

Foot

IORfoot References



Giacomozzi C, Leardini A, Caravaggi P.(2014) "Correlates between kinematics and baropodometric measurements for an integrated in-vivo assessment of the segmental foot function in gait."

[J Biomech. 2014 Aug 22;47\(11\):2654-9.](#)

Baropodometry and multi-segmental foot kinematics are frequently employed to obtain insight into the mechanics of the foot-ground interaction in both basic research and clinical settings. However, nothing hitherto has been reported on the full integration of kinematics with baropodometric parameters, and only a few studies have addressed the association between intersegmental kinematics and plantar loading within specific foot regions. The aim of this study was to understanding the relationships between foot joint mobility and plantar loading by focusing on the correlation between these two measures. An integrated pressure-force-kinematics system was used to measure plantar pressure and rotations between foot segments during the stance phase of walking in 10 healthy subjects. An anatomically-based mask was applied to each footprint to obtain six regions according to the position of the markers; hence each kinematic segment was paired with a corresponding area of the plantar surface. Relationships between segmental motion and relevant baropodometric data were explored by means of correlation analysis. Negative, weak-to-moderate correlations ($R(2) < 0.5$) were found between pressure (mean and peak) and inter-segmental range of motion across all foot joints except the Calcaneus-Midfoot. Temporal profiles of sagittal-plane kinematics and baropodometric parameters were well correlated, particularly at the ankle joint. Larger motion in the foot joints during walking was associated with lower plantar pressure in almost all regions. The study helps improve our understanding of the relationship between joint mobility and plantar loading in the healthy foot and represents a critical preliminary analysis before addressing possible clinical applications.

Carter SL, Sato N, Hopper LS (2017) "Kinematic repeatability of a multi-segment foot model for dance."

[Sports Biomech. 2017 Jul 21:1-19.](#)

The purpose of this study was to determine the intra and inter-assessor repeatability of a modified Rizzoli Foot Model for analysing the foot kinematics of ballet dancers. Six university-level ballet dancers performed the movements; parallel stance, turnout pli  , turnout stance, turnout rise and flex-point-flex. The three-dimensional (3D) position of individual reflective markers and marker triads was used to model the movement of the dancers' tibia, entire foot, hindfoot, midfoot, forefoot and hallux. Intra and inter-assessor reliability demonstrated excellent ($ICC \geq 0.75$) repeatability for the first metatarsophalangeal joint in the sagittal plane. Intra-assessor reliability demonstrated excellent ($ICC \geq 0.75$) repeatability during flex-point-flex across all inter-segmental angles except for the tibia-hindfoot and hindfoot-midfoot frontal planes. Inter-assessor repeatability ranged from poor to excellent ($0.5 > ICC \geq 0.75$) for the 3D segment rotations. The most repeatable measure was the tibia-foot dorsiflexion/plantar flexion articulation whereas the least repeatable measure was the hindfoot-midfoot adduction/abduction articulation. The variation found in the inter-assessor results is likely due to inconsistencies in marker placement. This 3D dance specific multi-segment foot model provides insight into which kinematic measures can be reliably used to ascertain in vivo technical errors and/or biomechanical abnormalities in a dancer's foot motion.

Dingenen B, Deschamps K, Delchambre F, Van Peer E, Staes FF, Matricali GA. (2017)

"Effect of taping on multi-segmental foot kinematic patterns during walking in persons with chronic ankle instability."

[J Sci Med Sport. 2017 Sep;20\(9\):835-840.](#)

OBJECTIVES:

To evaluate multi-segmental foot kinematic patterns in chronic ankle instability (CAI) participants during walking, and to investigate the influence of high-Dye and low-Dye taping on these kinematic patterns. DESIGN: Cross-sectional study.

METHODS: Kinematic data of 12 non-injured controls and 15 CAI participants were measured with a three-dimensional motion analysis system during barefoot walking. In addition, the CAI participants walked with high-Dye and low-Dye taping. A rigid Plug-in gait model and the Rizzoli 3D Multi-Segment Foot Model were used to measure multi-segmental foot kinematic patterns. One-dimensional statistical parametric mapping was used to compare barefoot walking of the control and CAI group, and to evaluate differences between walking barefoot and walking with high-Dye and low-Dye taping within the CAI group.

