Other Foot Models

Multi_Segment Foot Models Reviews

References for other Multi-Segment Foot Models

Bishop C, Paul G, Thewlis D. (2012) "Recommendations for the reporting of foot and ankle models."
J Biomech. 2012 Aug 31;45(13):2185-94.
Multiple marker sets and models are currently available for assessing foot and ankle kinematics in gait. Despite the presence of such a wide variety of models, the reporting of methodological designs remains inconsistent and lacks clearly defined standards. This review highlights the variability found when reporting biomechanical model parameters, methodological design, and model reliability. Further, the review clearly demonstrates the need for a consensus of what methodological considerations to report in manuscripts, which focus on the topic of foot and ankle biomechanics. We propose five minimum reporting standards, that we believe will ensure the transparency of methods and begin to allow the community to move towards standard modelling practice. The strict adherence to these standards should ultimately improve the interpretation and clinical useability of foot and ankle marker sets and their corresponding models.

Rankine L1, Long J, Canseco K, Harris GF. (2008) "Multisegmental foot modeling: a review."
Crit Rev Biomed Eng. 2008;36(2-3):127-81.
Over the past two decades, a number of multisegmental foot models have been developed in order to characterize foot kinematics. This paper reviews methods of multisegmental foot modeling, technical elements of the models, select clinical applications of the models, and future directions in this area of research. Technical areas discussed include angular derotation mechanisms and capture technology. Models discussed address two-, three-, four-, five-, and nine-segment approaches. Additional models which address foot segments using other definitions, are also discussed. Clinical applications of multisegmental foot models include pathologic gait characterization in rheumatoid arthritis, posterior tibial tendon dysfunction, and hallux rigidus. Areas of continued development, including soft tissue artifact and nomenclature, are also discussed.

Oxford Foot Model

Stebbins J, Harrington M, Thompson N, Zavatsky A, Theologis T. (2006) "Repeatability of a model for measuring multi-segment foot kinematics in children."
Gait Posture. 2006 Jun;23(4):401-10.
This study used a previously tested foot model and adapted it for use with children. A number of variations on this adapted model were implemented and tested for repeatability and accuracy on 15 healthy children on three occasions. These included redefinition of the long axes of the tibia and forefoot, assessment of the flexibility of the forefoot and evaluation of the variability of the wand marker on the heel for both static and dynamic trials. It was found that variations on the model produced only minimal changes in repeatability, the only significant change being elimination of the wand marker on the heel in the static trial, which reduced between-day variability of hindfoot motion in the transverse plane. However, some differences were evident in the mean values for all variations. Based on these results, the most accurate and appropriate version of the model is proposed, and average kinematic curves are presented based on the measurements from 14 healthy children.

Stebbins J, Harrington M, Thompson N, Zavatsky A, Theologis T.(2010) "Gait compensations caused by foot deformity in cerebral palsy."

Gait Posture. 2010 Jun;32(2):226-30.

Cerebral palsy (CP) is a complex syndrome, with multiple interactions between joints and muscles. Abnormalities in movement patterns can be measured using motion capture techniques, however determining which abnormalities are primary, and which are secondary, is a difficult task. Deformity of the foot has anecdotally been reported to produce compensatory abnormalities in more proximal lower limb joints, as well as in the contralateral limb. However, the exact nature of these compensations is unclear. The aim of this paper was to provide clear and objective criteria for identifying compensatory mechanisms in children with spastic hemiplegic CP, in order to improve the prediction of the outcome of foot surgery, and to enhance treatment planning. Twelve children with CP were assessed using conventional gait analysis along with the Oxford Foot Model prior to and following surgery to correct foot deformity. Only those variables not directly influenced by foot surgery were assessed. Any that spontaneously corrected following foot surgery were identified as compensations. Pelvic rotation, internal rotation of the affected hip and external rotation of the non-affected hip tended to spontaneously correct. Increased hip flexion on the affected side, along with reduced hip extension on the non-affected side also appeared to be compensations. It is likely that forefoot supination occurs secondary to deviations of the hindfoot in the coronal plane. Abnormal activity in the tibialis anterior muscle may be consequent to tightness and overactivity of the plantarflexors. On the non-affected side, increased plantarflexion during stance also resolved following surgery to the affected side.

Curtis DJ, Bencke J, Stebbins JA, Stansfield B.(2009) "Intra-rater repeatability of the Oxford foot model in healthy children in different stages of the foot roll over process during gait."

Gait Posture. 2009 Jul;30(1):118-21

BACKGROUND:

The repeatability of the Oxford foot model has been reported, but possible variations in the repeatability during the foot roll over process have not been examined. The aim of this study was to determine the relative and absolute repeatability of the model for each stage of the foot roll over process during gait and to compare foot kinematic data from this study with that from another centre as a preliminary examination of the model's inter-centre repeatability and validity.

