THE EVALUATION OF FOOT JOINT ANGLES AND FORCES DURING WALKING

Sumanth Babu Yalamanchili[1], Suresh Babu Surapaneni[2], Weijie Wang[3], Rami J. Abboud[4]

[1]Assistant Professor, Department of Orthopaedics, Dr. Pinnamaneni Siddhartha Institute of Medical Sciences and Research Foundation, Chinnaoutpalli, Andhra Pradesh.
[2]Professor, Department of Orthopaedics, Dr. Pinnamaneni Siddhartha Institute of Medical Sciences and Research Foundation, Chinnaoutpalli, Andhra Pradesh.
[3]Lecturer, Department of Orthopaedic and Trauma Surgery, TORT Centre, University of Dundee, Scotland, UK.
[4]Course Director, Department of Orthopaedic and Trauma Surgery, TORT Centre, University of Dundee, Scotland, UK.

ABSTRACT

BACKGROUND
Models such as the Plug-in-Gait model used in gait-analysis consider the foot as a rigid segment and are not adequate to interpret the foot kinematic and kinetic data. This study was to develop and validate a multi-segment foot model to measure the foot and the ankle kinetic and kinematic data during gait.

MATERIALS AND METHODS
Vicon® MX motion capturing system with 12 cameras, AMTI force plates, and Wang-foot model were used to evaluate the foot joint angles and forces in 23 subjects. The Vicon® motion system could not capture the complete trajectories for the markers in 12 subjects. Only 11 subjects with all data available around the force plate were analysed. Thirteen 9.5 mm retro-reflective markers were used to define a five-segment model. Subjects walked with the markers at their comfortable speed. Validation of the model was carried out by comparing the angles measured manually by a goniometer and angles calculated by our model on blocks mimicking the foot segments. Our model could calculate the angles and forces at the ankle, tarsometatarsal and metatarsophalangeal joints in three-dimensional planes.

RESULTS
Patterns obtained were comparable to normal walking and were consistent between subjects. There is significant amount of movement and force acting at the small joints of the foot and ankle, which the earlier models could not assess. This model adds a new function to the standard foot models and could be widely used in many fields like clinical assessment and sports medicine.

CONCLUSION
Wang-foot model is a simple tool to calculate the foot joint angles and force. This model can be used as a new tool to assess the foot and ankle joint movements and forces for patients, sportsmen and normal people. This is an advancement with additional functions over the Plug-in-Gait model.

KEYWORDS
Gait Analysis, The Foot, Joint Angles, Forces.

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BACKGROUND
Gait is the outcome of a complex interaction between many neuromuscular and structural elements of the locomotor system. Gait has been defined as "a method of locomotion involving the use of two legs alternatively, to provide both support and propulsion."[1] Earlier models such as the Vicon® Plug-in-Gait model used in gait analysis consider the foot as a single rigid segment. They had only two markers to track the foot and the ankle complex. Hence, the data interpreted from these models did not give much information on the intertarsal and tarsometatarsal joints. Several researchers used markers attached to the skin over the small bones of the foot to interpret the data.[2,3,4] However, very few studies presenting the kinematic and kinetic data of the foot using a multi-segmented model have been published.[5]

This study is being undertaken to develop a new model to measure the foot joint angles and forces during walking. This project may be helpful in understanding and developing a multi-segmented model and to evaluate the kinematic and kinetic data of the foot during walking. The aim of this study was to validate a new model using the designed markers placed on the foot to measure the movements of the foot joints and forces.

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Corresponding Author:
Dr. Suresh Babu Surapaneni,
Suresh Ortho & Multi-Speciality Clinic,
56-2-18, Koneru Satyanarayana Street,
Canara Bank Road,
Patamata, Vijayawada-520010.
Krishna District, Andhra Pradesh, India
E-mail: drssureshbabu@yahoo.com
DOI: 10.14260/jemds/2017/31

MATERIALS AND METHODS
Twenty-three subjects with an age range of 30 to 43 years were evaluated. Only eleven subjects were selected for the study (Table 1). The average age of the subjects was 32 years. All of them were male and the right foot of each subject was only evaluated. Subjects with previous lower limb injuries and current conditions affecting gait were not considered for the study. Twelve subjects were excluded from the study. Of the twelve subjects, Vicon® motion analysis system could not capture the markers during various stages of gait in six

subjects. In six subjects, the software and model could not calculate the angles, because parts of the markers have not got a complete trajectory, hence they were excluded.