RESULTS: Compared to the control group, CAI participants showed a decreased ankle dorsiflexion during loading response ($p=0.025$) and a more inverted calcaneus in relation to the shank during the initial swing phase ($p=0.024$). A more inverted position of the metatarsus in relation to the midfoot was observed after low-Dye taping during almost the entire stance phase ($p=0.017$). No significant differences were found for high-Dye taping.

CONCLUSIONS:

Significant differences in kinematic patterns were found in the ankle joint and rearfoot, but not in the mid- and forefoot in CAI participants. The application of low-Dye taping resulted in a significantly increased inverted position of the forefoot, which can be considered as a less desirable effect for patients with CAI. No other effects of high-Dye and low-Dye taping on kinematic patterns were revealed.

Leardini A, Aquila A, Caravaggi P, Ferraresi C, Giannini S. (2014) "Multi-segment foot mobility in a hinged ankle-foot orthosis: the effect of rotation axis position."

[Gait Posture. 2014 May;40\(1\):274-7.](#)

Hinged ankle-foot orthoses are prescribed routinely for the treatment of ankle joint deficits, despite the conflicting outcomes and the little evidence on their functional efficacy. In particular, the axis of rotation of the hinge is positioned disregarding the physiological position and orientation. A multi-segment model was utilized to assess in vivo the effect of different positions for this axis on the kinematics of foot joints. A special custom-made hinged orthosis was manufactured via standard procedures for a young healthy volunteer. Four locations for the mechanical axis were obtained by a number of holes where two nuts and bolts were inserted to form the hinge: a standard position well above the malleoli, at the level of the medial malleolus, at the level of the lateral malleolus, and the physiological between the two malleoli. The shank and foot were instrumented with 15 reflective markers according to a standard protocol, and level walking was collected barefoot and with the orthosis in the four mechanical conditions. The spatio-temporal parameters observed in the physiological axis condition were the closest to normal barefoot walking. As expected, ankle joint rotation was limited to the sagittal plane. When the physiological axis was in place, rotations of the ankle out-of-sagittal planes, and of all other foot joints in the three anatomical planes, were found to be those most similar to the natural barefoot condition. These preliminary measures of intersegmental kinematics in a foot within an ankle-foot orthosis showed that only a physiological location for the ankle mechanical hinge can result in natural motion at the remaining joints and planes.

Eerdekens M, Staes F, Pilkington T and Deschamps K(2017)

"A novel magnet based 3D printed marker wand as basis for repeated in-shoe multi segment foot analysis: a proof of concept."

Journal of Foot and Ankle Research (2017) 10:38.]

Abstract

Background: Application of in-shoe multi-segment foot kinematic analyses currently faces a number of challenges, including: (i) the difficulty to apply regular markers onto the skin, (ii) the necessity for an adequate shoe which fits various foot morphologies and (iii) the need for adequate repeatability throughout a repeated measure condition. The aim of this study therefore was to design novel magnet based 3D printed markers for repeated in-shoe measurements while using accordingly adapted modified shoes for a specific multi-segment foot model.

Methods: Multi-segment foot kinematics of ten participants were recorded and kinematics of hindfoot, midfoot and forefoot were calculated. Dynamic trials were conducted to check for intra and inter-session repeatability when combining novel markers and modified shoes in a repeated measures design. Intraclass correlation coefficients were calculated to determine reliability.

Results: Both repeatability and reliability were proven to be good to excellent with maximum joint angle deviations of 1.11° for intra-session variability and 1.29° for same-day inter-session variability respectively and ICC values of >0.91.

Conclusion: The novel markers can be reliably used in future research settings using in-shoe multi-segment foot

kinematic analyses with multiple shod conditions.

Deschamps K, Staes F, Bruyninckx H, Busschots E, Jaspers E, Atre A, Desloovere K.(2012) "Repeatability in the assessment of multi-segment foot kinematics."

Gait Posture. 2012 Feb;35(2):255-60.

