10-2011

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

Jason T. Long
*Marquette University*

Mei Wang
*Marquette University*, mei.wang@marquette.edu

Gerald F. Harris
*Marquette University*, gerald.harris@marquette.edu

*Journal of Experimental & Clinical Medicine*, Vol. 3, No. 5 (October 2011): 239-244. DOI. 

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

Jason T. Long
Orthopedic and Rehabilitation Engineering Center, Marquette University/Medical College of Wisconsin, Milwaukee, WI
Department of Orthopedic Surgery, Medical College of Wisconsin, Milwaukee, WI
Department of Orthopaedic Surgery, Cincinnati Children's Hospital Medical Center, Cincinnati, OH
Mei Wang
Orthopedic and Rehabilitation Engineering Center, Marquette University/Medical College of Wisconsin, Milwaukee, WI
Department of Orthopedic Surgery, Medical College of Wisconsin, Milwaukee, WI
Gerald F. Harris
Orthopedic and Rehabilitation Engineering Center, Marquette University/Medical College of Wisconsin, Milwaukee, WI
Department of Orthopedic Surgery, Medical College of Wisconsin, Milwaukee, WI
Department of Biomedical Engineering, Marquette University, Milwaukee, WI

# Abstract

## 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.



# Key words

foot and ankle, kinematics, lower extremity, Milwaukee foot model


# 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, 6, 7]

While efficient in design and application, these models share a common shortcoming in their single-segment representation of 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, 9, 10, 11, 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, 22, 23, 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.

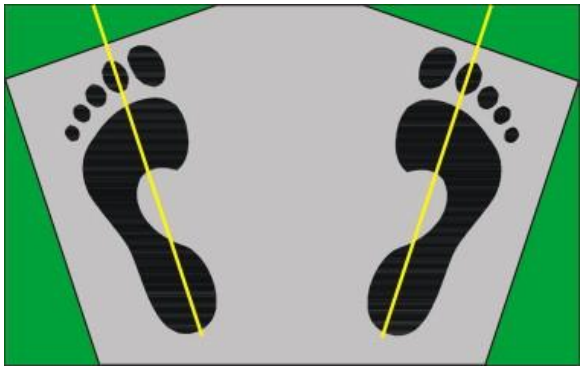

Figure 1. Schematic diagram of foot position template (FPT) used to replicate foot position between radiograph testing and motion analysis testing.

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. 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.

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 |

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).

Result sets from all three models (PIG, MFM, and NIM) were normalized to 0–100% of the gait cycle using a cubic spline interpolation implemented with the Matlab *interp1* function.

## 2.2. New integrated model

Previously described methods were used to establish the local reference system for the pelvis.[1, 2] The bias-compensated least squares solution[25, 26] was applied to the HJC calibration trials; once the HJC location was established, standard methods were also used to establish the local reference system for the thigh. For each of the multiple segments of the foot (tibia, hindfoot, forefoot, and hallux), two axis systems were created; marker-based axis system *M* was created based on motion analysis data, and bone-based axis system *B* was based on measurements of segment orientation taken from weightbearing radiographs.

While the original MFM used relative angle measurements and an iterative optimization approach for defining bone-based axis systems, the NIM approaches these calculations from a projection angle perspective. X-ray measurements were taken by referencing a segment's orientation to a particular global vector, thereby providing a measurement of global position when the participant is in a comfortable weightbearing position. Bone-based axis systems could then be constructed such that the projection of the system into the global planes would yield the offset angles measured from x-rays.

For each portion of the multisegmental foot, a relationship was assumed to exist between the marker-based axes $M_s$ and the bone-based axes $B_s$ in the static trial. This relationship was defined as the 3 × 3 transformation matrix *T* (Equation 1). The same relationship was assumed to exist between marker- and bone-based axes in the dynamic trials ($M_d$ and $B_d$, respectively; Equation 2). Given the positions of the anatomical markers affixed to the foot during dynamic trials, the orientations of bone-based axes could be determined at each data frame in the dynamic trial (Equation 3).