The instrumentation used in the current study were Vicon® MX 1.3 motion capture system manufactured by Oxford Metrics Limited, Oxford, U.K., AMTI force plates (Figure 1) and the software packages used include Vicon® Workstation, Vicon® Bodybuilder and Vicon® Polygon, and our indigenously developed model (Figure 2). Thirteen 9.5 mm diameter spherical reflective markers were used to determine five segments, i.e. the tibia, the talus, the calcaneum, the metatarsals and the phalanges (Figure 3, Table 2). Data obtained from the force plates and the cameras were analysed by the software.

Our Model
A model and its implement software were developed. This model considers the foot into several segments, the tibia, the talus, the metatarsus, the calcaneum and the phalanges. The angles at the ankle, the talocalcaneal, the tarsometatarsal and the metatarsophalangeal joints can be calculated with this software.

Validation of the Model
An experiment was done in order to validate the model. Reflective self-defined markers were specifically placed on the small blocks, mimicking the segments of the foot. The angles of these segments were measured manually with a goniometer. Trials were recorded using the Vicon® motion system. Marker data was captured and processed using our model. The results obtained from our model were similar to the angles measured manually with the goniometer. Hence, our model is reliable, repeatable and ready for use.[6]

Measurement Protocol
The cameras were calibrated for camera positioning and aperture setting. Subjects were asked to stand still with both feet over the AMTI force plates facing the cameras. The data were collected simultaneously from the markers and the force plate. Dynamic trials were recorded with the subjects walking at their natural pace. The subjects were instructed to walk along the walkway from one end to the other. Minimum of ten trials were recorded for each individual. Only the data from the right foot with a proper heel strike and stance phase over the force plate and with all the markers visible were used for further calculation and analysis.

Data Analysis
The gait cycle events were marked for these trials. Each trial was then processed using the pipeline feature of the Workstation and three-dimensional-lined model was generated. The processed trials and marker position were imported to the Bodybuilder. Wang-foot model was attached to the trials and the data were calculated to obtain joint parameters, e.g. angles and forces. The data from the force plates and the joint angles calculated by Wang-foot model were analysed. The averages of the angles and forces were displayed using Polygon.

RESULTS
The study group comprised of eleven healthy male volunteers in the age group of 30-35 years average age 32, standard deviation 1.732 (Table 1). Sometimes, Vicon® motion capturing system could not collect the complete marker trajectories in the swing and the stance phase of the gait cycle in twelve subjects out of 23 subjects. Hence, only eleven subjects were analysed. Data were analysed using the Wang-foot model and the joint angles and forces were displayed using the Polygon. Angles at the ankle, tarsometatarsal, metatarsophalangeal joints (Table 3) and the force loads for the ankle, calcaneum, metatarsals and phalanges (Table 4) were obtained. The data were obtained in the sagittal, frontal and transverse planes.

Angles
The Ankle Joint
The range for average angles at the ankle joint in the sagittal plane ranged from 15° to -5° (Figure 4.1). In the initial 10% of the cycle, i.e. the heel strike, the angle was plantar-flexed to 10° and then was dorsiflexed until -5° during the mid-stance phase. At the toe-off phase, the angle reached its peak about by the end of stance phase. The angle was 15° at the end of stance phase by about 60% of the cycle. The ranges of movements at the ankle in the frontal and transverse planes did not show much variation (Figure 4.2 and 4.3). The ranges of movements at the ankle in frontal and transverse planes were around some constant values depending on individuals.

The Tarsometatarsal Joint
The range for average angles at the tarsometatarsal joints in the sagittal plane was from -17° to 4° (Figure 5.1). In the mid-stance or single stance phase, the change in the angle was less. There was only 4° change in the angle. In the toe-off phase, by about 50 to 60 percent of the cycle the angle was plantar-flexed into its maximum about -16°. The average range at the tarsometatarsal joints in the frontal plane was between 2° and -2° (Figure 5.2). The movement taking place at the tarsometatarsal joint in the frontal plane is not much. There is lateral movement at the joint during the initial 10% of the cycle, which becomes a medial movement by around 50% of the cycle. The range of motion at the tarsometatarsal joints in the transverse plane is 17°, from 12° to -5° (Figure 5.3). In the transverse plane, the tendency of the tarsometatarsal joint is the same as in the frontal plane. The foot tends to rotate laterally in the initial 10% of the cycle and as it rotates medially as it approaches toe-off.