METHOD:

Eight healthy children were tested twice at the gait laboratory. Foot kinematics from this study were plotted against those from an earlier repeatability study and repeatability statistics calculated for the three rockers of stance phase and swing phase.

RESULTS:

Foot kinematics from this study and an earlier repeatability study produced similar kinematic patterns and joint angle ranges, but there were offsets in the absolute joint angles in the frontal and transverse planes. Relative and absolute repeatability were best in the sagittal plane (flexion/extension) with the poorest repeatability in the transverse plane (rotation and abduction/adduction). There was little difference in repeatability between the three rockers. Typical error of measurement varied between planes and segments from 0.9 degrees for maximum forefoot dorsiflexion in second rocker to 8.6 degrees for maximum hindfoot internal rotation in first rocker.

DISCUSSION:

Repeatability varied markedly between planes and segments but was consistent throughout the gait cycle. Further studies are needed to determine the inter-centre repeatability and validity of the model.

Carson MC, Harrington ME, Thompson N, O'Connor JJ, Theologis TN.(2001) "Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis."

J Biomech. 2001 Oct;34(10):1299-307.

An unbiased understanding of foot kinematics has been difficult to achieve due to the complexity of foot structure and motion. We have developed a protocol for evaluation of foot kinematics during barefoot walking based on a multi-segment foot model. Stereophotogrammetry was used to measure retroreflective markers on three segments of the foot plus the tibia. Repeatability was evaluated between-trial, between-day and between-tester using two subjects and two testers. Subtle patterns and ranges of motion between segments of the foot were consistently detected. We found that repeatability between different days or different testers is primarily subject to variability of marker placement more than inter-tester variability or skin movement. Differences between inter-segment angle curves primarily represent a shift in the absolute value of joint angles from one set of trials to another. In the hallux, variability was greater than desired due to vibration of the marker array used. The method permits objective foot measurement in gait analysis using skin-mounted markers. Quantitative and objective characterisation of the kinematics of the foot during activity is an important area of clinical and research evaluation. With this work we hope to have provided a firm basis for a common protocol for in vivo foot study.

Theologis TN, Harrington ME, Thompson N, Benson MK.(2003) "Dynamic foot movement in children treated for congenital talipes equinovarus."

J Bone Joint Surg Br. 2003 May;85(4):572-7.

The aim of this study was to define objectively gait function in children with treated congenital talipes equinovarus (CTEV) and a good clinical result. The study also attempted an analysis of movement within the foot during gait. We compared 20 children with treated CTEV with 15 control subjects. Clinical assessment demonstrated good results from treatment. Three-dimensional gait analysis provided kinematic and kinetic data describing movement and moments at the joints of the lower limb during gait. A new method was used to study movement within the foot during gait. The data on gait showed significantly increased internal rotation of the foot during walking which was partially compensated for by external rotation at the hip. A mild foot drop and reduced plantar flexor power were also observed. Dorsiflexion at the midfoot was significantly increased, which probably compensated for reduced mobility at the hindfoot. Patients treated for CTEV with a good clinical result should be expected to have nearly normal gait and dynamic foot movement, but there may be residual intoeing, mild foot drop, loss of plantar flexor power with compensatory increased midfoot dorsiflexion and external hip rotation.

van Hoeve S1, de Vos J1, Weijers P1, Verbruggen J1, Willems P2, Poeze M3, Meijer K2.(2015) "Repeatability of the Oxford Foot Model for Kinematic Gait Analysis of the Foot and Ankle."

Clin Res Foot Ankle. 2015 Aug 24;3. pii: 171.

INTRODUCTION:

Kinematic gait analysis via the multi-segmental Oxford foot model (OFM) may be a valuable addition to the biomechanical examination of the foot and ankle. The aim of this study is to assess the repeatability of the OFM in healthy subjects.

METHODS:

Nine healthy subjects, without a history of lower extremity injury, were recruited. Markers were placed according to the OFM requirements. Motion capture was conducted using the VICON NEXUS system on two separate test days, with two tests on each day conducted by two independent examiners. The range of motion (ROM) of the following inter-segments was selected for further analysis: forefoot-hindfoot, forefoot-tibia and hindfoot-tibia in frontal, sagittal and transverse planes. Each step was divided in two parts, a loading phase (from heel strike to midstance) and a push-off phase (from midstance to toe-off). The Intraclass correlation coefficient (ICC), standard error of the measurements with 90% confidence bounds (SEM90) and the Minimal Differences needed to be considered real (MD) with 95% confidence interval were calculated for inter-observer and intra-observer and effect of trial using SPSS.