(1) $B_s = M_s \cdot T$

(2) $B_d = M_d \cdot T$

(3) $B_d = M_d \cdot M_s^{-1} \cdot B_s$

## 2.3. Data analysis

NIM measurements of pelvis orientation (relative to global), hip motion, and knee motion were compared to their PIG counterparts; NIM measurements of hindfoot, forefoot, and hallux motion were compared to their MFM counterparts using pointwise correlation and cross-correlation techniques. Pointwise correlation was performed to ascertain similarity in curve morphology, while cross-correlation analysis was performed primarily to ascertain the presence of time offsets.

For each participant, correlation between NIM and PIG/MFM output was calculated at each time point across all trials for each kinematic measure. Each correlation calculation was performed on a pointwise basis to compute Pearson's linear correlation coefficient (*r*) and a *p* value indicating whether the correlation was significantly nonzero. These evaluations were also performed on pooled data from all participants. The correlation analysis was implemented using the Matlab *corr* function.

Cross-correlation between NIM and PIG/MFM output was calculated across all time points for each measure within each trial. Cross-correlation was implemented using the Matlab *xcorr* function; output was normalized such that the point of maximum cross-correlation was set to 1.

A repeatability assessment was also performed using data from the subset of three participants who attended multiple testing sessions in the laboratory. Repeatability was assessed using the coefficient of multiple correlation (CMC) as described by Kadaba.[28]

# 3. Results

## 3.1. Cross-correlation

For the majority of measures, including all sagittal plane measures, the point of peak cross-correlation was found at $t = 0$. This suggests that there is no time delay between NIM and PIG/MFM, and that output can be compared on a point-by-point basis across time without concern for temporal shifts. While several measures had nonzero points of peak correlation, these were fairly low in magnitude and were noted in distal foot segments which seemed most affected by the different methods of referencing marker-based axis systems to bony orientations.

## 3.2. Pointwise correlation

Pooled correlation output from all participants is presented in Figure 2. At each time point *t*, the *r* value represents the correlation between NIM and PIG/MFM values across multiple trials. Vertically shaded regions of the plot indicate portions of the gait cycle where the correlation between NIM and PIG/MFM is significantly nonzero.

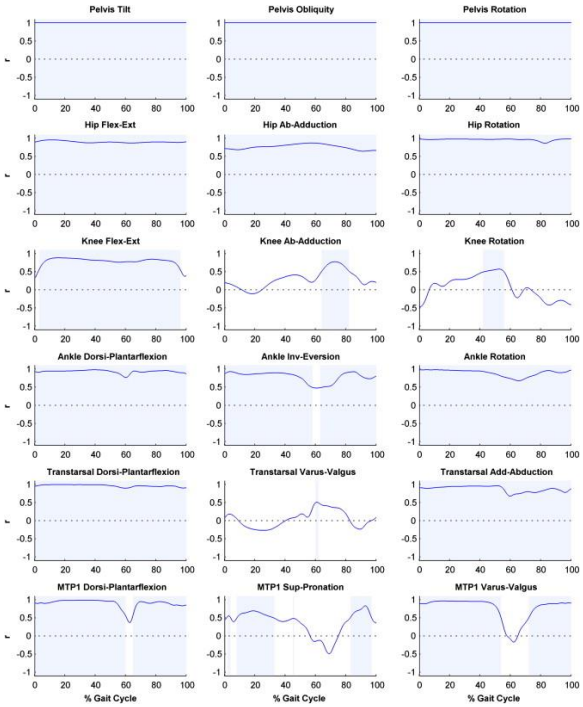


Figure 2. Pooled pointwise correlation results from all participants. Correlation coefficient *r* was calculated for each point in the data cycle between output from NIM and PIG/MFM. Data are plotted from 0% to 100% gait cycle; shaded regions indicate significant nonzero correlation.

High correlations are observed between NIM and PIG/MFM across the gait cycle for most segment/plane combinations. The major exceptions to this are at the knee in the coronal and transverse planes, and in the

coronal plane motion of the forefoot and hallux. Correlation values for knee measures are observed to demonstrate considerable fluctuation (−0.5 to 0.5) across the cycle, and these values are significant for only a small portion of the cycle in the coronal and transverse planes.

## 3.3. Repeatability assessment

Session-based CMC values are presented in Table 2[28] (intra-session values are available for all 10 participants; inter-session values are available for the three participants who made multiple visits to the lab). Inter-session values are presented for both raw data and data adjusted by removing the daily mean, following the method described by Kadaba.[28] Participant-based CMC values are presented in Table 3 [29, 30] for all 10 individuals. Each table includes previously reported comparison values; lower extremity values are those originally reported by Kadaba et al[28], while multisegmental foot values are those originally reported by Leardini et al[29] and Jenkyn and Nichol.[30] In nearly all cases, CMC values reported for this study meet or exceed the previously reported values.