A recently published systematic review on 3D multi-segment foot models has illustrated the lack of repeatability studies providing evidence for appropriate clinical decision making. The aim of the current study was to assess the repeatability of the recently published model developed by Leardini et al. [10]. Foot kinematics of six healthy adults were analyzed through a repeated-measures design including two therapists with different levels of experience and four test sessions. For the majority of the parameters moderate or good repeatability was observed for the within-day and between-day sessions. A trend towards consistently higher within- and between-day variability was observed for the junior compared to the senior clinician. The mean inter-session variability of the relative 3D rotations ranged between 0.9-4.2° and 1.6-5.0° for respectively the senior and junior clinician whereas for the absolute angles this variability increased to respectively 2.0-6.2° and 2.6-7.8°. Mean inter-therapist standard deviations ranged between 2.2° and 6.5° for the relative 3D rotations and between 2.8° and 7.6° for the absolute 3D rotations. The ratio of inter-therapist to inter-trial errors ranged between 1.8 and 5.5 for the relative 3D rotations and between 2.4 and 9.7 for the absolute 3D rotations. Absolute angle representation of the planar angles was found to be more difficult. Observations from the current study indicate that an adequate normative database can be installed in gait laboratories, however, it should be stressed that experience of therapists is important and gait laboratories should therefore be encouraged to put effort in training their clinicians.

Powell DW, Williams DS, Butler RJ. (2013) "A comparison of two multisegment foot models in high-and low-arched athletes."

[J Am Podiatr Med Assoc. 2013 Mar-Apr;103\(2\):99-105.](#)

Malalignment and dysfunction of the foot have been associated with an increased propensity for overuse and traumatic injury in athletes. Several multisegment foot models have been developed to investigate motions in the foot. However, it remains unknown whether the kinematics measured by different multisegment foot models are equivocal. The purpose of the present study is to examine the efficacy of two multisegment foot models in tracking aberrant foot function.

METHODS: Ten high-arched and ten low-arched female athletes walked and ran while ground reaction forces and three-dimensional kinematics were tracked using the Leardini and Oxford multisegment foot models. Ground reaction forces and joint angles were calculated with Visual 3D (C-Motion Inc, Germantown, MD). Repeated-measures analyses of variance were used to analyze peak eversion, time to peak eversion, and eversion excursions. **RESULTS:** The Leardini model was more sensitive to differences in peak eversion angles than the Oxford model. However, the Oxford model detected differences in eversion excursion values that the Leardini model did not detect.

CONCLUSIONS:

Although both models found differences in frontal plane motion between high- and low-arched athletes, the Leardini multisegment foot model is suggested to be more appropriate as it directly tracks frontal plane midfoot motion during dynamic motion..

Arnold JB, Mackintosh S, Jones S, Thewlis D. (2013) "Repeatability of stance phase kinematics from a multi-segment foot model in people aged 50 years and older."

[Gait Posture. 2013 Jun;38\(2\):349-51..](#)

Confidence in 3D multi-segment foot models has been limited by a lack of repeatability data, particularly in older populations that may display unique functional foot characteristics. This study aimed to determine the intra and inter-observer repeatability of stance phase kinematic data from a multi-segment foot model described by Leardini et al. [2] in people aged 50 years or older. Twenty healthy adults participated (mean age 65.4 years SD 8.4). A repeated measures study design was used with data collected from four testing sessions on two days from two observers. Intra (within-day and between-day) and inter-observer coefficient of multiple correlations revealed moderate to excellent similarity of stance phase joint range of motion (0.621-0.975). Relative to the joint range of motion (ROM), mean differences (MD) between sessions were highest for the within-day comparison for all planar ROM at the metatarsus-midfoot articulation (sagittal plane ROM 5.2° vs. 3.9°, MD 3.1°; coronal plane ROM 3.9 vs. 3.1°, MD 2.3°; transverse plane ROM 6.8° vs. 5.16°, MD 3.5°). Consequently, data from the metatarsus-midfoot articulation in the Istituto Ortopedico Rizzoli (IOR) foot model in adults aged over 50 years needs to be considered with respect to the findings of this study.

Deschamps K, Staes F, Bruyninckx H, Busschots E, Matricali GA, Spaepen P, Meyer C, Desloovere K. (2012) "Repeatability of a 3D multi-segment foot model protocol in presence of foot deformities."

