2014

Multi-segment Foot Kinematics in Young Adults: A Preliminary Study Comparing Two Biomechanical Gait Models

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Abstract: Multi-segment biomechanical foot models are commonly used to track foot kinematics during motion analysis, but due to the complexity of foot mechanics there is a lack of technical uniformity in existing foot models. Two of the most commonly used multi-segment models are the Oxford and Leardini foot models. The purpose of this study was to compare selected foot kinematics collected using these models. Five participants (mean age = 24 (±2) yrs; height = 173.2 (±12.1) cm; mass = 74.4 (±17.6) kg) volunteered for the study and marker placement models were applied consecutively in the same session. Five gait trials with right foot contact on an AMTI force plate and five gait trials with left foot contact on a force plate were collected with each subject, for both models. The three most representative gait cycles were selected for analysis. Spatial-temporal values for both models were highly repeatable, as well as sagittal and frontal plane rotations of the hindfoot relative to tibia. Transverse plane rotation of the hindfoot relative to tibia and frontal and transverse plane rotations of the forefoot relative to hindfoot have generally repeatable patterns with small deviations between models, likely due to a difference in segment definitions. Foot kinematics using both the Oxford Foot and a modified Leardini model are in good agreement with previously published studies. The findings of this study indicate varied agreement between these two models, but further research is needed.

1. Introduction

Stereophotogrammetry is widely used in clinical motional analysis settings for the evaluation and treatment of foot pathologies. Clinical problems such as clubfoot [1,2], rheumatoid arthritis [3-6], or posterior tibial tendon dysfunction [7-11] are often evaluated using this method. Previously, the kinematics of the ankle and foot had been evaluated using biomechanical models that identified the foot as a single rigid body, using only one marker on the foot and one on the ankle [12-16]. Limitations of this method include the inability to evaluate frontal and transverse plane motion and un-identification of multiple foot joints (e.g. hindfoot, midfoot, forefoot). Because of these limitations, there has been an effort in the past decade to use a multi-segment foot model [17-19], which accounts for the movement of multiple joints within the foot.

Many multi-segment foot models have been proposed and found to be reliable [20-24], but vary in number of segments and placement of markers. One model defined as many as nine segments in the foot [24], but most models have used only three or four segments [18,19,22,25-28]. Overall, there is a lack of technical uniformity in the multi-segment foot models and a standard model has yet to be identified. The use of intracortical bone pins has been identified as the 'gold standard' for tracking joint movement because of the elimination of skin motion artefact, but because this method is invasive, its clinical use is limited [29,30]. This has resulted in the development and wide use of skin-mounted passive marker methods.

Two models that have been used fairly widely are the Oxford Foot model (OFM) [28] and the Leardini model (LM) [18]. Previous studies have described the reliability of the OFM in both adult and pediatric populations [22,28,31] and the external validity in pediatric populations [32]. The OFM has been used to evaluate joint movement in many clinical populations, including rheumatoid arthritis [4-6], clubfoot [2],

hemiplegic cerebral palsy [33], patellofemoral pain syndrome [34-36], and others. Reliability of the LM has been established, and this marker set has also been used in clinical populations such as talocalcaneal coalition [37], calcaneal fractures [38], ankle replacement [39], and tibiocalcaneal fusion to total ankle arthroplasty [40].

In this study, the OFM and a modified Leardini foot model (MLM), both consisting of three foot segments, were compared in normal, healthy, college-aged adults. The purpose of this study was to compare selected foot kinematics in the OFM and MLM. The authors intended to further examine the consistency of these marker sets and to assess the similarities and differences in foot kinematics between the two models.

2. Methods

2.1 Subjects

Volunteers were recruited from the student population at Grand Valley State University. Two female and three male subjects between the ages of 21 and 26, average age 24 ± 2 years, were tested. Participants were screened and excluded if they possessed any of the following: significant medical condition (e.g. uncontrolled high blood pressure, unstable heart disease, respiratory disease, or neurological condition such as multiple sclerosis that would preclude sustained walking), significant orthopaedic injury to the lower extremities within the past six months, or reconstructive surgery (e.g. ACL reconstruction) to joint(s) of the lower extremity. All five subjects who volunteered were included in the study.