Table 2. Intra-session CMC values calculated for 10 participants and inter-session CMC values calculated for three participants. Corresponding measures as reported by Kadaba et al[28] are provided for comparison. (Note that Kadaba's original measurements of ankle motion are listed here for comparison to hindfoot motion.) Unavailable comparison measures are indicated by a dash

| | | **Intra-session CMC** | | **Inter-session CMC** | | **Inter-session CMC (mean removed)** | |
|---|---|---|---|---|---|---|---|
| | | **Current** | **Kadaba 1989** | **Current** | **Kadaba 1989** | **Current** | **Kadaba 1989** |
| Pelvis | Sagittal | 0.7212 | 0.643 | 0.4971 | 0.240 | 0.7594 | 0.649 |
| | Coronal | 0.9808 | 0.956 | 0.9559 | 0.883 | 0.9626 | 0.943 |
| | Transverse | 0.9113 | 0.878 | 0.8818 | 0.768 | 0.8950 | 0.854 |
| Hip | Sagittal | 0.9972 | 0.994 | 0.9853 | 0.978 | 0.9941 | 0.994 |
| | Coronal | 0.9865 | 0.957 | 0.9645 | 0.882 | 0.9755 | 0.948 |
| | Transverse | 0.9665 | 0.893 | 0.7597 | 0.483 | 0.9169 | 0.841 |
| Knee | Sagittal | 0.9938 | 0.994 | 0.9850 | 0.985 | 0.9883 | 0.991 |
| | Coronal | 0.9791 | 0.962 | 0.8543 | 0.783 | 0.8931 | 0.858 |
| | Transverse | 0.9508 | 0.918 | 0.8103 | 0.534 | 0.9116 | 0.849 |
| Hindfoot | Sagittal | 0.9747 | 0.978 | 0.9155 | 0.933 | 0.9571 | 0.967 |
| | Coronal | 0.9417 | — | 0.8165 | — | 0.8927 | — |
| | Transverse | 0.7758 | 0.885 | 0.4589 | 0.612 | 0.6629 | 0.858 |
| Forefoot | Sagittal | 0.9472 | — | 0.8749 | — | 0.9115 | — |
| | Coronal | 0.9306 | | 0.7669 | | 0.8705 | |
| | Transverse | 0.9552 | | 0.7928 | | 0.9177 | |
| Hallux | Sagittal | 0.9732 | | 0.9378 | | 0.9505 | |
| | Coronal | 0.9290 | | 0.8445 | | 0.8952 | |
| | Transverse | 0.9599 | | 0.8736 | | 0.9471 | |

Table 3. Intra- and inter-participant CMC values calculated for 10 participants. Corresponding measures as reported by Leardini et al[29] and Jenkyn and Nichol[30] are provided for comparison. Unavailable comparison measures are indicated by a dash

| | | **Intra-participant CMC** | | | **Inter-participant CMC** | | |
|---|---|---|---|---|---|---|---|
| | | **Current** | **Leardini 1999** | **Jenkyn 2007** | **Current** | **Leardini 1999** | **Jenkyn 2007** |
| Pelvis | Sagittal | 0.7680 | — | — | 0.1296 | — | — |
| | Coronal | 0.9858 | | | 0.8509 | | |
| | Transverse | 0.9335 | | | 0.7464 | | |
| Hip | Sagittal | 0.9971 | — | — | 0.9142 | — | — |
| | Coronal | 0.9880 | | | 0.6675 | | |
| | Transverse | 0.9673 | | | 0.5643 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Knee | Sagittal | 0.9949 | — | — | 0.9453 | — | — |
| | Coronal | 0.9831 | | | 0.7048 | | |
| | Transverse | 0.9602 | | | 0.4243 | | |
| Hindfoot | Sagittal | 0.9796 | 0.91 | 0.92 | 0.6532 | 0.61 | 0.71 |
| | Coronal | 0.9457 | 0.85 | 0.71 | 0.4568 | 0.36 | 0.31 |
| | Transverse | 0.7919 | 0.76 | 0.58 | 0.1201 | 0.35 | 0.41 |
| Forefoot | Sagittal | 0.9567 | — | — | 0.4492 | — | — |
| | Coronal | 0.9415 | | 0.85 | 0.6042 | | 0.70 |
| | Transverse | 0.9621 | | — | 0.5214 | | — |
| Hallux | Sagittal | 0.9759 | 0.95 | — | 0.8124 | 0.65 | — |
| | Coronal | 0.9360 | 0.76 | | 0.5939 | 0.36 | |
| | Transverse | 0.9673 | 0.89 | | 0.6723 | 0.62 | |