RESULTS:

There was a linear correlation between the number of trials and the ICC's ($r2=0.49$, $p<0.001$), with six trial leading to good ICC's. Inter-observer repeatability: In the loading phase almost all ICC's were good or excellent (0.53-0.97) with only one parameter below 0.60. In the push-off phase two parameters scored moderate agreement, where the other 7 parameters had well to excellent agreement. The SEM90 values were varying from 0.85° to 2.49° in the loading phase and from 0.92° to 4.40° in the push-off phase. Intra-observer repeatability: In the loading phase all ICC's were good or excellent (0.71-0.97). In the push-off phase two parameters scored moderate agreement and the other 7 parameters had well to excellent agreement. The SEM90 ranged from 1.15° to 4.53° in the loading phase and in the push-off phase from 1.71° to 5.49°. The SEM90 values were varying from 0.85° to 2.49° in the loading phase and from 0.92° to 4.40° in the push-off phase. Intra-observer repeatability: In the loading phase all ICC's were good or excellent (0.71-0.97). In the push-off phase two parameters scored moderate agreement and the other 7 parameters had good to excellent agreement.

CONCLUSION:

The repeatability analysis presented in this study provide excellent basis for objective measurement of the ankle and foot biomechanics. Results for inter-observer and intra-observer repeatability showed moderate to excellent ICC's and acceptable SEM90. Best result were found in the sagittal plane (flexion/extension) followed by the frontal plane (abduction/adduction) and the transverse plane (inversion/eversion).

Milwaukee Foot Model

Canseco K, Long J, Smedberg T, Tarima S, Marks RM, Harris GF.(2012) "Multisegmental foot and ankle motion analysis after hallux valgus surgery."
Foot Ankle Int. 2012 Feb;33(2):141-7.

BACKGROUND:

Gait changes in patients with hallux valgus, including altered kinematic and temporal-spatial parameters, have been documented in the literature. Although operative treatment can yield favorable clinical and radiographic results, restoration of normal gait in this population remains unclear. Segmental kinematic changes within the foot and ankle during ambulation after operative correction of hallux valgus have not been reported. The aim of this study was to analyze changes in multisegmental foot and ankle kinematics in patients who underwent operative correction of hallux valgus.

METHODS:

A 15-camera Vicon Motion Analysis System was used to evaluate 24 feet in 19 patients with hallux valgus preoperatively and postoperatively. The Milwaukee Foot Model was used to characterize segmental kinematics and temporal-spatial parameters (TSPs). Preoperative and postoperative kinematics and TSPs were compared using paired nonparametric methods; comparisons with normative data were performed using unpaired nonparametric methods. Outcomes were evaluated using the SF-36 assessment tool.

RESULTS:

Preoperatively, patients with hallux valgus showed significantly altered temporal-spatial and kinematic parameters. Postoperatively, kinematic analysis demonstrated restoration of hallux position to normal. Hallux valgus angles and intermetatarsal angles were significantly improved, and outcomes showed a significant increase in performance of physical activities. Temporal-spatial parameters and kinematics in the more proximal segments were not significantly changed postoperatively.

CONCLUSION:

Postoperative results demonstrated significant improvement in foot geometry and hallux kinematics in the coronal and transverse planes. However, the analysis did not identify restoration of proximal kinematics.

CLINICAL RELEVANCE:

Further investigation is necessary to explore possible causes/clinical relevance and appropriate treatment interventions for the persistently altered kinematics.

Canseco K, Rankine L, Long J, Smedberg T, Marks RM, Harris GF.(2010) “Motion of the multisegmental foot in hallux valgus.”

Foot Ankle Int. 2010 Feb;31(2):146-52.

BACKGROUND:

Hallux valgus is a common condition characterized by lateral deviation of the large toe and medial deviation of the first metatarsal. While some gait analyses of patients with hallux valgus have been performed using plantar pressures, very little is known about the kinematics of gait in this population. The purpose of this study was to evaluate triplanar kinematics in patients with hallux valgus using a multisegmental foot model. MATERIALS AND METHODS:

A 15-camera Vicon Motion Analysis System was used to evaluate the gait of 38 feet in 33 patients with mild to severe hallux valgus. The Milwaukee foot model was used to characterize dynamic foot and ankle kinematics and temporal-spatial parameters. Values were compared with normal subjects. Outcomes were evaluated using the SF-36 assessment tool. RESULTS:

Patients with hallux valgus showed significantly decreased velocity and stride length and prolonged stance. Significant alterations in gait kinematics were observed in various planes in all segments (hallux, forefoot, hindfoot, and tibia) of the foot and ankle, particularly in the ranges of motion of the hallux and the forefoot. CONCLUSION:

The results demonstrate significantly altered kinematic and temporal-spatial parameters reflective of reduced ambulatory function in patients with hallux valgus. As reports describing multisegmental foot and ankle kinematics in this population are limited, this study is valuable in characterizing gait in patients with hallux valgus. CLINICAL RELEVANCE:

A better understanding of altered gait dynamics of the multisegmental foot in patients with hallux valgus provides valuable insight on how distal pathology affects proximal segments.