2.2 Oxford Foot model

The OFM defined by Stebbins et al. [28] combined with the fully body Plug in Gait [41] was utilized in this study (Table 1). The Plug in Gait marker set defines trunk and leg segments, while the OFM defines the three segments of the foot.

Table 1

Positions and segment definitions of markers for OFM

Marker name	Position	Segment
KNE	Lateral femoral condyle	Femur
MKNE*	Medial femoral condyle	Femur
TUB	Tibial tuberosity	Tibia
HFB	Head of fibular	Tibia
ANK	Lateral malleolus	Tibia
MMA*	Medial malleolus	Tibia
SHN	Anterior aspect of mid-shank	Tibia
HEE	Posterior distal aspect of heel	Hindfoot
PCA*	Posterior calcaneus proximal	Hindfoot
CPG	Wand marker on posterior calcaneus	Hindfoot
STL	Sustentaculum tali	Hindfoot
LCA	Lateral calcaneus	Hindfoot

P1M	Base of first metatarsal	Forefoot
P5M	Base of fifth metatarsal	Forefoot
D1M*	Head of first metatarsal	Forefoot
D5M	Head of fifth metatarsal	Forefoot
TOE	Between second and third metatarsal heads	Forefoot
HLX	Base of hallux	Hallux

*Used in static trial only

2.3 Modified Leardini model

The second marker set used in this study was a MLM (Table 2) in combination with a full body marker set developed by the Mary Free Bed Motion Analysis Center. The Leardini model was modified by minimal alteration of the placement of PT and ST markers. In prior studies (personal communication with the Mary Free Bed Motion Analysis Center) it was determined that as long as ST and PT markers were equidistant from the heel marker, the precise location of the bony landmarks were not critical. The reasoning behind this modification was the difficulty in palpating PT and ST anatomical landmarks and maintaining consistency in marker placement.

Table 2

Positions and segment definitions of markers for MLM

Marker name	Position	Segment
KNE	Lateral femoral condyle	Femur
MCD*	Medial femoral condyle	Femur
TUB	Tibial tuberosity	Shank
HFB	Head of fibular	Shank
SHN	Crest of distal tibia	Shank
LML	Lateral malleolus	Shank
MML*	Medial malleolus	Shank
CA	Upper central ridge of posterior calcaneus	Calcaneus
PT	Peroneal tubercle	Calcaneus
ST	Sustentaculum tali	Calcaneus
TN	Navicular tuberosity	Midfoot
FMB	Base of first metatarsal	Metatarsus
FMH	Head of first metatarsal	Forefoot
SMB	Base of second metatarsal	Forefoot and Midfoot
SMH	Head of second metatarsal	Forefoot
VMB	Base of fifth metatarsal	Metatarsus
VMH	Head of fifth metatarsal	Forefoot

*Used in static trial only

2.4 Anatomical reference frames

Technical and anatomical reference frames for each model were defined as in the original Stebbins et al. [28] and Leardini et al. [18] studies.

2.5 Instrumentation

Nine and fourteen mm diameter reflective markers were placed on the surface of the body. A full body marker set was used for both models. Eight MX-T40 cameras and Nexus motion capture software (120 Hz, Vicon Motion System Ltd., Oxford Metrics, UK) were used to track 3D marker trajectories through stance and swing phases of walking. Gaps (less than 15 frames) in marker trajectories were automatically filled using a Woltring, third-order spline interpolating function. Raw kinematic data were filtered using a Woltring filter and error prediction value (MSE) of 15 [42-44]. Two force plates (1200 Hz, Advanced Mechanical Technology Inc., Watertown, MA) were used to collect ground reaction force data. Gait events and parameters were automatically detected based on clean force plate strikes using Vicon Nexus software. The camera configuration and calibration procedure was the same as that used for a full body gait analysis. Vicon BodyBuilder software was used to determine three-dimensional joint angles, moments and powers, as well as gait events and ground reaction forces.