# 4. Discussion

## 4.1. Correlation

Results of the correlation analysis demonstrate a high correlation between NIM and the standardized models. The majority of the kinematic measures demonstrated $r > 0.9$ for the entire gait cycle. The primary areas where these large magnitude and/or long duration correlations were not observed were at the hip (reduced magnitude in coronal plane), knee (coronal and transverse planes; reduced magnitude in sagittal plane), forefoot, and hallux (coronal plane).

Because NIM and PIG use identical means for establishing the pelvis reference system, similarities in pelvis kinematics were expected. Reduced correlations observed at the hip joint are largest in magnitude and most significant in the coronal plane; these agree with previous findings[9, 10, 12] which demonstrate that a functionally determined HJC falls lateral to an anthropometrically predicted HJC. The HJC is the proximal end of the thigh segment; when repositioned laterally from its predictively determined location, shifts toward hip adduction and knee valgus would be expected.

In comparing NIM to standardized models at the knee joint, it is important to note that the NIM knee represents the "crossover point" between PIG and MFM. In PIG, the knee is the articulation between two segments (thigh and shank) modeled with joint centers determined via anthropometric prediction. In MFM, the knee joint is not present; kinematics of the bone-based tibia segment are calculated relative to global. Therefore, there are no standardized measures to which NIM knee kinematics can be directly compared. Knee measures are complicated by changes at both the proximal and distal segments. At the proximal segment, the lateral shift imposed on HJC location leads to measures of increased knee valgus. At the distal segment, increased external rotation is observed and attributed to the bone-based referencing methods employed for the NIM tibia, as dependence of the bone-based matrix on the orientation of the bimalleolar axis generally imposes a more externally rotated position on it.

Reduced correlations in the forefoot and hallux probably stem from differences in radiographic referencing methods between MFM and NIM. MFM does not incorporate any measurements of forefoot or hallux rotation about the longitudinal axis; its relative referencing methods result in a forefoot segment which is not rotated about its long axis relative to the hindfoot segment, and a hallux which is similarly aligned with the forefoot segment. NIM also uses zero values for these measures, but its global referencing methods create segments which have zero rotation about their long axes.

## 4.2. Repeatability

Measures of repeatability showed good agreement with values previously established as clinical standards.[28, 31] The lowest within-session values were measured at the pelvis in the sagittal plane (pelvic tilt) and at the hindfoot in the transverse plane (internal/external rotation). The variability in pelvic motion agrees with previous findings by Kadaba[28], while variability in hindfoot motion corresponds to measurements of variability in transverse plane ankle motion by Kadaba. Kadaba attributed the relatively poor repeatability of pelvic tilt to a combination of a small range of motion and the measurement of pelvic position to the global reference frame. Data in the current study may be affected by similar factors, as the average sagittal plane pelvic range of motion for the three participants ($3.06 \pm 0.88°$) was similar to that reported by Kadaba. Several within-session measures also demonstrated values much higher than those previously reported; in particular, transverse plane hip motion (internal/external rotation) demonstrated a within-session CMC (0.9665) value 6% better than that originally reported by Kadaba (0.893).

Between-session CMC values showed similar trends to within-session CMC values, with the lowest repeatability again observed in pelvic tilt and hindfoot rotation. Several other measures demonstrated large decreases from

their within-session levels, again mimicking the trend described by Kadaba. However, most measures were similar to or higher than measures from previous studies; in particular, the measure of hip motion in the coronal plane (abduction/adduction; 0.9645 raw, 0.9755 adjusted) was higher than that reported by Kadaba (0.882 raw, 0.948 adjusted). This improved repeatability may reflect an advantage of using a functionally determined HJC, as the location of the HJC is determined independent from the accuracy of anatomical marker location, minimizing the effect of error in marker reapplication between sessions.