Long JT, Eastwood DC, Graf AR, Smith PA, Harris GF.(2010) “Repeatability and sources of variability in multi-center assessment of segmental foot kinematics in normal adults.”

Gait Posture. 2010 Jan;31(1):32-6.

Multi-site application of biomechanical models can be a powerful tool as quantitative methods are employed to improve clinical care and to assess larger populations for research purposes. However, the use of such models depends on adequate validation to assure reliability in inter-site measures. We assessed repeatability and sources of variability associated with the assessment of segmental foot kinematics using the Milwaukee Foot Model during multiple testing sessions at two sites. Six healthy ambulators were instrumented and tested during comfortable ambulation; data were analyzed with variance components analysis using a mixed effects linear model. Results indicated that the largest source of variability was inter-subject; measurement error associated with Site and Session fell below 3.5 degrees in over 80% of position measurements and below 2.5 degrees in over 80% of ROM measurements. These findings support the continued use of the segmental foot model at multiple sites for clinical and research purposes.

Long JT, Wang M, Winters JM, Harris GF.(2008) “A multisegmental foot model with bone-based referencing: sensitivity to radiographic input parameters.”

Conf Proc IEEE Eng Med Biol Soc. 2008;2008:879-82

We present a new kinematic model measuring the three-dimensional orientation of multiple segments of the foot and ankle. The model defines neutral alignments based on the alignments of the underlying bony segments, and indexes the orientation of skin-mounted markers to the bony anatomy using measures from weightbearing x-rays. The sensitivity of the model to these radiographic input parameters was analyzed using data from walking trials. Kinematic output in each plane was found to be most sensitive to perturbations of radiographic measurements in that same plane; however, perturbations in the coronal and transverse planes demonstrated significant carry-over into other planes. The analysis highlights the importance of accurately accounting for the underlying anatomy in measuring intersegmental kinematics.

Canseco K, Long J, Marks R, Khazzam M, Harris G.(2009) "Quantitative motion analysis in patients with hallux rigidus before and after cheilectomy."

J Orthop Res. 2009 Jan;27(1):128-34

The purpose of this study was to quantify changes in temporal-spatial parameters and multisegmental foot/ankle kinematics in a group of patients with hallux rigidus following cheilectomy. Three-dimensional motion analysis was conducted using a 15-camera Vicon Motion Analysis System on a population of 19 patients who underwent cheilectomy for hallux rigidus. Data were analyzed using the four-segment Milwaukee Foot Model. Preoperative and postoperative tests were compared using paired parametric methods. Results showed significant improvements in walking speed, cadence, stride length, and stance/swing ratio from preoperative to postoperative state. Altered hallux and forefoot positions preoperatively showed shifts towards normal after cheilectomy. Although clinical improvements in pain and passive range of motion were statistically significant, similar improvements in range of motion were not demonstrated during ambulatory testing. The results of this study provide insight into ambulatory improvements following cheilectomy, and suggest further study of the rehabilitation process to improve the recovery of functional range of motion.

Marks RM, Long JT, Ness ME, Khazzam M, Harris GF.(2009) "Surgical reconstruction of posterior tibial tendon dysfunction: prospective comparison of flexor digitorum longus substitution combined with lateral column lengthening or medial displacement calcaneal osteotomy."

Gait Posture. 2009 Jan;29(1):17-22.

Posterior tibial tendon dysfunction (PTTD) may require surgical intervention when nonoperative measures fail. Different methods of bony reconstruction may supplement tendon substitution. This study compares two types of bony procedures used to reinforce reconstruction of the posterior tibial tendon-the lateral column lengthening (LCL), and the medial displacement calcaneal osteotomy (MDCO). Twenty patients with PTTD were evaluated before and after scheduled reconstruction comprised of either flexor digitorum longus (FDL) substitution combined with MDCO (MDCO group, 14 patients) or FDL substitution with LCL fusion or osteotomy (LCL group, 6 patients). Foot/ankle kinematics and temporal-spatial parameters were analyzed using the Milwaukee Foot Model, and results were compared to a previously evaluated normal population of 25 patients. Post-operatively, both patient groups demonstrated significantly improved stride length, cadence and walking speed, as well as improved hindfoot and forefoot position in the sagittal plane. The LCL group also demonstrated greater heel inversion. All post-operative subjects revealed significant improvement in the talo-MT1 angle in the A/P and lateral planes, calcaneal pitch and medial cuneiform-MT5 height. Surgical reconstruction of PTTD with either the LCL or MDCO shows comparable improvements in gait parameters, with better heel inversion seen with the LCL, but improved 1st ray plantarflexion and varus with the MDCO. Both procedures demonstrated comparable improvements in radiographic measurements.

