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ORIGINAL ARTICLE

A Model for the Evaluation of Lower Extremity Kinematics with Integrated Multisegmental Foot Motion

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Background/Purpose: Current models for assessing lower extremity motion during gait benefit from ease of use in the clinical environment. However, underlying assumptions regarding joint location and distal segment motion limit their effectiveness and accuracy. The aim of this study was to develop a model for lower extremity motion analysis, which integrates functional methods for estimating hip joint center (HJC) location and a multisegmental approach to modeling motion of the foot and ankle. The new model is capable of tracking the motion of six segments (pelvis, bilateral thigh, tibia, hindfoot, forefoot, and hallux) during stance and swing.
Methods: Ten healthy young adults underwent gait analysis with the new model and two existing standardized models, PlugInGait (PIG) and Milwaukee Foot Model (MFM), and results were compared between models.
Results: Pointwise correlation results demonstrate good agreement with existing standardized models in several measures; areas of lesser correlation are well-explained by differences in methods of locating joint centers and referencing to the underlying anatomy. Repeatability analysis with the coefficient of multiple correlation (CMC) found values greater than 0.9 for 16 of 18 segment/plane couplets.
Discussion: Correlation and repeatability analyses suggest the new model is well-suited for clinical and research applications. This model of lower extremity motion with integrated multisegmental foot kinematics will improve clinicians' ability to characterize patient populations, plan treatment, and monitor progress.

1. Introduction

The quality of lower extremity kinematic measurement is intrinsically linked to the quality of the model used for the assessment. Measurement accuracy, repeatability of model measurements, and ease of application, are all key factors which determine whether a given model performs sufficiently. Clinical gait analysis requires a model which can be applied to patients regardless of age or cognition, and which uses instrumentation that is not affected by gait pathology (e.g., medial thigh instrumentation which is obscured or repositioned by the contralateral limb during scissoring gait). A model also becomes more valuable as it provides more information on a per-trial basis, making the integration of multisegmental foot motion into standardized measurements of lower extremity motion particularly useful. More and better information may ultimately lead to improved treatment planning, as recommendations for therapy, bracing, and surgery can all stem from measures of joint kinematics.

Both anthropometric and cluster-based models have seen extensive use in the clinical arena, with the Conventional Gait Model [CGM, a.k.a. Kadaba model, Helen Hayes model, PlugInGait (PIG)][1,2] and the Cleveland Clinic Model[3] being notable examples of each. Despite their widespread clinical acceptance, these modeling methods are not without shortcomings. Both methods are based on the assumption that the same set of rules relates skin-mounted markers to underlying bony anatomy for all participants uniformly.[4] Both models also rely on the repeatable placement of markers with high accuracy; the repeatability of this placement, and the effects of inaccuracy, have been reported by several investigators.[5–7]

While efficient in design and application, these models share a common shortcoming in their single-segment representation of

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the foot, which is unable to clearly represent commonly seen deformities such as midfoot break or pes planovalgus. Predictive methods for calculating hip joint center (HJC) location also limit their usefulness, as a number of investigators[8–12] have demonstrated the improved accuracy and robustness of a functional method for calculating HJC location. While functional methods require some additional calibration and higher level computations, these requirements are now well within the realm of feasibility for most motion analysis labs.

Unlike lower extremity biomechanical modeling, the literature presents no clear standard for the modeling of multiple segments of the foot and ankle. Published models differ in both the number of segments being tracked and the definition of those segments' neutral alignment. Some previous reports have defined the neutral position based on a patient's comfortable standing position;[13,14] others have used an imposed position such as subtalar neutral[15] or vertical tibia.[16,17] However, the ability of these models to adequately represent deformities such as calcaneal valgus or collapsed longitudinal arch has been questioned.[16,18] These participant-specific alignments make comparisons across and between groups difficult, as the "zero position" for each segment is dependent on the participant's original neutral position. An alternative solution is the use of anatomically-based indexing methods that allow referencing of tracked anatomical markers to underlying bony orientation. Such methods have been incorporated previously into the Milwaukee Foot Model (MFM)[19,20] and used in a series of characterizations of patients with foot and ankle pathology.[21–24]

The purpose of this study was to develop a full 3D lower extremity model integrating multiple segments of the foot (hindfoot, forefoot, and hallux) into a standard lower extremity model (pelvis, hip, and knee), while incorporating previously defined functional methods for determining HJC location.[8,25,26] Following the scheme of the Milwaukee Foot Model, radiographic referencing methods were included to relate the orientation of marker-based axes to bone-based axes for the multiple segments of the foot.