Similar trends were observed in measures of participant-based measures of repeatability. Intra-participant measures exceeded 0.9 for 16 of 18 segment/plane couplets, meeting or exceeding values published for similar segments by Leardini et al[29] and Jenkyn et al.[30] Inter-participant measures demonstrated a substantial decrease from intra-participant measures for most segment/plane couplets, which also agrees with findings from previous investigators. Recent work by our group suggests that the majority of variability associated with a radiograph-based multisegment foot model is due to inter-participant differences (Long et al, unpublished data); these findings appear to be borne out by the results presented in this study.

Overall, measures of repeatability from most segment/plane couplets are similar to or greater than previously established values. This suggests that the NIM is well-suited for clinical application. To our knowledge, this represents the first incorporation of a multisegmental foot model utilizing bony referencing methods into a model of the more proximal lower extremities. Results of statistical analyses confirm that the new model is highly correlated with standardized model output, and its within- and between-session repeatability equals or exceeds the current clinical standard. While the new model demonstrates differences from standardized models in a number of areas, these differences are accounted for by differences between segment axis systems and referencing methods. The model appears well-suited for routine application in both the clinical and research environments; its output may require some modification and streamlining to accommodate regular clinical use.

## Acknowledgments

This work was supported in part by a grant from the Department of Education, NIDRR grant number H133E100007. However, the contents do not necessarily represent the policy of the Department of Education, and you should not assume endorsement by the Federal Government. Pilot study resources were provided by an intramural grant from the Department of Orthopedic Surgery at the Medical College of Wisconsin.

## References

1 R.B. Davis 3rd, S. Ounpuu, D. Tyburski, J.R. Gage. **A gait analysis data collection and reduction technique.** *Hum Mov Sci*, 10 (1991), pp. 575-587

2 M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten. **Measurement of lower extremity kinematics during level walking.** *J Orthop Res*, 8 (1990), pp. 383-392

3 A. Cappozzo, F. Catani, U. Della Croce, A. Leardini. **Position and orientation in space of bones during movement: anatomical frame definition and determination.** *Clin Biomech*, 10 (1995), pp. 171-178

4 I.W. Charlton, P. Tate, P. Smyth, L. Roren. **Repeatability of an optimised lower body model.** *Gait Posture*, 20 (2004), pp. 213-221

5 J.P. Holden, S.J. Stanhope. **The effect of variation in knee center location estimates on net knee joint moments.** *Gait Posture*, 7 (1998), pp. 1-6

6 R. Stagni, A. Leardini, A. Cappozzo, M. Grazia Benedetti, A. Cappello. **Effects of hip joint centre mislocation on gait analysis results.** *J Biomech*, 33 (2000), pp. 1479-1487

7 G. Gorton, D. Hebert, B. Goode. **Assessment of the kinematic variability between twelve Shriners motion analysis laboratories.** *Gait Posture*, 13 (2001), p. 247