The Metatarsophalangeal Joint
The average range of movement at the metatarsophalangeal joints in the sagittal plane is 40°, from 5° to 45° (Figure 6.1). During the heel-strike phase, the metatarsophalangeal joints start plantar-flexing. In the single stance phase, there is not much of a difference in the joint angles, but as the toe-off approaches by about 60% of the cycle the angle reaches a maximum dorsiflexion of 40° (Figure 6.1). The average range of motion at the metatarsophalangeal joints in the frontal plane is seven degrees from -2° to -9°. The pattern is similar to the angles in the sagittal plane, but the amount of movement at 60% of the cycle at the toe-off phase is only seven degrees (Figure 6.2). In the transverse plane during the single stance phase, the angles remain constant for about 50% of the cycle. The average range of motion is 14° from 7° to -7° (Figure 6.3). The change in the angles is more evident during the toe-off phase, similar to the movement in the sagittal and frontal planes.

Forces

The Ankle

The forces at the ankle joint take place in most of the stance phase of the gait cycle. Hence, the forces are transmitted through the ankle throughout the stance phase. Forces across the ankle are transmitted in all the three planes, but maximum values occur in the sagittal plane. The force across the ankle in the horizontal direction is eight (N/Body Mass, Figure 7.1). Major force across the ankle is transmitted in the vertical direction. The force in the vertical direction is 30 (N/Body Mass, Figure 7.2). The force in the vertical direction is nearly three times that of the body mass. The ankle joint force curves cover almost whole of the stance phase from zero to sixty percent of the gait cycle.

Calcaneum

The force across the calcaneus is transmitted mainly during the heel-strike phase of the gait cycle. Force acts on the calcaneus mainly during the initial 20% of the stance phase. It is noted that only during the initial impact most of the force is transmitted through the calcaneus.

Maximum force transmitted through the calcaneus in the horizontal planes is fifteen (N/Body Mass, Figure 8.1). The maximum force acting on the calcaneus in the vertical direction is 22 (N/Body Mass, Figure 8.2). The maximum force is noted at about 20% of the gait cycle. There is not much force acting at the end of the gait cycle. This may be due to double stance phase, where the phalanges and other bones play a major role.

The Metatarsals

Forces across the metatarsals are transmitted after the heel-strike phase. There is not much force on the metatarsals during the initial 10% of the gait cycle. The forces at the metatarsals are present throughout the stance phase, till about 60% of the gait cycle. The maximum force acting on the metatarsals is eight (N/Body Mass) in the medio-lateral direction (Figure 9.1) and 21 (N/Body Mass) in the antero-posterior direction (Figure 9.2). In the vertical plane, the force reaches its maximum about 23 (N/Body Mass, Figure 9.3). It is noted that in both the antero-posterior and vertical directions, the forces have similar values.

The Phalanges

Most of the force through the phalanges is transmitted during the latter half of the stance phase. There is a steep increase in the force acting on the phalanges during the toe-off as expected. During the initial half of the stance phase, there is not much force acting on the toes. Maximum force acting on the phalanges is eight (N/Body Mass) in the medio-lateral direction (Figure 10.1) and eleven (N/Body Mass) in the antero-posterior direction (Figure 10.2). The force acting on the phalanges is maximum in the vertical direction. In the first half of the stance phase, there is not much force acting on the phalanges. The force is maximum during toe-off, because all the toes will take the force during the toe-off where the maximum force acting on the phalanges in the vertical direction is 28 (N/Body Mass, Figure 10.3).

	Average	Standard Deviation
Age	32	1.732
Height	172.82	6.655
Weight	76.22	12.879
Body mass index	25.55	3.696
Foot length	26.79	0.988
Width of the foot	10.1	0.3741

Table 1. Age and Anthropometric Data of 11 Subjects

Marker	Location of Markers
1	Medial joint line of knee
2	Lateral joint line of knee
3	Antero-medial aspect of tibia
4	Medial malleolus
5	Lateral malleolus
6	Calcaneal tuberosity
7	Lateral aspect of the calcaneus
8	Base of the 2nd metatarsal
9	Head of first metatarsal
10	Head of fifth metatarsal
11	Nail of 1st phalanx
12	Nail of 5th phalanx
13	Mid-point between 2nd and 3rd metatarsal heads

Table 2. The Marker Placement for Static and Dynamic Trials

	Sagittal	Frontal	Transverse
Ankle	15º to -5º	0º to 2º	0º to 2º
Tarsometatarsal	-17º to 4º	2º to -2º	12º to -5º
Metatarsophalangeal	5º to 45º	-2º to -9º	7º to -7º

Table 3. Angles Calculated by Our Model

	Vertical	Antero-Posterior	Medio-Lateral
Ankle	30 N/ Body mass	8 N/ Body mass	8 N/ Body mass
Calcaneum	22 N/ Body mass	15 N/ Body mass	15 N/ Body mass
Metatarsals	23 N/ Body mass	21 N/ Body mass	8 N/ Body mass
Phalanges	28 N/ Body mass	11 N/ Body mass	8 N/ Body mass

