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A multi-segment foot model based on anatomically registered technical coordinate systems: Method repeatability in pediatric feet

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Several multi-segment foot models to measure the motion of intrinsic joints of the foot have been reported. Use of these models in clinical decision making is limited due to lack of rigorous validation including inter-clinician, and inter-lab variability measures. A model with thoroughly quantified variability may significantly improve the confidence in the results of such foot models. This study proposes a new clinical foot model with the underlying strategy of using separate anatomic and technical marker configurations and coordinate systems. Anatomical landmark and coordinate system identification is determined during a static subject calibration. Technical markers are located at optimal sites for dynamic motion tracking. The model is comprised of the tibia and three foot segments (hindfoot, forefoot and hallux) and inter-segmental joint angles are computed in three planes. Data collection was carried out on pediatric subjects at two sites (Site 1: n = 10 subjects by two clinicians and Site 2: five subjects by one clinician). A plaster mold method was used to quantify static intra-clinician and inter-clinician marker placement variability by allowing direct comparisons of marker data between sessions for each subject. Intra-clinician and inter-clinician joint angle variability were less than 48 For dynamic walking kinematics, intra-clinician, inter-clinician and inter-laboratory variability were less than 68 for the ankle and forefoot, but slightly higher for the hallux. Inter-trial variability accounted for 2–48 of the total dynamic variability. Results indicate the proposed foot model reduces the effects of marker placement variability on computed foot kinematics during walking compared to similar measures in previous models.

1. Introduction

The Newington gait model, commonly used for clinical gait analysis over the past two decades, treats the body as a series of rigid links starting at the pelvis and ending at the feet [1]. This model represents the foot as a single segment with all motions attributed to a two degree of freedom ankle joint, significantly oversimplifying foot anatomy and failing to isolate segmental motions distal to the ankle joint. The human shank and foot complex is a multi-joint mechanism which determines the critical interaction between the lower limb and the ground during locomotion. Dynamic analysis of these joints is necessary for clinicians to distinguish between typically developing and pathological foot function [2–4].

Several foot models have been published to measure multi-segment foot motions [5]. In most models, the foot is partitioned into three segments: hindfoot, forefoot and hallux. The fundamental challenge with foot modeling is marker placement error, which is amplified in angular calculations due to close proximity of markers on small segments. Compared to typical spacing on long bones, small errors in marker locations on the foot result in relatively large errors in angular calculations. As feet and segments become smaller, as with pediatric subjects, this problem is magnified. A repeatability study of the Oxford foot model on pediatric subjects observed higher variability of inter-segmental angles as compared to previous values reported for adult subjects and expressed the need for a better marker placement protocol, especially for pediatric subjects [6,7].

Initially foot models were limited by lack of rigorous anatomical coordinate definitions [8–10]. Some models required X-ray exposure of patients to reference external markers to the anatomical geometry of the underlying bones [11]. These explicitly stated that some measurements were difficult to obtain from radiographic views and others impossible, such as forefoot position in the coronal plane. Other studies, aimed to establish anatomically based coordinate systems, suggested collecting extra trials using either a special jig [12] or optimization routines to

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plantar surface. F1p is the anterior/posterior axis. The forefoot sagittal plane is defined by Vector F1p and the superior/inferior axis which is normal to the plantar surface. The medial/lateral axis is orthogonal to these two.

Option 2: Starting with the definition in Option 1, rotate this coordinate system about the medial/lateral axis by a lateral weight bearing radiograph measure of the angle between the 1st metatarsal and the ground. A new coordinate system is then established with the medial axis defined as perpendicular to the rotated anterior/posterior axis and the plantar surface normal, and the superior/inferior axis orthogonal to these two.

Option 3: Marker inclination. Starting with the Option 1 definition, first approximate the forefoot inclination angle using the two optional markers on the 1st metatarsal, MT1BM and MT1HM. Define F2 as vector from MT1BM to MT1HM. Define the projection of this vector in the sagittal plane of the forefoot using the coordinate system defined in Option 1 as F2s. The angle between F2s and the anterior/posterior axis defined in Option 1 is the marker based forefoot inclination. Use this angle in Option 2.

A.1.4. Hallux

A.1.4.1. Markers

The toe triad consists of three markers approximately arranged to form the vertices of a right triangle. The triad is adhered to the nail of the hallux such that the long axis alignment reflects hallux valgus. TOE2 is the most anterior marker, TOE3 is the most lateral marker, and TOE1 is the vertex of the two legs of the triangle formed by the triad.

A.1.4.2. Reference anatomical coordinate system

The anterior/posterior axis is the vector from the posterior marker TOE1 to the anterior marker TOE2. The superior/inferior axis is perpendicular to the plane defined by the anterior/posterior axis and the vector from the lateral marker TOE3 to TOE1. The medial/lateral axis is orthogonal to the superior/inferior and anterior/posterior axes (see Tables A.1 and A.2).

Table A.1
Dynamic marker set used in the mSHCG model.

Marker	Segment: anatomical location	Critical alignment
TIB	Shank: distal lateral tibia (wand)	None, technical only
TIBU[a]	Shank: anterior surface of tibia, relatively superior	None, technical only, optional
TIBL[a]	Shank: anterior surface of tibia, relatively inferior	None, technical only, optional
ANK	Shank: lateral malleolus	Anterior/posterior
PCAL	Hindfoot: posterior tuberosity	Medial/lateral
LCAL	Hindfoot: lateral calcaneus, superior to bulge in heel pad	Medial/lateral symmetry with LCAL
MCAL	Hindfoot: medial calcaneus, superior to bulge in heel pad	Medial/lateral symmetry with MCAL
MT1B	Forefoot: base of 1st metatarsal (avoid FHL tendon)	None, technical only
MT1H	Forefoot: head of 1st metatarsal (avoid FHL tendon)	None, technical only
MT5H	Forefoot: head of 5th metatarsal (avoid FDL tendon and metarso-phalangeal joint)	None, technical only
TOE1,2,3[a]	Hallux: toe triad placed on the nail of hallux	Align posterior and anterior markers with hallux long axis

9 mm spherical markers were used for these points, except for the hallux triad which consisted of 4 mm spheres.
[a] Markers which were not present in the original SHCG model.

Table A.2
Additional static marker locations used in the mSHCG model. These points are identified with small (4 mm) hemispherical markers, though virtual points collected with a pointer device may be used.

Marker	Segment: anatomical location	Critical alignment
MMAL	Shank: medial malleolus	Anterior/posterior
CALPT[a]	Hindfoot: peroneal trochlea	Superior/inferior Anterior/posterior, optional
MT23B	Forefoot: midpoint of bases of 2nd and 3rd metatarsals	Medial/lateral
MT23H	Forefoot: midpoint of heads of 2nd and 3rd metatarsals	Medial/lateral
MT1BM[a]	Forefoot: medial aspect of base of 1st metatarsal	Superior/inferior, optional
MT1HM[a]	Forefoot: medial aspect of head of 1st metatarsal	Superior/inferior, optional

[a] Markers which were not present in the original SHCG model.

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