2.6 Experimental procedure

This study was approved by the Institutional Review Board at Grand Valley State University and informed consent was obtained from participants prior to data collection. Participants underwent a physical screen which was used to include or exclude them from the study. In general, the screen included postural alignment, lower extremity strength, and measures of femoral and tibial torsion. Additional measures included ankle and knee width, leg length, foot progression angle, weight-bearing and non-weight-bearing ankle/foot position, hip range of motion, genu valgus/varus, and pelvic width, height and depth. All subjects were barefoot, and either the Oxford Foot [28] marker set with Plug In Gait [41] or the modified Leardini [18] with the Mary Free Bed biomechanical gait model was applied to the entire body. Markers were attached to the skin using a double-sided tape by a single examiner with experience in gait analysis. Nine mm diameter markers were used on the foot and ankle, and markers located on the shank and above were fourteen mm diameter. A static trial with the subject standing in an anatomical position with the knees in 5-10 degrees of flexion, facing two of the cameras, was collected. Markers only utilized in the static trial (noted in Tables 1 and 2) were then removed. Subjects then practiced walking through the capture area at a self-selected pace in order to settle into their normal gait. Once data collection began, the subject walked across a 10m walkway. Five trials of right foot contact with a force plate and five trials of left foot contact with a force plate were collected. Kinematic and kinetic data were simultaneously collected. After all necessary data were collected, the first marker model was removed and the second marker model was applied. Static and dynamic trials, as described above, were repeated. Selection of which marker set model to use first was random.

2.7 Data analysis

Only gait cycles with clean force plate strikes were included in the study. Of the five clean strikes for both the left and right feet of each subject, the three most representative cycles for each side were selected.

Gait cycles were considered representative if they were consistent within the subject and followed the general trends of previously published data [18,28]. Gait cycles for the right and left feet were combined and average foot kinematics computed across all five subjects. Descriptive statistics (mean and standard deviation) were used to describe sample and selected kinematic variables. These mean values were chosen to best represent the motion of the foot in each phase of stance. There were limitations in this method due to the classification of a dynamic motion into a static average. Visual differences in kinematic and spaciotemporal variables were noted between the two gait models.

3. Results

Selected variables of mean foot kinematics for all five subjects were compared between models. Spaciotemporal parameters between the two models were nearly identical (Table 3). Both models expressed small standard deviation values, meaning that spaciotemporal values were consistent across subjects.

Table 3

Physical and spaciotemporal gait characteristics of participants

	OFM Mean (SD)	MLM Mean (SD)
Physical characteristics		
Age (years)	24 (2)	-
Gender (M:F)	3:2	-
Height (cm)	173.2 (12.1)	-
Mass (kg)	74.4 (17.6)	-
BMI (kg/m^2)	24.4 (2.6)	-
Spaciotemporal parameters		
Cadence (steps/min)	116 (8.3)	114 (8.0)
Foot Off (% GC)	61.4 (1.35)	61.0 (1.84)
Single Support (s)	0.40 (0.02)	0.41 (0.02)
Double Support (s)	0.24 (0.04)	0.24 (0.05)
Step Length (m)	0.65 (0.04)	0.64 (0.05)
Stride Length (m)	1.28 (0.06)	1.27 (0.09)
Walking Speed (m/s)	1.24 (0.07)	1.24 (0.09)

Motion of the hindfoot relative to tibia was similar between both models (Table 4). The MLM showed approximately 6 degrees greater plantarflexion during pre-swing in the sagittal plane, but the general pattern in this rotation was nearly identical between models (Figs. 1 and 2). In the frontal plane, the models were similar except for a slightly greater eversion during mid-stance in the MLM. The main difference between the two models in the hindfoot relative to tibia appeared in the transverse plane, where the MLM showed abduction during all of stance phase and the OFM showed internal rotation (analogous to adduction) during all of stance phase.