Table 4. Forces Calculated by Our Model

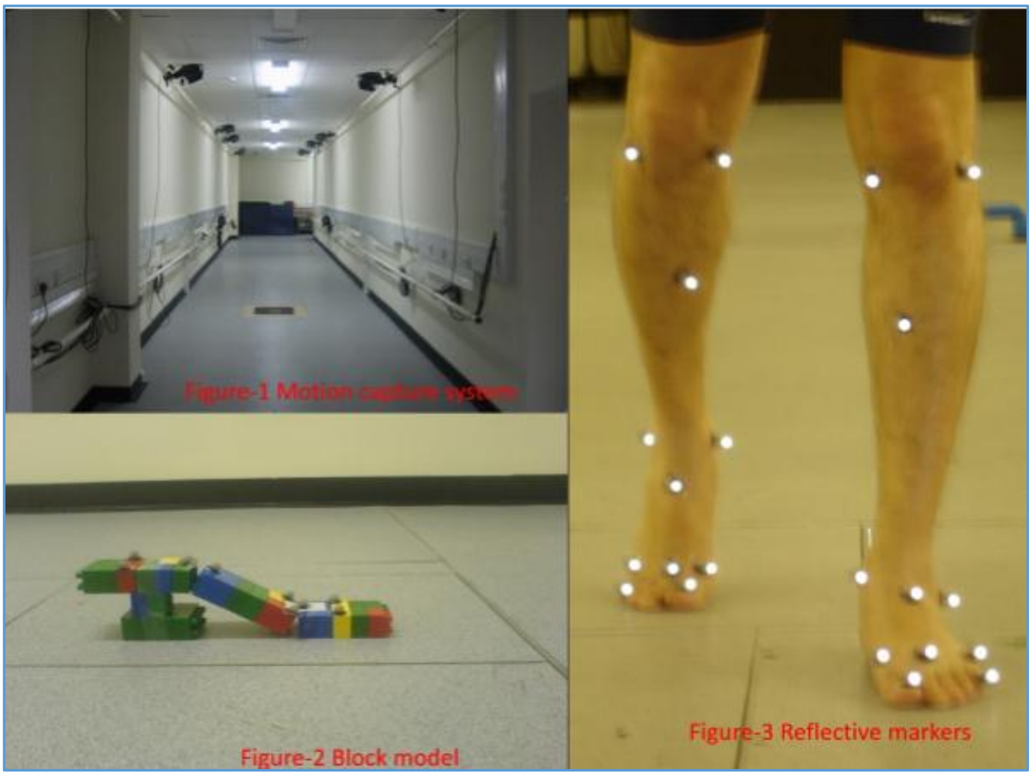


Figure 1. Vicon® MX Motion Capturing System
Figure 2. Validation of Our Model
Figure 3. Subject with the Reflective Markers