[*Gait Posture*. 2012 Jul;36\(3\):635-8.](#)

Repeatability studies on 3D multi-segment foot models (3DMFMs) have mainly considered healthy participants which contrasts with the widespread application of these models to evaluate foot pathologies. The current study aimed at establishing the repeatability of the 3DMFM described by Leardini et al. in presence of foot deformities. Foot kinematics of eight adult participants were analyzed using a repeated-measures design including two therapists with different levels of experience. The inter-trial variability was higher compared to the kinematics of healthy subjects. Consideration of relative angles resulted in the lowest inter-session variability. The absolute 3D rotations between the Sha-Cal and Cal-Met seem to have the lowest variability in both therapists. A general trend towards higher $\sigma(\text{sess})/\sigma(\text{trial})$ ratios was observed when the midfoot was involved. The current study indicates that not only relative 3D rotations and planar angles can be measured consistently in patients, also a number of absolute parameters can be consistently measured serving as basis for the decision making process.

Benedetti MG, Manca M, Ferraresi G, Boschi M, Leardini A.(2011) "A new protocol for 3D assessment of foot during gait: application on patients with equinovarus foot."

[*Clin Biomech \(Bristol, Avon\)*. 2011 Dec;26\(10\):1033-8.](#)

BACKGROUND:

The aim of this study is to assess the clinical value of a recently introduced original protocol for full three dimensional analysis of ankle rotations in patients with equinovarus foot. METHODS: A preliminary study merging the Total3Dgait protocol and the conventional Vicon® Plug-in-Gait marker-sets on five patients with foot deformity was performed to compare the output exactly over the same gait cycles. In the second study, 15 patients with equinus varus foot were assessed retrospectively by means of the Total3Dgait protocol before and after surgery. Data on ankle kinematics were compared to those of a control group. The Functional Ambulation Categories scale and other goals such as orthosis/aids removal, decrease in foot pain, healing of calluses and sores were considered as measures of clinical outcome. FINDINGS: The Total3Dgait protocol provides additional joint motion, in the coronal and transverse planes. Kinematics in the three anatomical planes improved significantly although no changes in time-distance parameters were evident. Improvement in clinical outcome measures was also achieved. INTERPRETATION:

The new protocol provides valuable additional data in measuring full three dimensional kinematics of the foot during gait. Whereas the speed of walking was unchanged after surgery for most of patients, the kinematic changes in the three anatomical planes, as measured by the new protocol, were the only measures able to demonstrate motion changes induced by surgery at the foot and to explain subject-specific gains as improvement in stability during walking, relief of pain, calluses and sores, and removal or modification of foot orthosis and aids.

Leardini A, Benedetti MG, Berti L, Bettinelli D, Nativo R, Giannini S.(2007) “Rear-foot, mid-foot and fore-foot motion during the stance phase of gait.”
[Gait Posture. 2007 Mar;25\(3\):453-62.](#)

This paper proposes a new protocol designed to track a large number of foot segments during the stance phase of gait with the smallest possible number of markers, with particular clinical focus on coronal plane alignment of the rear-foot, transverse and sagittal plane alignment of the metatarsal bones, and changes at the medial longitudinal arch. The shank, calcaneus, mid-foot and metatarsus were assumed to be 3D rigid bodies. The longitudinal axis of the first, second and fifth metatarsal bones and the proximal phalanx of the hallux were also tracked independently. Skin markers were mounted on bony prominences or joint lines, avoiding the course of main tendons. Trajectories of the 14 markers were collected by an eight-camera motion capture system at 100 Hz on a population of 10 young volunteers. Three-dimensional joint rotations and planar angles were calculated according to anatomically based reference frames. The marker set was well visible throughout the stance phase of gait, even in a camera configuration typical of gait analysis of the full body. The time-histories of the joint rotations and planar angles were well repeatable among subjects and consistent with clinical and biomechanical knowledge. Several dynamic measurements were originally taken, such as elevation/drop of the medial longitudinal arch and of three metatarsal bones, rear-foot to fore-foot rotation and transverse plane deformation of the metatarsus. The information obtained from this protocol, consistent with previous clinical knowledge, enhanced our understanding of the dynamics of the human foot during stance.