Forefoot relative to hindfoot motion was not as consistent between the two models (Table 5). In the frontal plane, the OFM reported mild pronation at the end of loading response and beginning of mid-stance, whereas the MLM showed only inversion (similar to supination) throughout all of stance. The inversion reported from the MLM was greater than the supination of the OFM through the entire gait cycle. Both models displayed a reduction in supination/inversion during terminal stance. The transverse plane showed only abduction for both models, but the MLM showed 6-8 degrees more abduction than the OFM. During pre-swing, the OFM displayed a decrease in abduction while the MLM displayed an increase in abduction.

Table 4

Kinematics of hindfoot relative to tibia for OFM and MLM represented as mean (standard deviation)

Rotation	Initial contact		Loading response		Mid stance		Terminal stance		Pre-swing	
	OFM	MLM	OFM	MLM	OFM	MLM	OFM	MLM	OFM	MLM
DF(+)/PF(-)	5.3 (2.0)	0.3 (3.5)	-2.0 (3.0)	-5.2 (5.0)	9.6 (1.8)	6.9 (5.0)	11.6 (1.9)	10.0 (4.7)	-4.9 (4.2)	-11.3 (8.2)
Inv(+)/Ev(-)	3.8 (5.2)	3.0 (2.8)	0.4 (4.2)	-1.0 (5.2)	-1.1 (4.8)	-3.3 (6.2)	3.2 (5.3)	1.7 (4.2)	6.7 (4.7)	4.6 (5.8)
Int(+)/Ext(-)	12.3 (5.7)	*10.8 (4.8)	4.3 (4.9)	*8.4 (3.8)	10.2 (6.2)	*10.0 (3.6)	14.7 (6.7)	*9.5 (4.8)	4.2 (4.5)	*13.1 (6.5)

*Rotation defined as Abd(+)/Add(-)

Table 5

Kinematics of forefoot relative to hindfoot for OFM and MLM represented as mean (standard deviation)

Rotation	Initial contact		Loading response		Mid stance		Terminal stance		Pre-swing	
	OFM	MLM	OFM	MLM	OFM	MLM	OFM	MLM	OFM	MLM
DF(+)/PF(-)	-7.9 (1.8)		-4.0 (1.3)		-0.9 (2.5)		3.4 (3.6)		-13.2 (4.3)	
Sup(+)/Pron(-)	3.7 (4.7)	*10.9 (8.2)	-0.7 (5.8)	*12.1 (8.5)	0.5 (5.5)	*10.9 (7.5)	4.1 (5.0)	*11.6 (7.3)	0.0 (5.0)	*2.8 (7.3)
Add(+)/Abd(-)	-4.8 (5.8)	**11.1 (5.7)	-6.4 (5.0)	**9.0 (7.0)	-6.9 (5.0)	**10.4 (6.4)	-6.8 (5.4)	**10.0 (5.9)	-0.9 (4.7)	**12.9 (7.0)

*Rotation defined as Inv(+)/Ev(-)