2. Methods

2.1. Experimental procedures

Ten young healthy ambulators were tested in the Motion Analysis Laboratory at the Medical College of Wisconsin (MCW). Participants ranged in age from 25 years to 36 years and included four males and six females. The study was approved by the MCW Institutional Review Board, and all participants provided informed consent prior to participating in the study.

Prior to motion testing, standing radiographs of the foot were acquired for each individual using a foot position template (FPT) to standardize posture. Each participant stood on a piece of firm cardboard in a comfortable position. A single investigator traced both feet and marked the positions of the calcaneal tuberosity (CT) and head of the second metatarsal (MT2). The FPT was then marked with a line between CT and MT2, representing the longitudinal axis of the foot. The cardboard was cut along a line perpendicular to this longitudinal axis just distal to the toes, and also cut along a line parallel to the axis just lateral of the footprint (Figure 1). Radio-opaque markers were used to mark the line so it could be redrawn on x-rays. The FPT was used to reposition the individual's feet for acquisition of lateral, A/P, and modified coronal plane weightbearing radiographs; the cut edges of the FPT were used to align the x-ray plate for the lateral and coronal plane views.

Participants were instrumented with reflective markers (diameter = 16 mm) secured to specific anatomical and technical locations with thin-profile double-sided adhesive (Table 1). Anatomical locations were identified via palpation by a single investigator.

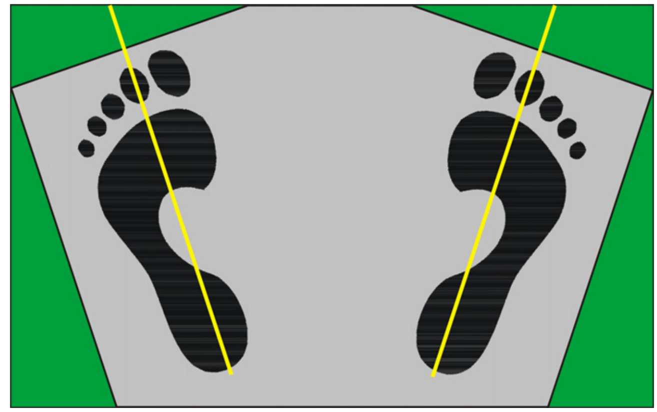

Figure 1 Schematic diagram of foot position template (FPT) used to replicate foot position between radiograph testing and motion analysis testing.

Following instrumentation, data collection began with a Vicon 524 Motion Analysis System (Vicon Motion Systems; Centennial, CO, USA; 15 cameras, fs = 120 Hz). A "static" trial was captured first, in which the individual resumed his comfortable posture on the FPT. Knee alignment devices (KADs) were used during the capture of the static trial for assessment of knee joint center location and axis orientation following the standard KAD protocol.[27] Following collection of static trial data, the participant went through several "HJC calibration" trials using a protocol of active sagittal and coronal plane motion described by Piazza.[12] These trials were followed by walking trials at a freely selected speed along the laboratory walkway (length = 6 m). For purposes of repeatability testing, three participants returned to the lab for two more identical testing sessions.

Lower extremity data was then processed using the standardized PIG lower extremity model included with Vicon Workstation software, the MFM, and the new integrated model (NIM, written in the Matlab environment). The NIM calculated motion between six adjacent segments using Euler angle methods with a sagittal-coronal-transverse order of derotation, providing three-dimensional kinematics for the: (1) pelvis (orientation relative to global); (2) hip (thigh relative to pelvis); (3) knee (tibia relative to thigh); (4) ankle (hindfoot relative to tibia); (5) transtarsal (forefoot relative to hindfoot), and (6) MTP1 (hallux relative to forefoot).

Table 1 Anatomical markers with placement notes. With the exception of the SACR, all markers are placed bilaterally

Marker name	Placement
SACR	Midpoint of line between left and right PSIS
ASI	ASIS
THI	Midpoint of line between greater trochanter and lateral femoral epicondyle
KNE	Lateral femoral epicondyle
TIB	Midpoint of line between lateral femoral epicondyle and lateral malleolus
MSAT	Medial superior anterior aspect of tibia
MMAL	Medial malleolus
LMAL	Lateral malleolus
TCAL	Calcaneal tuberosity
MCAL	Medial aspect of calcaneus
LCAL	Lateral aspect of calcaneus
T5ML	Tuberosity of fifth metatarsal
MH1M	Head of first metatarsal
LH5M	Head of fifth metatarsal
XHAL, YHAL, ZHAL	Triad mounted on hallux, oriented such that XHAL points anteriorly and YHAL points laterally