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Short communication

A comparison of dorsal and heel plate foot tracking methods on lower extremity dynamics

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ABSTRACT

The primary method to model ankle motion during inverse dynamic calculations of the lower limb is through the use of skin-mounted markers, with the foot modeled as a rigid segment. Motion of the foot is often tracked via the use of a marker cluster triad on either the dorsum, or heel, of the foot/shoe. The purpose of this investigation was to evaluate differences in calculated lower extremity dynamics during the stance phase of gait between these two tracking techniques. In an analysis of 7 subjects, it was found that sagittal ankle angles and sagittal ankle, hip and knee moments were strongly correlated between the two conditions, however, there was a significant difference in peak ankle plantar flexion and dorsiflexion angles. Frontal ankle angles were only moderately correlated and there was a significant difference in peak ankle eversion and inversion, resulting in moderate correlations in frontal plane moments and a significant difference in peak hip adductor moments. We demonstrate that the technique used to track the foot is an important consideration in interpreting lower extremity dynamics for clinical and research purposes.

1. Introduction

Various methods have been proposed to analyze ankle and intra-foot dynamics utilizing multiple markers to represent the different segments (Arndt et al., 2007; Collins et al., 2009; Lundgren et al., 2008). However, when analysis does not require intra-foot dynamics, the foot is typically modeled as a rigid segment and ankle motion is defined as foot relative to shank movement (Collins et al., 2009; Kadaba et al., 1990). These methods often implement the use of marker cluster sets to track anatomical segments defined by skin-mounted markers. In fact, certain types of analysis software (e.g. C-Motion) require a minimum of a three-marker array to calibrate, and subsequently track, the segments defined by the skin-mounted markers. A review of the literature over the past two decades found a similar amount of studies that used either a dorsal cluster (DP) (Collins et al., 2009; Ferrari et al., 2008) or heel cluster (HP) (Ho et al., 2012; Luo and Stefanyshyn, 2012) while implementing this methodology to track ankle motion. Because the DP tracks the mid-foot, whereas the HP tracks the calcaneus (Jenkyn and Nicol, 2007), a potential discrepancy could exist between the two tracking methods leading to differing clinical and research interpretations.

To date, there are no published data comparing the influence of these two foot cluster systems on lower extremity biomechanics; thus, this study examined the differences in lower extremity dynamics during the stance phase of gait when tracking the foot with HP and DP triads.

2. Methods

2.1. Subjects

Seven (4 male, 3 female) healthy young adults were tested at the Musculoskeletal Biomechanics Research Laboratory of the University of Southern California; informed consent was obtained from all participants. Their average age, height, and weight were 30.3 ± 3.5 years, 1.79 ± 0.10 m, and 77.6 ± 10.1 kg, respectively. The sample size was selected *a priori* using data from previous studies examining ankle and intra-foot kinematics during walking (Lundgren et al., 2008; Westblad et al., 2002). The sample size of the present study ($n=7$) provided a power factor above 80% for all significant variables.

2.2. Protocol

Skin-mounted markers were placed on the following anatomical landmarks of the dominant lower extremity: distal phalanx of the second toe, first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral knee joint and greater trochanter. To define the pelvis, markers were attached to the L5/S1 joint space, bilateral iliac crests and anterior superior iliac spines (ASIS). To track the segments defined by the skin-mounted markers, non-collinear tracking marker plates were placed on the dominant thigh and shank, and HP and DP triads were affixed to the dominant foot (Fig. 1). After a standing calibration trial, all skin-

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Fig. 1. Representative subject instrumented with the static foot marker set and dorsal and heel plate tracking clusters.

mounted markers were removed, with the exception of L5/S1 and bilateral ASIS, which were used to track the pelvis. Subsequently, each participant completed at least 3 successful trials of barefoot walking at their self-selected speed. A successful trial was operationally defined as a walking trial in which the stance phase of the dominant limb – defined as the leg with which they would kick a ball – was entirely on the force plate.

2.3. Equipment and data collection

Three-dimensional marker coordinates were collected at 60 Hz and reconstructed using Qualisys Track Manager Software (Qualisys, Gothenburg, Sweden). Visual 3D (C-motion, Rockville, MD) was used to process the raw coordinate data and compute segmental dynamics for the dominant lower extremity. The ankle joint was modeled such that 0° was the joint angle between the foot and shank during the relaxed standing trial. The pelvis was modeled as a cylinder and the lower extremity segments as cone frustra. The local coordinate systems of the pelvis, thigh, shank, and foot were derived from the standing calibration trial and joint kinematics were calculated using Euler angles with the following order of rotations: flexion/extension, abduction/adduction, internal/external rotation. The ankle joint angle was defined as the orientation of the foot relative to the shank, the knee joint angle was defined as the orientation of the shank relative to the thigh, and the hip joint angle was defined as the orientation of the thigh relative to the pelvis. Net joint moments were calculated using standard inverse dynamics equations and normalized to body mass.