** Rotation defined as Abd(+)/Add(-)

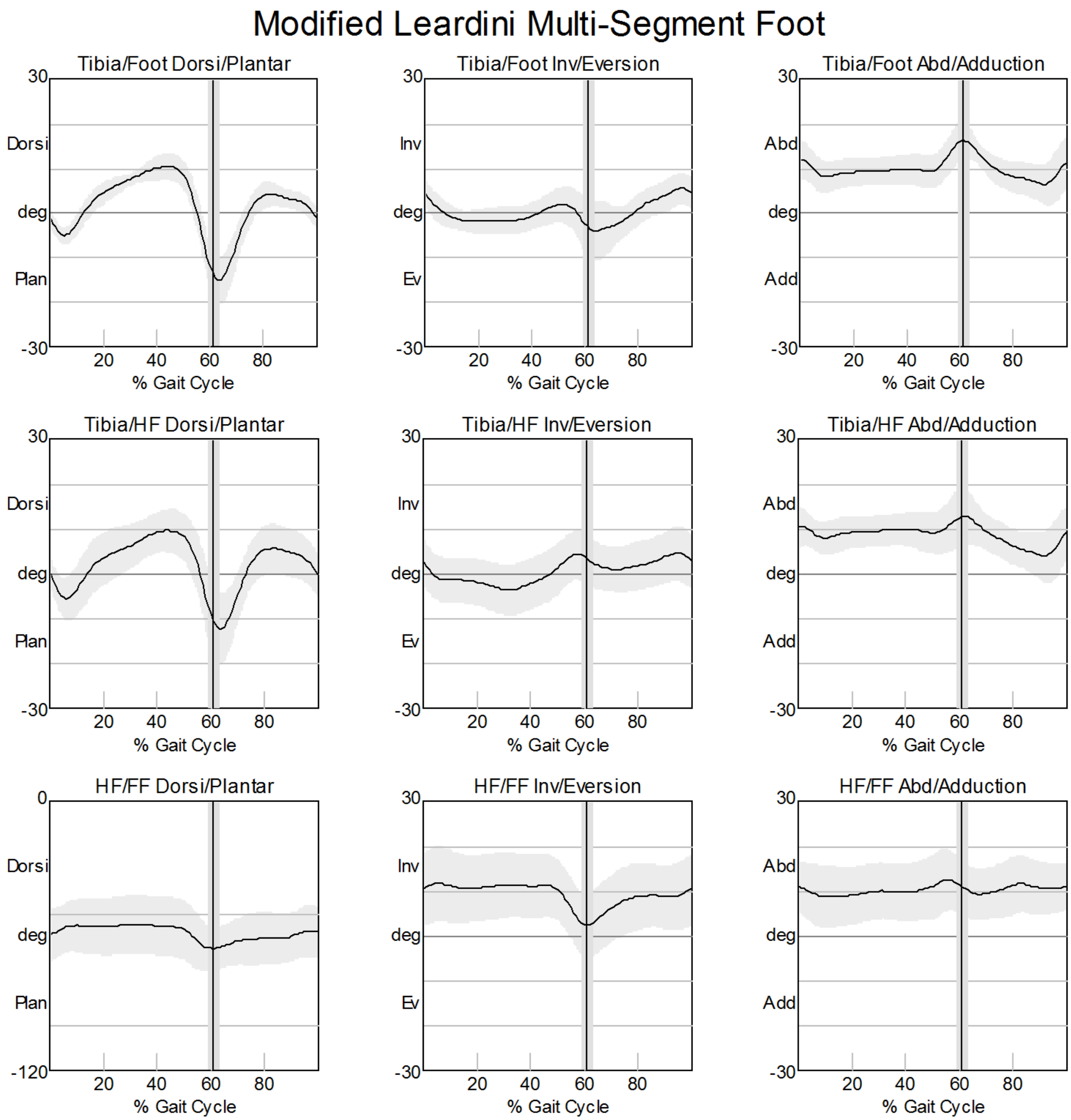

Fig. 1. Inter-segment foot angles from 5 healthy, college-aged adults using the MLM, normalized to 100% of the gait cycle. Shaded band shows mean ± 1 standard deviation across all subjects. First column defines sagittal plane rotation, second column defines frontal plane rotation, and third column defines transverse plane rotation, with each row depicting the different segment relationships.