Canseco K, Long J, Marks R, Khazzam M, Harris G.(2008) "Quantitative characterization of gait kinematics in patients with hallux rigidus using the Milwaukee foot model."

J Orthop Res. 2008 Apr;26(4):419-27.

The purpose of this study was to provide a quantitative analysis of the changes that occur in the foot and ankle during the gait of patients with hallux rigidus. Using a 15-camera Vicon Motion Analysis System, gait analysis was conducted on a population of 22 patients with hallux rigidus and compared to that of 25 healthy ambulators. Weight-bearing radiographs were measured to index marker positions to underlying bony anatomy. The Milwaukee Foot Model was used to perform three-dimensional analysis of dynamic foot and ankle motion, and temporal-spatial parameters were also calculated. Values were compared to controls using unpaired parametric methods (Student t-test, $p < 0.002$). The hallux rigidus population showed significant alterations in gait patterns as compared to controls in various planes in all segments (hallux, forefoot, hindfoot, and tibia) of the foot and ankle, particularly in the range of motion of the hallux and the forefoot. Prolonged stance phase was also observed. As reports regarding the quantitative study of the multisegment foot and ankle are limited, this study was useful in providing characterization of gait patterns in patients with hallux rigidus.

Ness ME, Long J, Marks R, Harris G.(2008) "Foot and ankle kinematics in patients with posterior tibial tendon dysfunction."

Gait Posture. 2008 Feb;27(2):331-9.

The purpose of this study is to provide a quantitative characterization of gait in patients with posterior tibial tendon dysfunction (PTTD), including temporal-spatial and kinematic parameters, and to compare these results to those of a Normal population. Our hypothesis was that segmental foot kinematics were significantly different in multiple segments across multiple planes. A 15 camera motion analysis system and weight-bearing radiographs were employed to evaluate 3D foot and ankle motion in a population of 34 patients with PTTD (30 females, 4 males) and 25 normal subjects (12 females, 13 males). The four-segment Milwaukee Foot Model (MFM) with radiographic indexing was used to analyze foot and ankle motion and provided kinematic data in the sagittal, coronal and transverse planes as well as temporal-spatial information. The temporal-spatial parameters revealed statistically significant deviations in all four metrics for the PTTD population. Stride length, cadence and walking speed were all significantly diminished, while stance duration was significantly prolonged ($p<0.0125$). Significant kinematic differences were noted between the groups ($p<0.002$), including: (1) diminished dorsiflexion and increased eversion of the hindfoot; (2) decreased plantarflexion of the forefoot, as well as abduction shift and loss of the varus thrust in the forefoot; and (3) decreased range of motion (ROM) with diminished dorsiflexion of the hallux. The study provides an impetus for improved orthotic and bracing designs to aid in the care of distal foot segments during the treatment of PTTD. It also provides the basis for future evaluation of surgical efficacy. The course of this investigation may ultimately lead to improved treatment planning methods, including orthotic and operative interventions.

Khazzam M, Long JT, Marks RM, Harris GF.(2007) "Kinematic changes of the foot and ankle in patients with systemic rheumatoid arthritis and forefoot deformity."

J Orthop Res. 2007 Mar;25(3):319-29.

Minimal published data exist characterizing the effect of rheumatoid arthritis of the forefoot (RA) on multi-segmental gait kinematics. The purpose of this study was to examine specific changes in segmental foot motion in patients with RA as compared to persons without foot/ankle pathology. This was a cross-sectional, descriptive study consisting of 22 preoperative adult patients (29 feet) diagnosed with RA and 25 adult patients with no known foot pathology (Control). All RA patients were evaluated by the same orthopaedic surgeon. This group consisted of 20 women and 2 men with a mean age of 54 years (range, 17-76 years). The Control cohort consisted of 13 men and 12 women with a mean age of 41 years (range, 27-73 years). Foot and ankle motion data for the RA population were obtained using a 15-camera Vicon Motion Analysis System (Vicon Motion Systems, Inc., Lake Forest, CA). Anterior-posterior, lateral, and modified coronal radiographic views were obtained to relate marker position to underlying bony anatomy. Temporal and three-dimensional kinematic parameters were obtained via the 4-segment Milwaukee Foot Model. Quantitative comparisons of range of motion values during the seven phases of gait were made between RA and Control ankles using unpaired nonparametric methods. The RA group showed significant differences ($p < 0.001$) as compared to Controls with prolonged stance time, shortened stride length, increased cadence, and a walking speed that was 80% of Control. Overall, kinematic data in the RA cohort showed significant differences ($p < 0.001$) in motion for tibial, hindfoot, and forefoot motion as compared to Controls. The effect of RA on segmental foot motion is poorly understood. This study characterized the effect that RA has on motion about the foot and ankle during gait, providing insight into this pathology to improve quantitative assessment, treatment planning, and rehabilitative care.