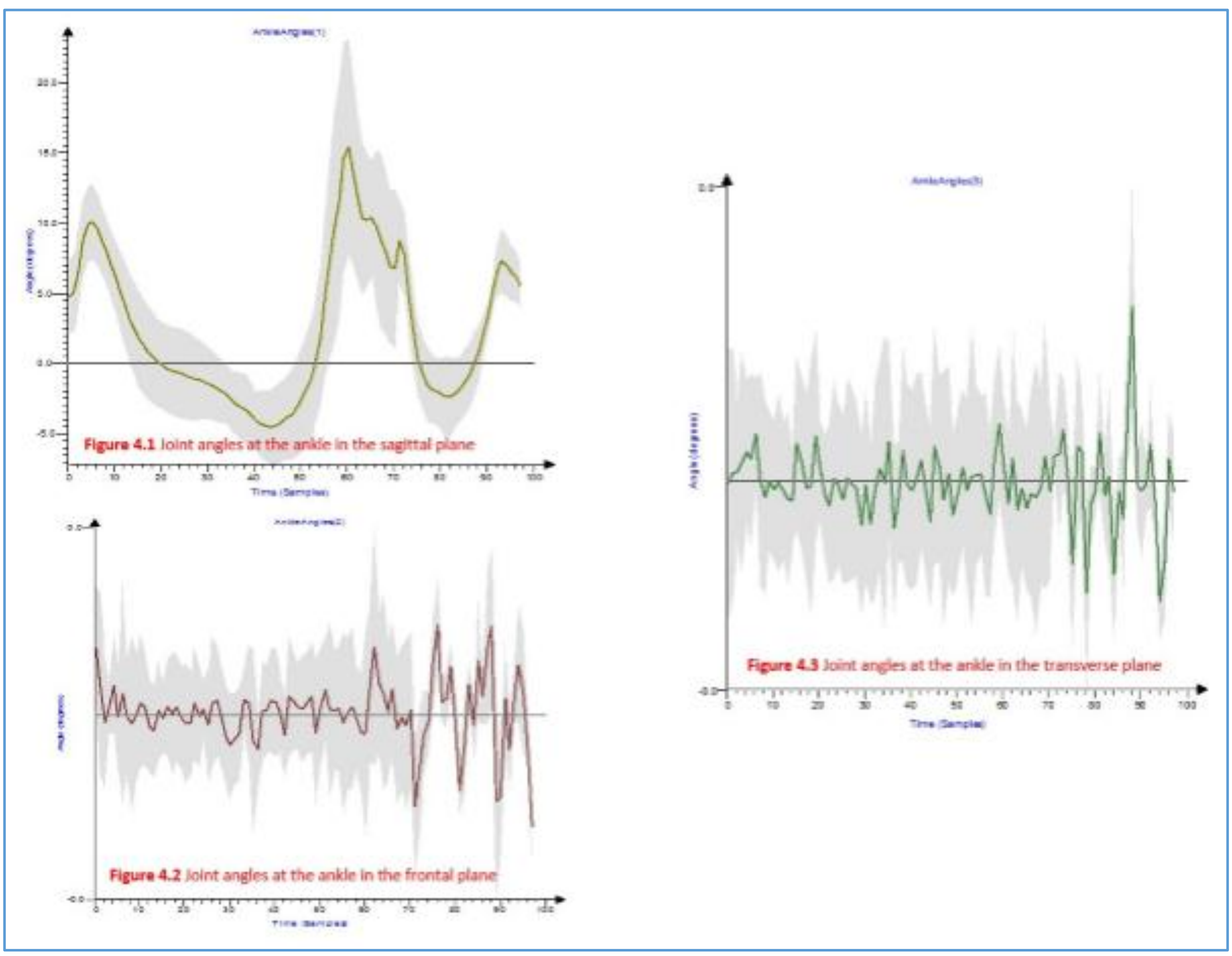


Figure 4.1 Joint Angles at the Ankle in the Sagittal Plane
Figure 4.2 Joint Angles at the Ankle in the Frontal Plane
Figure 4.3 Joint Angles at the Ankle in the Transverse Plane