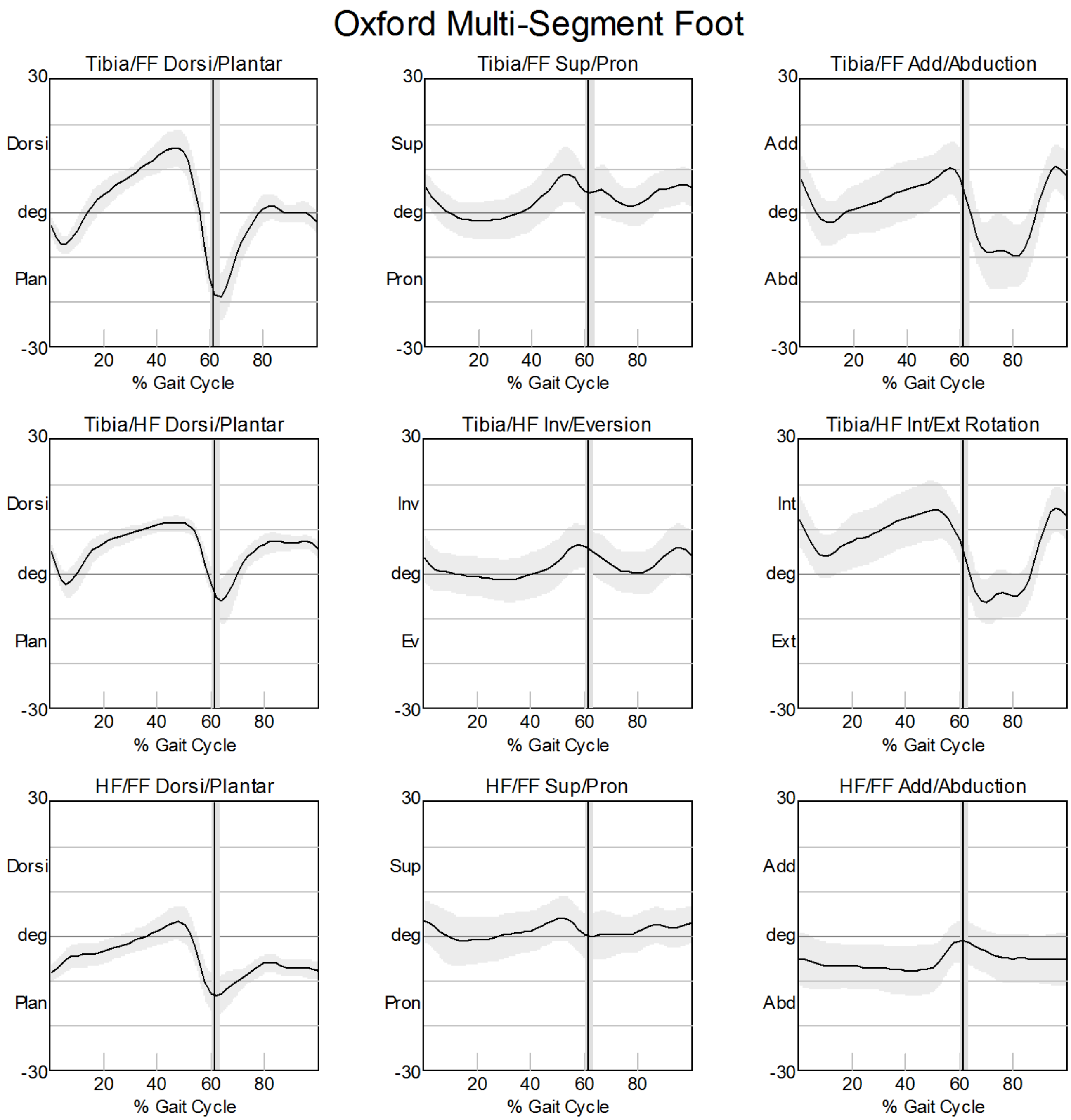

Fig. 2. Inter-segment foot angles from 5 healthy, college-aged adults using the OFM, normalized to 100% of the gait cycle. Shaded band shows mean ± 1 standard deviation across all subjects. First column defines sagittal plane rotation, second column defines frontal plane rotation, and third column defines transverse plane rotation, with each row depicting the different segment relationships.

4. Discussion

This study compared two multi-segmental foot models for healthy, college-aged adults in order to examine the consistency of the OFM and a MLM. A single examiner consecutively applied both markers sets to each participant, eliminating inter-tester reliability and inter-session reliability variables. The findings indicate spaciotemporal values between the two models are very consistent as well as kinematics in the hindfoot relative to the tibia. Kinematics of the forefoot relative to the hindfoot showed generally similar trends with a few slight dissimilarities. The foot relative to tibia angles from the MLM and forefoot relative to tibia angles from the OFM were not able to be compared because of differences in segment definition. The MLM compares both the midfoot and hindfoot motion to motion of the tibia, whereas the OFM compares motion of the forefoot to motion of the tibia. These graphs are displayed to illustrate differences in motion between the two definitions (Figs. 1 and 2).