Articles using the IORfoot model

Takabayashi T, Edama M, Nakamura E, Yokoyama E, Kanaya C and Kubo M (2017) “Coordination among the rearfoot, midfoot, and forefoot during walking.”
[Journal of Foot and Ankle Research 10:42](#)

Abstract

Background: Examining coordination between segments is essential for prevention and treatment of injuries. However, traditional methods such as ratio, cross-correlation technique, and angle-time plot may not provide a complete understanding of intersegmental coordination. The present study aimed to quantify the coordination among the rearfoot, midfoot, and forefoot segments during walking.

Methods: Twenty healthy young men walked barefoot on a treadmill. Reflective markers were fixed to their right shank and foot based on the Leardini foot model. Three-dimensional joint angles were calculated at the distal segment, and were expressed relative to the adjacent proximal segment. The coupling angle representing intersegmental coordination was calculated by using the modified vector coding technique, and categorized into the following four coordination patterns: in-phase with proximal dominance, in-phase with distal dominance, anti-phase with proximal dominance, and anti-phase with distal dominance.

Results: The results showed that the midfoot was dominantly everted compared with the rearfoot and forefoot during the early stance (i.e., the rearfoot-midfoot coordination and midfoot-forefoot coordination were mainly in-phase with distal and proximal dominance, respectively).

Conclusion: This result may suggest that the midfoot plays a more significant role than the rearfoot and forefoot during early stance. The results of the present study can help in understanding the interaction of the intersegmental foot kinematic time series during walking. The results could be used as data to distinguish the presence of injuries or abnormal inter-segmental foot motions such as pes planus. Additionally, these data might be used in the future in a

comparison with data on foot deformities.

Monaghan GM, Lewis CL, Hsu WH, Saltzman E, Hamill J, Holt KG.(2012) "Forefoot angle determines duration and amplitude of pronation during walking."

[Gait Posture. 2013 May;38\(1\):8-13](#)

The biomechanical mechanisms that link foot structure to injuries of the musculoskeletal system during gait are not well understood. This study had two parts. The purpose of part one was to determine the relation between clinical rearfoot and forefoot angles and foot angles as they make contact with the ground. The purpose of part two was to determine the effects of large vs. moderate values of both forefoot and rearfoot inversion angles at foot contact on foot kinematics. Clinical foot angle, the relationship between the foot and an axis extrinsically defined relative to the ground, was calculated from digital photographs taken in a prone position. During three speeds of over-ground walking, we measured frontal plane rearfoot and forefoot angle relative to the ground at foot contact, and the following stance phase kinematic measures: amplitude of rearfoot and forefoot eversion, duration of rearfoot and forefoot eversion, and duration between heel-off and onset of rearfoot and forefoot inversion. We found that the clinical forefoot angle predicted the forefoot angle at foot contact. Individuals with a large inversion forefoot angle at contact also had greater amplitude of forefoot eversion and everted longer during stance. We discuss the possible mechanisms for the increased risk of injury to the hip reported for individuals that have a large clinical forefoot angle in non-weight bearing. Equally important is the finding that rearfoot angle at contact did not predict the motions of the rearfoot or forefoot during stance.

Lin SC, Chen CP, Tang SF, Wong AM, Hsieh JH, Chen WP.(2013) "Changes in windlass effect in response to different shoe and insole designs during walking."

[Gait Posture. 2013 Feb;37\(2\):235-41.](#)