Myers KA, Wang M, Marks RM, Harris GF.(2004) "KValidation of a multisegment foot and ankle kinematic model for pediatric gait."

IEEE Trans Neural Syst Rehabil Eng. 2004 Mar;12(1):122-30.

This paper reports the development, accuracy, reliability, and validation protocol of a four-segment pediatric foot and ankle model. The four rigid body segments include: 1) tibia and fibula; 2) hindfoot–talus, navicular, and calcaneus; 3) forefoot–cuboid, cuneiforms, and metatarsals; and 4) hallux. A series of Euler rotations compute relative angles between segments. Validation protocol incorporates linear and angular testing for accuracy and reliability. Linear static system resolution is greatest in the Y orientation at 0.10 +/- 0.14 mm and 0.05 level of significance and 99.96% accuracy. Dynamic linear resolution and accuracy are 0.43 +/- 0.39 mm and 99.8%, respectively. Angular dynamic resolution computes to 0.52 +/- 3.36 degrees at 99.6% accuracy. These calculations are comparable to the Milwaukee adult foot and ankle model.

Kidder SM, Abuzzahab FS Jr, Harris GF, Johnson JE.(1996) "A system for the analysis of foot and ankle kinematics during gait."

IEEE Trans Rehabil Eng. 1996 Mar;4(1):25-32

A five-camera Vicon (Oxford Metrics, Oxford, England) motion analysis system was used to acquire foot and ankle motion data. Static resolution and accuracy were computed as 0.86 +/- 0.13 mm and 98.9%, while dynamic resolution and accuracy were 0.1 +/- 0.89 and 99.4% (sagittal plane). Spectral analysis revealed high frequency noise and the need for a filter (6 Hz Butterworth low-pass) as used in similar clinical situations. A four-segment rigid body model of the foot and ankle was developed. The four rigid body foot model segments were 1) tibia and fibula, 2) calcaneus, talus, and navicular, 3) cuneiforms, cuboid, and metatarsals, and 4) hallux. The Euler method for describing relative foot and ankle segment orientation was utilized in order to maintain accuracy and ease of clinical application. Kinematic data from a single test subject are presented.

Other Multi-Segment Foot Models

Woodburn J, Nelson KM, Siegel KL, Kepple TM, Gerber LH.(2004) "Multisegment foot motion during gait: proof of concept in rheumatoid arthritis."

J Rheumatol. 2004 Oct;31(10):1918-27.

OBJECTIVE: To test a multisegment foot model for kinematic analysis during barefoot walking in patients with well established rheumatoid arthritis (RA) and foot impairments.

METHODS: Five healthy adult subjects and 11 RA patients with advanced disease were studied. Foot impairments were assessed using standardized outcomes and clinical examination techniques. A 6-camera 60 Hz video-based motion analysis system was used to measure motion of the shank, rearfoot, forefoot, and hallux segments and the vertical displacement of the navicular. Face validity and estimates of repeatability were determined. Motion patterns were calculated and comparisons were made between healthy subjects and patients with RA. Relationships between clinical impairment and abnormal motion were determined through inspection of individual RA cases.

RESULTS: Across the motion variables, the within-day and between-day coefficient of multiple correlation values ranged from 0.677 to 0.982 for the healthy subjects and 0.830 to 0.981 for RA patients. Based on previous studies, motion parameters for the healthy subjects showed excellent face validity. In RA patients, there was reduced range of motion across all segments and all planes of motion, which was consistent with joint stiffness. In the RA patients, rearfoot motion was shifted towards eversion and external rotation and peak values for these variables were increased, on average, by 7 degrees and 11 degrees, respectively. Forefoot range of motion was reduced in all 3 planes (between 31% and 53%), but the maximum and minimum angles were comparable to normal. The navicular height, during full foot contact, was on average 3 mm lower in the RA patients in comparison to normal. The hallux was less extended in the RA subjects in comparison to normal (21 degrees vs 33 degrees) during the terminal stance phase. Individual cases showed abnormal patterns of motion consistent with their clinical impairments, especially those with predominant forefoot pain or pes planovalgus.

CONCLUSION: In RA, multisegment foot models may provide a more complete description of foot motion abnormalities where pathology presents at multiple joints, leading to complex and varied patterns of impairment. This technique may be useful to evaluate functional changes in the foot and to help plan and assess logical, structurally based corrective interventions.