Sagittal and frontal plane rotations of the hindfoot relative to tibia as well as spaciotemporal parameters are most repeatable between the two models tested. Transverse plane rotation of the hindfoot relative to tibia and frontal and transverse plane rotations of the forefoot relative to hindfoot have generally repeatable patterns with small deviations between models. These similarities and differences are likely due to the variation in forefoot and hindfoot segment definitions. Marker placement on the shank and hindfoot are similar between models, with the OFM using two additional hindfoot markers. Marker placement on the forefoot, however, differs between models because of the addition of a midfoot in the MLM. In the OFM, the P1M and P5M markers assist in defining the forefoot, while these same markers (FMB and VMB) in the MLM assist in defining the midfoot. Therefore, forefoot relative to hindfoot rotations showed minor variances.

During the stance phase, hindfoot relative to tibia rotations of the MLM are in good agreement with calcaneus relative to shank kinematics previously published using the LM on healthy young adults [45]. The general pattern of sagittal plane motion is nearly identical between the two reports, but the mean band from the results using the MLM shows a 3-5 degree offset in comparison to using the LM. In the frontal plane, both the pattern and magnitude of hindfoot motion is in agreement between the two models. In the transverse plane, the main difference between the two models occurs during the beginning and end of stance phase. During loading response and pre-swing the LM model shows the hindfoot in adduction, while the MLM model shows the hindfood in abduction. There is also a 5 degree offset in abduction between the two models, which may be due to marker placement. Results of the hindfoot relative to tibia rotations using the MLM are also consistent with the original Leardini publications using young adult populations [18,20]. Offsets in magnitude are the only main differences between these reports, with the most significant being a 10 degree offset in the transverse plane between the MLM and both LMs [18,20]. Forefoot relative to hindfoot rotations of the MLM are also very consistent with LM results other than a 5 degree offset for both the frontal and transverse planes [18].

Results from the OFM model are in good agreement with previously published data using this marker model on children [28,46]. No published normative data on young adults using the OFM exists, but as a child’s foot is developmentally similar to an adult’s by ages three and a half to seven [48], these populations can still be compared with the young adults participating in the current study. Future studies should focus on establishing a normal database of foot kinematics on healthy adults using the OFM. In one previously

published study [46], the general patterns of all hindfoot relative to tibia and forefoot relative to hindfoot motions are consistent with the results of the current study, but only the sagittal plane of the hindfoot relative to tibia matches our results numerically. The other five graphs have between a 5 and 15 degree offset between the two studies. The most significant difference in these five graphs occurs in the transverse plane of forefoot/hindfoot rotations where a 10 degree offset results in full adduction of the forefoot during the entire gait cycle [46]. Compared to another study on children [28], the results of this study agree both in patterns and magnitude in all but one rotation. The results of the current study indicate a greater increase in internal rotation of the hindfoot relative to tibia during mid-stance than what was shown in previously published results [28]. A greater decrease in internal rotation during terminal stance follows this motion in the current study.

Although the results of the current study are generally agreeable with previous research, some limitations exist. First, the small sample size limits the generalizability of results and prevents the use of statistical analyses, and future research should focus on expanding this normal population. Second, the presence of skin motion artefact may have produced some variability in results, although it has been found that artefact at the foot is less than that at the shank and thigh [47]. Third, the recruitment of participants for this study may have produced a biased population and again limited the generalizability of results, as it consisted of only college students at Grand Valley State University.

In conclusion, the findings of this study indicate that the sagittal and frontal plane rotations of the hindfoot relative to tibia are most comparable between the OFM and a MLM. The transverse plane rotation of the hindfoot relative to tibia and the frontal plane rotation of the forefoot relative to hindfoot show some similarities with mild differences in either pattern or magnitude. The transverse plane rotation of the forefoot relative to hindfoot is the least repeatable between the two models. Both models are in general agreement with previously existing research, but additional research is needed to further determine consistency between the OFM and MLM.

Acknowledgements:

Gordon Alderink, P.T., Ph.D., project advisor.
Amy Lenz, M.S., Engineer at Mary Free Bed Motion Analysis Center, technical advisor.

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