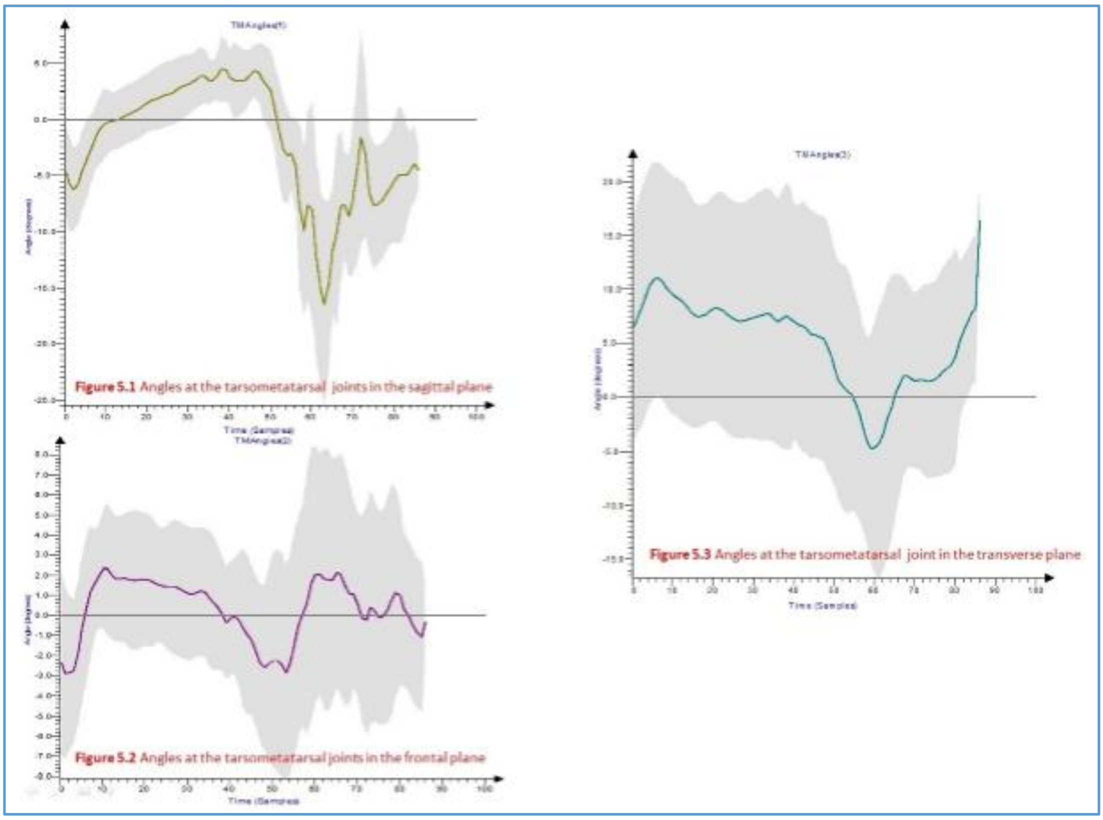


Figure 5.1 Angles at the Tarsometatarsal Joints in the Sagittal Plane
Figure 5.2 Angles at the Tarsometatarsal Joints in the Frontal Plane
Figure 5.3 Angles at the Tarsometatarsal Joint in the Transverse Plane

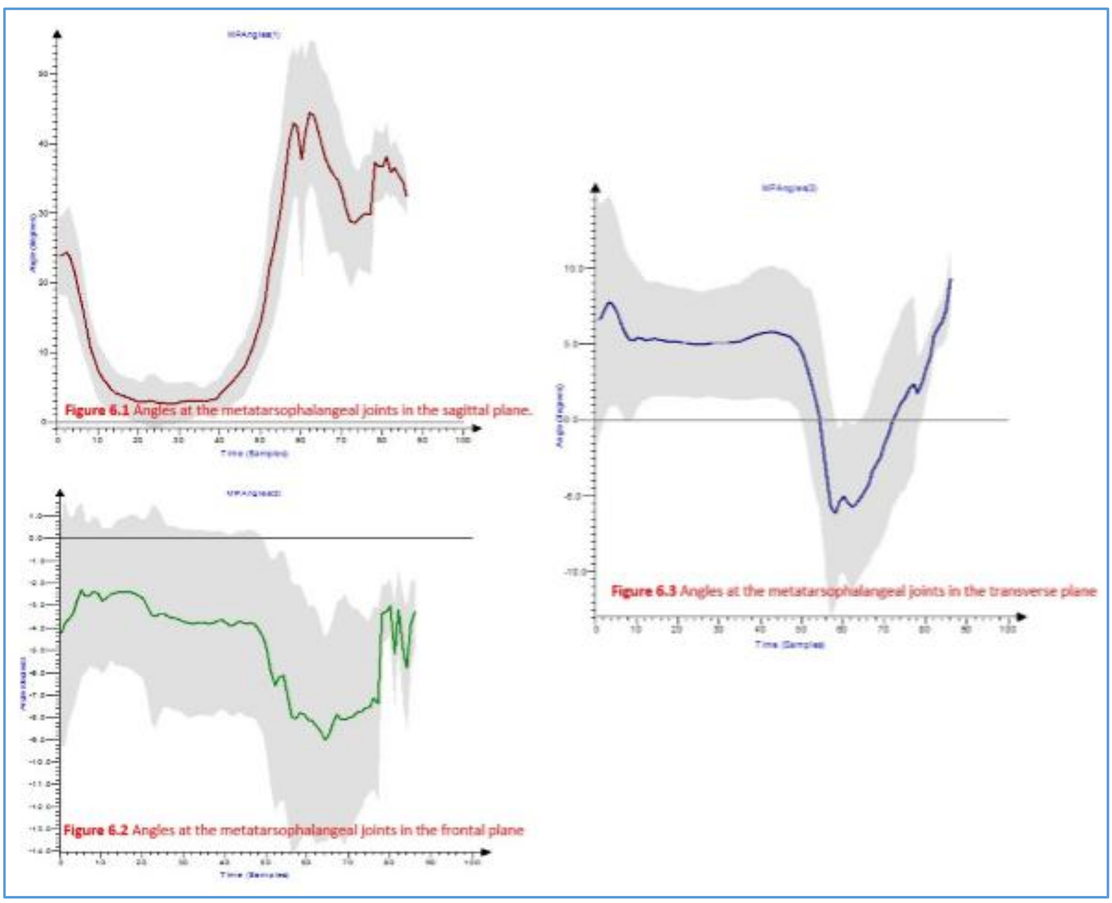
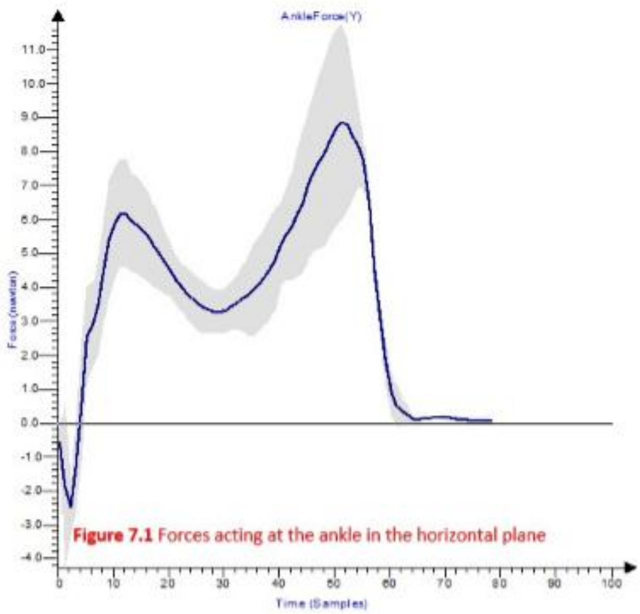