Lower extremity dynamics were computed and normalized to the stance phase of gait (101 points); successful walking trials were then averaged for each respective subject (Growney et al., 1997; Kadaba et al., 1989; Lundgren et al., 2008). Using previously established methodology, coefficients of multiple correlations (CMC) were calculated (Growney et al., 1997; Kadaba et al., 1989) in order to compare the mean normalized stance phase ankle kinematics, and ankle, knee and hip kinetics, between the HP and DP methods. A CMC value approaching 1 indicates similarity in the curves, whereas a CMC value approaching 0 indicates dissimilarity (Growney et al., 1997). Mean peak joint angles were analyzed using Paired-t tests. Microsoft Excel (Version 2010; Redmond, WA) and SPSS (Version 18; Armonk, NY) were used for the statistical analyses.

3. Results

Intra-subject, mean sagittal plane ankle angles (CMC=0.805; Fig. 2a) and net moments (CMC=0.882) were strongly correlated between conditions, however, when compared to the HP, the DP presented with significantly higher average peak dorsiflexion (16.1° vs. 13.5°; $p=0.032$; Table 1) and plantar flexion angles (12.4° vs. 4.6°; $p=0.008$; Table 1). In the frontal plane, use of the DP resulted in significantly greater peak ankle inversion (2.5°vs. 0.8°; $p=0.019$; Table 1) but less average peak ankle eversion (8.8° vs. 11.3°; $p=0.037$; Table 1). Furthermore, frontal plane ankle angles were only moderately correlated (CMC=0.722; Fig. 2b) and frontal plane net ankle moments were weakly correlated (CMC=0.453; Fig. 3a).

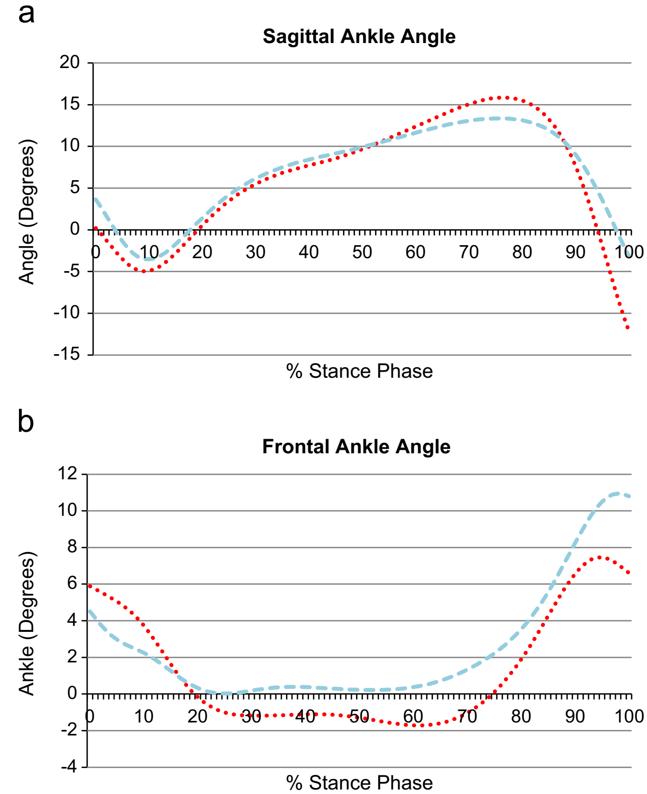

Fig. 2. Ensemble average, (a) sagittal and (b) frontal, stance-phase ankle kinematics across the seven subjects. Dotted line represents the dorsal plate. Dashed line represents the heel plate. Positive angles are dorsiflexion and eversion, respectively. Sagittal plane ankle angles were strongly correlated between conditions ($R=0.805$), whereas frontal plane ankle angles were moderately correlated ($R=0.722$). Note that the time to peak angles were not consistent across subjects.

Intra-subject mean sagittal plane net knee (CMC=0.832) and hip (CMC=0.800) moments were strongly correlated between the conditions. Frontal plane net knee (CMC=0.681; Fig. 3b) and hip (CMC=0.679; Fig. 3c) moments were moderately correlated; the DP also presented with significantly lower average peak hip adductor moments (0.17 Nm/kg vs. 0.19 Nm/kg; $p=0.006$; Table 1). The calculated differences between the DP and HP for all other average peak knee and hip sagittal and frontal moments were small and non-significant (Table 1).

4. Discussion

This study differentiates the effects of two (rigid-segment) foot tracking marker sets on lower extremity dynamics; the HP tracks the calcaneus and the DP tracks forefoot motion. Our findings in ankle kinematics, as calculated with the HP, are similar to those reported for calcaneal–tibial motion by Lundgren et al. (2008), who examined rear-, mid- and forefoot motion during gait in 6 subjects via the use of intra-cortical pins. These researchers demonstrated that *forefoot* tracking methods presented with more inversion throughout stance than methods that tracked calcaneal–tibial motion. This corroborates our findings that use of a DP, relative to use of a HP, results in a shift in the frontal plane kinematic curves towards inversion.

An important finding from this analysis was the relatively weaker frontal plane ankle kinetic correlations between the two conditions. This difference can be attributed to the altered location of the ground reaction force vectors with respect to the ankle joint, across conditions. Specifically, with the foot functioning as a lever, changes in the moment arm about the ankle can be magnified by