8 V. Camomilla, A. Cereatti, G. Vannozzi, A. Cappozzo. **An optimized protocol for hip joint centre determination using the functional method.** *J Biomech*, 39 (2006), pp. 1096-1106
9 J.L. Hicks, J.G. Richards. **Clinical applicability of using spherical fitting to find hip joint centers.** *Gait Posture*, 22 (2005), pp. 138-145
10 A. Leardini, A. Cappozzo, F. Catani, S. Toksvig-Larsen, A. Petitto, V. Sforza, G. Cassanelli, *et al.* **Validation of a functional method for the estimation of hip joint centre location.** *J Biomech*, 32 (1999), pp. 99-103
11 S.J. Piazza, A. Erdemir, N. Okita, P.R. Cavanagh. **Assessment of the functional method of hip joint center location subject to reduced range of hip motion.** *J Biomech*, 37 (2004), pp. 349-356
12 S.J. Piazza, N. Okita, P.R. Cavanagh. **Accuracy of the functional method of hip joint center location: effects of limited motion and varied implementation.** *J Biomech*, 34 (2001), pp. 967-973
13 B.A. MacWilliams, M. Cowley, D.E. Nicholson. **Foot kinematics and kinetics during adolescent gait.** *Gait Posture*, 17 (2003), pp. 214-224
14 S.I. Ringleb, S.J. Kavros, B.R. Kotajarvi, D.K. Hansen, H.B. Kitaoka, K.R. Kaufman. **Changes in gait associated with acute stage II posterior tibial tendon dysfunction.** *Gait Posture*, 25 (2007), pp. 555-564
15 J. Tome, D.A. Nawoczenski, A. Flemister, J. Houck. **Comparison of foot kinematics between subjects with posterior tibialis tendon dysfunction and healthy controls.** *J Orthop Sports Phys Ther*, 36 (2006), pp. 635-644
16 M.C. Carson, M.E. Harrington, N. Thompson, J.J. O'Connor, T.N. Theologis. **Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis.** *J Biomech*, 34 (2001), pp. 1299-1307
17 J. Woodburn, P.S. Helliwell, S. Barker. **Three-dimensional kinematics at the ankle joint complex in rheumatoid arthritis patients with painful valgus deformity of the rearfoot.** *Rheumatology (Oxford),* 41 (2002), pp. 1406-1412
18 J. Simon, L. Doederlein, A.S. McIntosh, D. Metaxiotis, H.G. Bock, S.I. Wolf. **The Heidelberg foot measurement method: development, description and assessment.** *Gait Posture*, 23 (2006), pp. 411-424
19 S.M. Kidder, F.S. Abuzzahab Jr., G.F. Harris, J.E. Johnson. **A system for the analysis of foot and ankle kinematics during gait.** *IEEE Trans Rehabil Eng*, 4 (1996), pp. 25-32
20 K.A. Myers, M. Wang, R.M. Marks, G.F. Harris. **Validation of a mutlisegment foot and ankle kinematic model for pediatric gait.** *IEEE TSNRE*, 12 (2004), pp. 122-130
21 M. Khazzam, J.T. Long, R.M. Marks, G.F. Harris. **Preoperative gait characterization of patients with ankle arthrosis.** *Gait Posture*, 24 (2006), pp. 85-93
22 M. Khazzam, J.T. Long, R.M. Marks, G.F. Harris. **Kinematic changes of the foot and ankle in patients with systemic rheumatoid arthritis and forefoot deformity.** *J Orthop Res*, 25 (2007), pp. 319-329
23 K. Canseco, J. Long, R. Marks, M. Khazzam, G. Harris. **Quantitative motion analysis in patients with hallux rigidus before and after cheilectomy.** *J Orthopaed Res*, 27 (2009), pp. 128-134
24 M.E. Ness, J. Long, R. Marks, G. Harris. **Foot and ankle kinematics in patients with posterior tibial tendon dysfunction.** *Gait Posture*, 27 (2008), pp. 331-339
25 S.S.H.U. Gamage, J. Lasenby. **New least squares solutions for estimating the average centre of rotation and the axis of rotation.** *J Biomech*, 35 (2002), pp. 87-93
26 K. Halvorsen. **Bias compensated least squares estimate of the center of rotation.** *J Biomech*, 36 (2003), pp. 999-1008
27 A.G. Schache, R. Baker, L.W. Lamoreux, A.G. Schache, R. Baker, L.W. Lamoreux. **Defining the knee joint flexion-extension axis for purposes of quantitative gait analysis: an evaluation of methods.** *Gait Posture*, 24 (2006), pp. 100-109
28 M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten, J. Gainey, G. Gorton, G.V. Cochran. **Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait.** *J Orthopaed Res*, 7 (1989), pp. 849-860
29 A. Leardini, M.G. Benedetti, F. Catani, L. Simoncini, S. Giannini. **An anatomically based protocol for the description of foot segment kinematics during gait.** *Clin Biomech*, 14 (1999), pp. 528-536

30 T.R. Jenkyn, A.C. Nicol, T.R. Jenkyn, A.C. Nicol. **A multi-segment kinematic model of the foot with a novel definition of forefoot motion for use in clinical gait analysis during walking.** *J Biomech*, 40 (2007), pp. 3271-3278

31 T.F. Besier, D.L. Sturnieks, J.A. Alderson, D.G. Lloyd. **Repeatability of gait data using a functional hip joint centre and a mean helical knee axis.** *J Biomech*, 36 (2003), pp. 1159-1168