Figure 6.1 Angles at the Metatarsophalangeal Joints in the Sagittal Plane
Figure 6.2 Angles at the Metatarsophalangeal Joints in the Frontal Plane
Figure 6.3 Angles at the Metatarsophalangeal Joints in the Transverse Plane



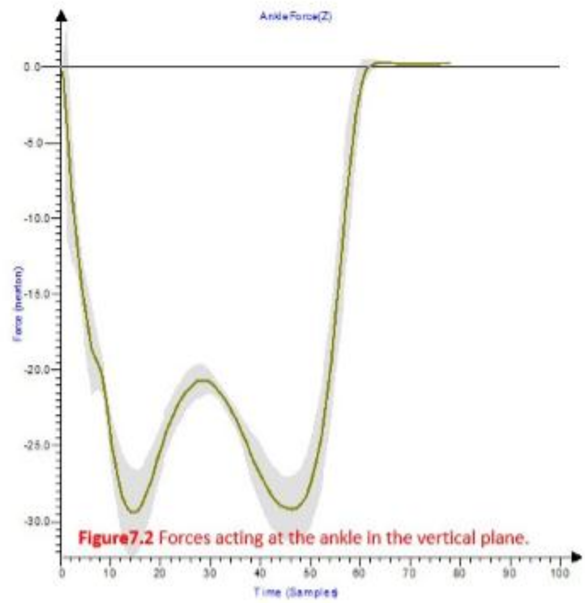
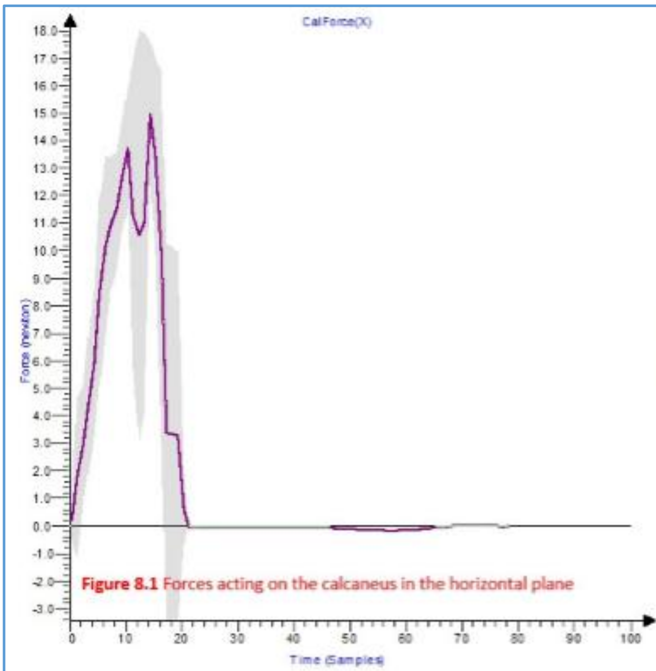


Figure 7.1 Forces Acting at the Ankle in the Horizontal Plane
Figure 7.2 Forces Acting at the Ankle in the Vertical Plane