Saraswat P, MacWilliams BA, Davis RB.(2012) "A multi-segment foot model based on anatomically registered technical coordinate systems: method repeatability in pediatric feet."

Gait Posture. 2012 Apr;35(4):547-55.

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 4°. For dynamic walking kinematics, intra-clinician, inter-clinician and inter-laboratory variability were less than 6° for the ankle and forefoot, but slightly higher for the hallux. Inter-trial variability accounted for 2-4° 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.

Jenkyn TR, Anas K, Nichol A.(2009) "Foot segment kinematics during normal walking using a multisegment model of the foot and ankle complex."

J Biomech Eng. 2009 Mar;131(3):

Gait analysis using optical tracking equipment has been demonstrated to be a clinically useful tool for measuring three-dimensional kinematics and kinetics of the human body. However, in current practice, the foot is treated as a single rigid segment that articulates with the lower leg, meaning the motions of the joints of the foot cannot be measured. A multisegment kinematic model of the foot was developed for use in a gait analysis laboratory. The foot was divided into hindfoot, talus, midfoot, and medial and lateral forefoot segments. Six functional joints were defined: Ankle and subtalar joints, frontal and transverse plane motions of the hindfoot relative to midfoot, supination-pronation twist of the forefoot relative to midfoot, and medial longitudinal arch height-to-length ratio. Twelve asymptomatic subjects were tested during barefoot walking with a six-camera optical stereometric system and passive markers organized in triads. Repeatability of reported motions was tested using coefficients of multiple correlation. Ankle and subtalar joint motions and twisting of the forefoot were most repeatable. Hindfoot motions were least repeatable both within subjects and between subjects. Hindfoot and forefoot pronations in the frontal place were found to coincide with dropping of the medial longitudinal arch between early to midstance, followed by supination and rising of the arch in late stance and swing phase. This multisegment foot model overcomes a major shortcoming in current gait analysis practice-the inability to measure motion within the foot. Such measurements are crucial if gait analysis is to remain relevant in orthopaedic and rehabilitative treatment of the foot and ankle.

Jenkyn TR, Nicol AC.(2007) "A multi-segment kinematic model of the foot with a novel definition of forefoot motion for use in clinical gait analysis during walking."

Biomech. 2007;40(14):

A multi-segment kinematic model of the foot was developed for use in a gait analysis laboratory. The foot was divided into hindfoot, talus, midfoot and medial and lateral forefoot segments. Six functional joints were defined: ankle and subtalar joints, frontal and transverse plane motions of the hindfoot relative to midfoot, supination/pronation twist of the forefoot relative to midfoot and medial longitudinal arch height-to-length ratio. Twelve asymptomatic subjects were tested during barefoot walking with a six-camera optical stereometric system and auto-reflective markers organized in triads. Repeatability of the joint motions was tested using coefficients of multiple correlation. Ankle and subtalar joint motions and twisting of the forefoot were most repeatable. Hindfoot motions were least repeatable both within-subjects and between-subjects. Hindfoot and forefoot pronation in the frontal plane was found to coincide with dropping of the medial longitudinal arch between early to mid-stance, followed by supination and rising of the arch in late stance and swing phase. This multi-segment foot model addresses an unfortunate shortcoming in current gait analysis practice-the inability to measure motion within the foot. Such measurements are crucial if gait analysis is to remain relevant in the orthopaedic and rehabilitative treatment of the foot and ankle.

J. Wilken, S Rao, C Saltzman, HJ Yack "The effect of arch height on kinematic coupling during walking."

2011 - *Clinical Biomechanics (26) 318-323.*

The purpose of the current study was to assess kinematic coupling within the foot in individuals across a range of arch heights. Seventeen subjects participated in this study. Weight-bearing lateral radiographs were used to measure the arch height, defined as angle between the 1st metatarsal and the calcaneus. A kinematic model including the 1st metatarsal, lateral forefoot, calcaneus and tibia was used to assess foot kinematics during walking. Four coupling ratios were calculated: calcaneus frontal to forefoot transverse plane motion (Calcaneal EV/Forefoot AB), calcaneus frontal to transverse plane motion (Calcaneus EV/AB), forefoot sagittal to transverse plane motion (Forefoot DF/AB), and 1st metatarsal sagittal to transverse plane motion (1st Metatarsal DF/AB). Pearson product moment correlations were used to assess the relationship between arch height and coupling ratios. Mean (SD) radiographic arch angles of 129.8 (12.1) degrees with a range from 114 to 153 were noted, underscoring the range of arch heights in this cohort. Arch height explained approximately 3%, 38%, 12% and 1% of the variance in Calcaneal EV/Forefoot AB, Calcaneus EV/AB, Forefoot DF/AB and 1st Metatarsal DF/AB respectively. Calcaneal EV/Forefoot AB, Calcaneus EV/AB, Forefoot DF/AB and 1st Metatarsal DF/AB coupling ratios of 1.84±0.80, 0.56±0.35, 0.96±0.27 and 0.43±0.21were noted, consistent with the twisted foot plate model, windlass mechanism and midtarsal locking mechanisms. Arch height had a small and modest relationship with kinematic coupling ratios during walking.
[PMID: Reference]
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Multi-Segment Foot Kinetics

