Gait & Posture 49 (2016) 136–143

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Predicting tibiotalar and subtalar joint angles from skin-marker data with dual-fluoroscopy as a reference standard

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ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form 13 May 2016
Accepted 23 June 2016

Keywords:
Ankle
Hindfoot
Dynamic imaging
Inverse kinematics
Motion capture

ABSTRACT

Evidence suggests that the tibiotalar and subtalar joints provide near six degree-of-freedom (DOF) motion. Yet, kinematic models frequently assume one DOF at each of these joints. In this study, we quantified the accuracy of kinematic models to predict joint angles at the tibiotalar and subtalar joints from skin-marker data. Models included 1 or 3 DOF at each joint. Ten asymptomatic subjects, screened for deformities, performed 1.0 m/s treadmill walking and a balanced, single-leg heel-rise. Tibiotalar and subtalar joint angles calculated by inverse kinematics for the 1 and 3 DOF models were compared to those measured directly in vivo using dual-fluoroscopy. Results demonstrated that, for each activity, the average error in tibiotalar joint angles predicted by the 1 DOF model were significantly smaller than those predicted by the 3 DOF model for inversion/eversion and internal/external rotation. In contrast, neither model consistently demonstrated smaller errors when predicting subtalar joint angles. Additionally, neither model could accurately predict discrete angles for the tibiotalar and subtalar joints on a per-subject basis. Differences between model predictions and dual-fluoroscopy measurements were highly variable across subjects, with joint angle errors in at least one rotation direction surpassing 10° for 9 out of 10 subjects. Our results suggest that both the 1 and 3 DOF models can predict trends in tibiotalar joint angles on a limited basis. However, as currently implemented, neither model can predict discrete tibiotalar or subtalar joint angles for individual subjects. Inclusion of subject-specific attributes may improve the accuracy of these models.

1. Introduction

The complex, interrelated motion of the tibiotalar and subtalar joints is a critical component of the foot and ankle. The tibiotalar joint provides the primary means for dorsiflexion/plantarflexion during gait, while the subtalar joint undergoes inversion/eversion, facilitating forward progression of the center of pressure from heel-strike to late stance [1,2]. Based on these canonical descriptions, biomechanical models frequently assign a single degree-of-freedom (DOF) to each joint, with dorsiflexion/plantarflexion and inversion/eversion defining the tibiotalar and subtalar joints, respectively (e.g., [3–7]). These single DOF models, in combination with inverse kinematics, are widely used. However, investigators rarely estimate independent tibiotalar and subtalar articulation, as reflective skin markers cannot be used to directly measure articulation of these joints in the absence of a suitable marker location for the talus [6,8]. Instead, articulation of the hindfoot is typically represented as movement of the calcaneus relative to the tibia (e.g., [9–11]). A limitation of this typical representation is that it does not discern how injuries or disease states disproportionately affect articulation of the tibiotalar and subtalar joints. Dynamic imaging techniques, including computed tomography (CT), magnetic resonance imaging, and dual-fluoroscopy have been employed to measure kinematics of the tibiotalar and subtalar joints independently (e.g., [12–16]). However, these

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http://dx.doi.org/10.1016/j.gaitpost.2016.06.031
0966-6362/

methodologies are not widely available and involve time intensive data post-processing, making them less practical than skin-maker motion analysis for studies involving large sample sizes.

Biomechanical models that incorporate multiple DOF at the tibiotalar and subtalar joints may have the ability to predict independent kinematics for these joints using skin-maker data and standard inverse kinematic techniques. However, to our knowledge, prior studies have not assessed the accuracy of joint angle predictions from inverse kinematic simulations using multi-DOF models versus those using 1 DOF models. Moreover, the accuracy of such predictions has not been previously assessed by direct comparison to in vivo measurements.

The objective of this study was to compare joint angles predicted from inverse kinematic simulations using 1 and 3 DOF models to a reference standard. Here, the 1 DOF model assumed two hinge joints for the tibiotalar and subtalar joints, offering dorsiflexion/plantarflexion and inversion/eversion, respectively, while the 3 DOF model assumed that both joints could undergo rotations about three axes. Joint angle predictions from each model were derived from only skin-marker data, and then compared to joint angles of the same subjects measured in vivo using a validated dual-fluoroscopy system.

2. Methods

2.1. Subjects

Ten control subjects (5 male; age 30.9 ± 7.2 years; height 1.72 ± 0.11 m; weight 70.2 ± 15.9 kg) participated in this study under informed consent and ethics board approval (University of Utah, IRB#65620). Each subject was screened to ensure no history of foot or ankle disorders. Radiographs of both feet were acquired and screened for varus/valgus hindfoot malalignment, osteophytes, and/or osteoarthritis as assessed by Kellgren-Lawrence grades greater than 1. All subjects were included given these criteria.