Windlass effect occurs during the pre-swing phase of gait cycle in which the peak tensile strain and force of the plantar aponeurosis (PA) is reached. The increased dorsiflexion angle of the 1st metatarsophalangeal (MTP) joint is the main causing factor. The aim of this study was to investigate thoroughly in finding the appropriate shoe and insole combination that can effectively decrease the windlass effect. Foot kinematic analyses of 10 normal volunteers (aged 25.2 ± 2.1 years, height of 167.4 ± 9.1 cm, and weight of 66.2 ± 18.1 kg) were performed during gait under the conditions of barefoot, standard shoe (SS) with flat insole (FI) or carbon fiber insole (CFI), and rocker sole shoe (RSS) with FI or CFI. The shoe cover consisting of transparent polymer was used for accurate measurement of kinematic data as specific areas on the cover can be cut away for direct placement of reflective markers onto the skin. Under barefoot condition, the mean of maximum dorsiflexion angle of the 1st MTP joint was measured to be $48.0 \pm 7.3^\circ$, and decreased significantly to $28.2 \pm 5.7^\circ$ when wearing SS with FI, and $24.1 \pm 5.7^\circ$ when wearing SS with CFI. This angle was further decreased to around 13° when wearing RSS with FI or CFI. Subjects wearing footwear alone can increase the minimum medial longitudinal angle and decrease the maximum plantarflexion angle of metatarsus related to the calcaneus as compared with barefoot condition, resulting in flatter medial foot arch. Results suggested that RSS is the effective footwear in reducing the windlass effect regardless the type of insole inserted. The findings in this study provided us with the evidences in finding the appropriate footwear for treating foot disorders such as plantar fasciitis by effectively reducing the windlass effect.

Caravaggi P, Leardini A, Crompton R.(2010) "Kinematic correlates of walking cadence in the foot."

[J Biomech. 2010 Aug 26;43\(12\):2425-33.](#)

Evidence has frequently been reported of modifications in gait patterns within the lower limb related to the cadence of walking. Most reports have concerned relationships between cadence and kinematic and the kinetic changes occurring in the main joints and muscles of the lower limb as a whole. The aim of the present study was to assess whether significant changes are also measurable in kinematics of the foot segments. An existing 15 marker-set protocol allowed a four-segment foot and shank model to be defined for relative rotations between the segments to be calculated. Stereophotogrammetry was employed to record marker position data from ten subjects walking at three cadences. The slow- and normal cadence datasets showed similar profiles of joint rotation in three anatomical planes, but significant differences were found between these and the fast cadence. At all joints, frame-by-frame statistical analysis revealed increased dorsiflexion from heel-strike to midstance ($p < 0.05$) and increased plantarflexion from midstance to toe-off ($p < 0.05$) with increasing cadence. From foot-flat to heel-rise, the fast cadence kinematic data showed a decreased range of motion in the sagittal-plane between forefoot and rearfoot (3.2 degrees ± 1.2 degrees at slow cadence; 2.0 degrees ± 0.8 degrees at fast cadence; $p < 0.05$). The cadences imposed and the multisegment protocol revealed significant kinematic changes in the joints of the foot during barefoot walking.

Shod versus Barefoot

Sinclair J, Taylor PJ, Hebron J, Chockalingam N(2014) "Differences in multi-segment foot kinematics measured using skin and shoe mounted markers."

[The Foot and Ankle Online Journal 7 \(2\): 7](#)

Models with three segments have been implemented in order to represent the movement of the foot in a comprehensive way during walking and running, however the efficacy of mounting such a system of markers externally onto the shoe has not been explored. The aim of the current investigation was to determine whether 3-D three-segment foot kinematics differ between skin and shoe-mounted markers. Twelve male participants walked and ran at 1.25m/s and 4.0m/s along a 22 m runway. Multi-segment foot kinematics were captured simultaneously using markers placed externally on the shoe and on the skin through windows cut in the shoe. Wilcoxon tests were used to compare the 3-D kinematic parameters, and coefficients of multiple correlations (CMC) were employed to contrast the 3-D kinematic waveforms. Strong correlations were observed between the calcaneus-tibia waveforms $R^2 \geq 0.957$. However, at the more distal foot articulations lower correlations were found midfoot-calcaneus $R^2 \geq 0.484$, metatarsus-midfoot $R^2 \geq 0.538$ and metatarsus-calcaneus $R^2 \geq 0.335$. Significant differences between in discrete kinematic parameters were also observed between skin and shoe mounted markers, at the midfoot-calcaneus, forefoot-midfoot and forefoot-calcaneus articulations. The results indicate that shoe mounted markers do not fully represent true foot movement, and should therefore be interpreted with caution during examination of multiple-segment foot kinematics.

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