Bruening DA, Cooney KM, Buczek FL.(2012) “Analysis of a kinetic multi-segment foot model. Part I: Model repeatability and kinematic validity.”
Gait Posture. 2012 Apr;35(4):529-34.
Kinematic multi-segment foot models are still evolving, but have seen increased use in clinical and research settings. The addition of kinetics may increase knowledge of foot and ankle function as well as influence multi-segment foot model evolution; however, previous kinetic models are too complex for clinical use. In this study we present a three-segment kinetic foot model and thorough evaluation of model performance during normal gait. In this first of two companion papers, model reference frames and joint centers are analyzed for repeatability, joint translations are measured, segment rigidity characterized, and sample joint angles presented. Within-tester and between-tester repeatability were first assessed using 10 healthy pediatric participants, while kinematic parameters were subsequently measured on 17 additional healthy pediatric participants. Repeatability errors were generally low for all sagittal plane measures as well as transverse plane Hindfoot and Forefoot segments (median<3°), while the least repeatable orientations were the Hindfoot coronal plane and Hallux transverse plane. Joint translations were generally less than 2mm in any one direction, while segment rigidity analysis suggested rigid body behavior for the Shank and Hindfoot, with the Forefoot violating the rigid body assumptions in terminal stance/pre-swing. Joint excursions were consistent with previously published studies

Bruening DA, Cooney KM, Buczek FL.(2012) “Analysis of a kinetic multi-segment foot model part II: kinetics and clinical implications.”
Gait Posture. 2012 Apr;35(4):535-40.

Kinematic multi-segment foot models have seen increased use in clinical and research settings, but the addition of kinetics has been limited and hampered by measurement limitations and modeling assumptions. In this second of two companion papers, we complete the presentation and analysis of a three segment kinetic foot model by incorporating kinetic parameters and calculating joint moments and powers. The model was tested on 17 pediatric subjects (ages 7-18 years) during normal gait. Ground reaction forces were measured using two adjacent force platforms, requiring targeted walking and the creation of two sub-models to analyze ankle, midtarsal, and 1st metatarsophalangeal joints. Targeted walking resulted in only minimal kinematic and kinetic differences compared with walking at self selected speeds. Joint moments and powers were calculated and ensemble averages are presented as a normative database for comparison purposes. Ankle joint powers are shown to be overestimated when using a traditional single-segment foot model, as substantial angular velocities are attributed to the mid-tarsal joint. Power transfer is apparent between the 1st metatarsophalangeal and mid-tarsal joints in terminal stance/pre-swing. While the measurement approach presented here is limited to clinical populations with only minimal impairments, some elements of the model can also be incorporated into routine clinical gait analysis.

Dixon PC, Böhm H, Döderlein L.(2012) “Ankle and midfoot kinetics during normal gait: a multi-segment approach.”

J Biomech. 2012 Apr 5;45(6):1011-6.

Multi-segment foot models are increasingly being used to evaluate intra and inter-segment foot kinematics such as the motion between the hindfoot/tibia (ankle) and the forefoot/hindfoot (midfoot) during walking. However, kinetic analysis have been mainly restricted to one-segment foot models and could be improved by considering a multi-segment approach. Therefore, the aims of this study were to (1) implement a kinetic analysis of the ankle and theoretical midfoot joints using the existing Oxford Foot Model (OFM) through a standard inverse dynamics approach using only marker, force plate and anthropometric data and (2) to compare OFM ankle joint kinetics to those output by the one-segment foot plugin-gait model (PIG). 10 healthy adolescents fitted with both the OFM and PIG markers performed barefoot comfortable speed walking trials over an instrumented walkway. The maximum ankle power generation was significantly reduced by approximately 40% through OFM calculations compared to PIG estimates ($p<0.001$). This result was not caused by a decrease in OFM computed joint moments, but by a reduction in the angular velocity between the tibia/hindfoot (OFM) compared to the tibia/foot (PIG) ($p<0.001$). Additionally, analysis revealed considerable midfoot loading. One-segment foot models overestimate ankle power, and may also overestimate the contribution of the triceps surae. A multi-segment approach may help quantify the important contribution of the midfoot ligaments and musculature to power generation. We therefore recommend the use of multi-segment foot models to estimate ankle and midfoot kinetics, especially when surgical decision-making is based on the results of three-dimensional gait analysis.

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