2.2. Skin-marker motion capture & dual-fluoroscopy

Skin-marker motion capture and dual-fluoroscopy data of each subject were collected during 1.0 m/s treadmill walking and a balanced, single-leg heel-rise (Fig. 1A). Walking was selected as a common activity. The heel-rise was chosen to examine a large range of dorsiflexion/plantarflexion. Skin-marker data was spatially and temporally synced to the dual-fluoroscopy data using an

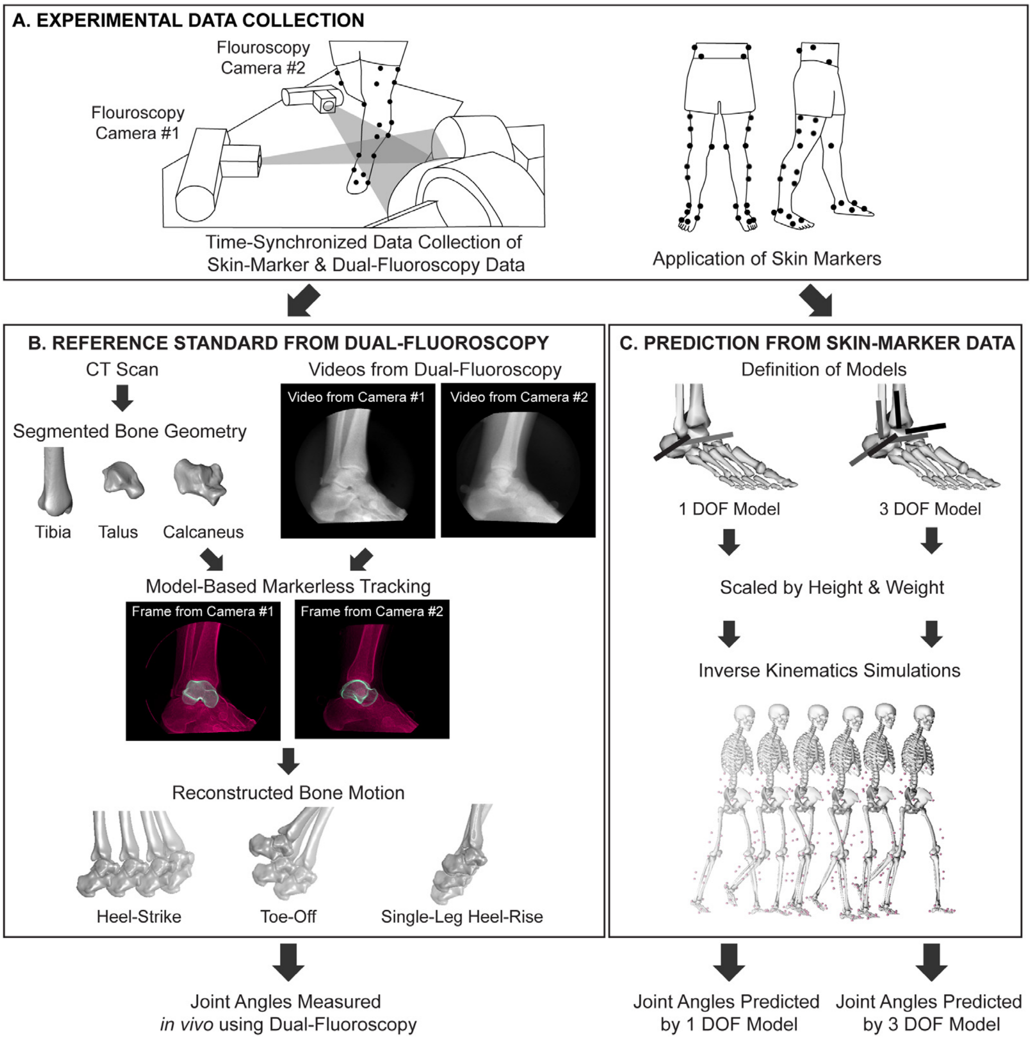

Fig. 1. Flowchart of experimental and computational methods. (A) For each subject, experimental skin-marker data and dual-fluoroscopy data were simultaneously collected. Note, at the foot and ankle, the skin-marker set included markers on the medial and lateral malleoli, calcaneal tuberosity, dorsal aspects of the second and fifth phalanxes, dorsal web space between the fourth and fifth metatarsals, and the dorsal-medial aspect of the first metatarsal head. (B) Using only the skin-marker data, tibiotalar and subtalar joint angles were predicted from inverse kinematic simulations using the 1 DOF and 3 DOF models. (C) Independently, tibiotalar and subtalar joint angles were measured using dual-fluoroscopy. The joint angles predicted from skin-marker data were then compared to those measured using dual-fluoroscopy.