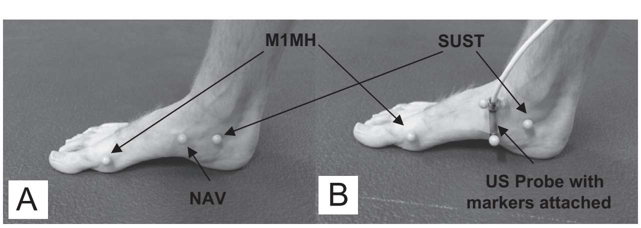

Fig. 1. Standard (A) and US/MC setup (B).

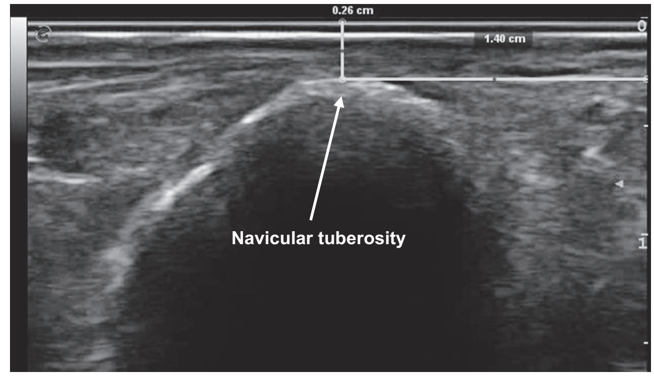

Fig. 2. US image of navicular tuberosity.

4. Discussion

In comparison to the more proximal joints in the lower limb, the relative motion between the bones of the foot is small even in the primary plan of movement. Therefore the impact of STA and other sources of error in motion analysis of the foot is an important issue, with inaccurate measurements potentially clouding the identification of clinically relevant changes to kinematic variables. In particular, the NT landmark is used in a number of multi-segment foot models (Carson et al., 2001; Hyslop et al., 2010; Leardini et al., 2007), and functional measures of navicular height have been proposed as a key clinical variables that can be used to identify disease driven abnormal foot function (Woodburn et al., 2004) and drive design rules for orthotic interventions (Gibson et al., in Press). Improving the accuracy of measurements relating to its position and range of movement may allow better estimates of foot function to be established.

Nester et al. (2007) found saggital plane differences of 2.8° and 3.5° for calcaneus to navicular and navicular to medial forefoot angles respectively when comparing measurements using bone pins and skin mounted markers. This potential combined difference is similar to the results found in the present study, supporting the validity of the US/MC technique when measuring MLA angle during stance.

The combined and isolated effects of soft tissue artefact and marker placement error were assessed in this study. The estimate of minimum navicular height of 4 mm higher found using the standard protocol is potentially clinically significant, for example Allen and Glasoe (2000) found statistically significant differences of 2.5 mm in navicular drop test values between individuals with a history of anterior cruciate ligament injury and uninjured controls. The offsets associated with marker placement error were non systematic, although the mean effect in this sample was to increase the overestimate of navicular