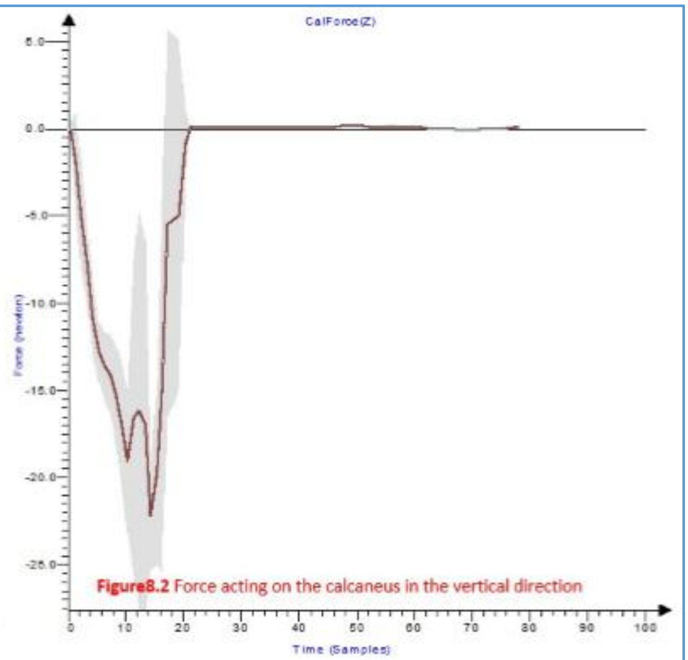


Figure 8.1 Forces Acting on the Calcaneus in the Horizontal Plane
Figure 8.2 Forces Acting on the Calcaneus in the Vertical Direction

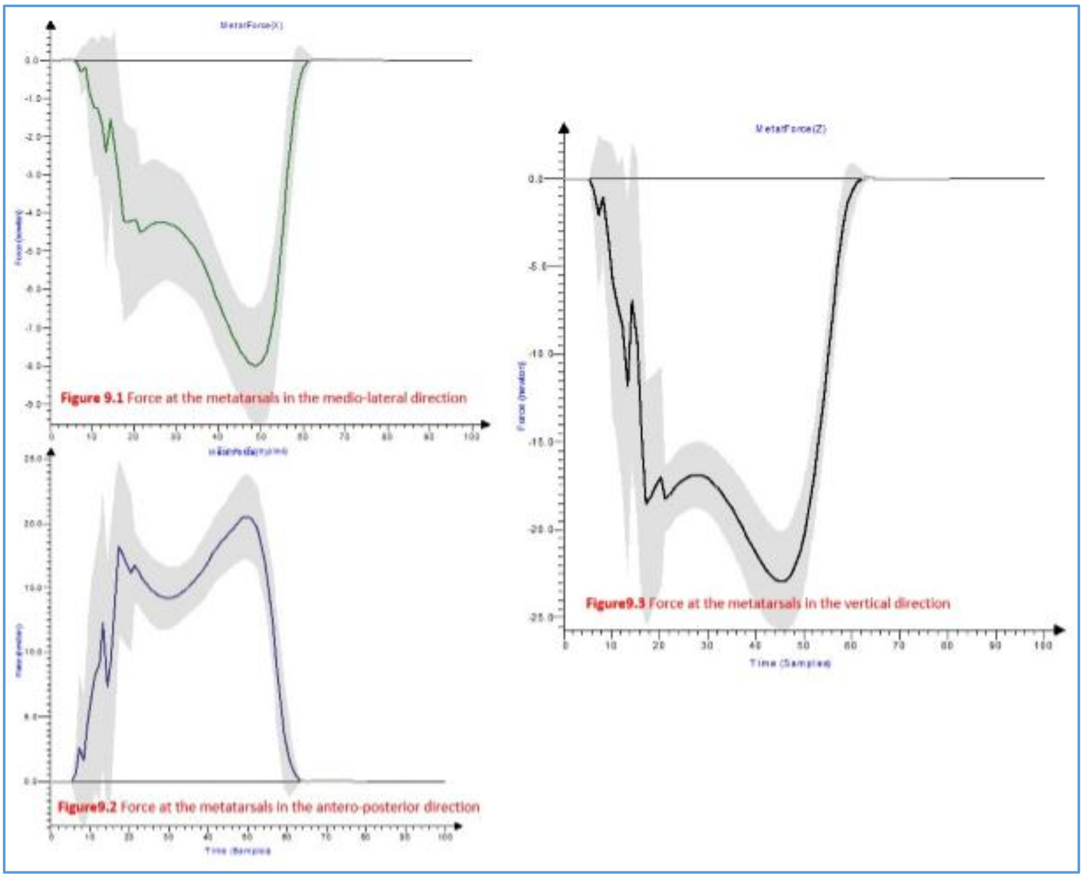


Figure 9.1 Force at the metatarsals in the medio-lateral direction

Figure9.2 Force at the metatarsals in the antero-posterior direction

Figure9.3 Force at the metatarsals in the vertical direction

Figure 9.1 Forces at the Metatarsals in the Medio-Lateral Direction
Figure 9.2 Forces at the Metatarsals in the Antero-Posterior Direction
Figure 9.3 Forces at the Metatarsals in the Vertical Direction

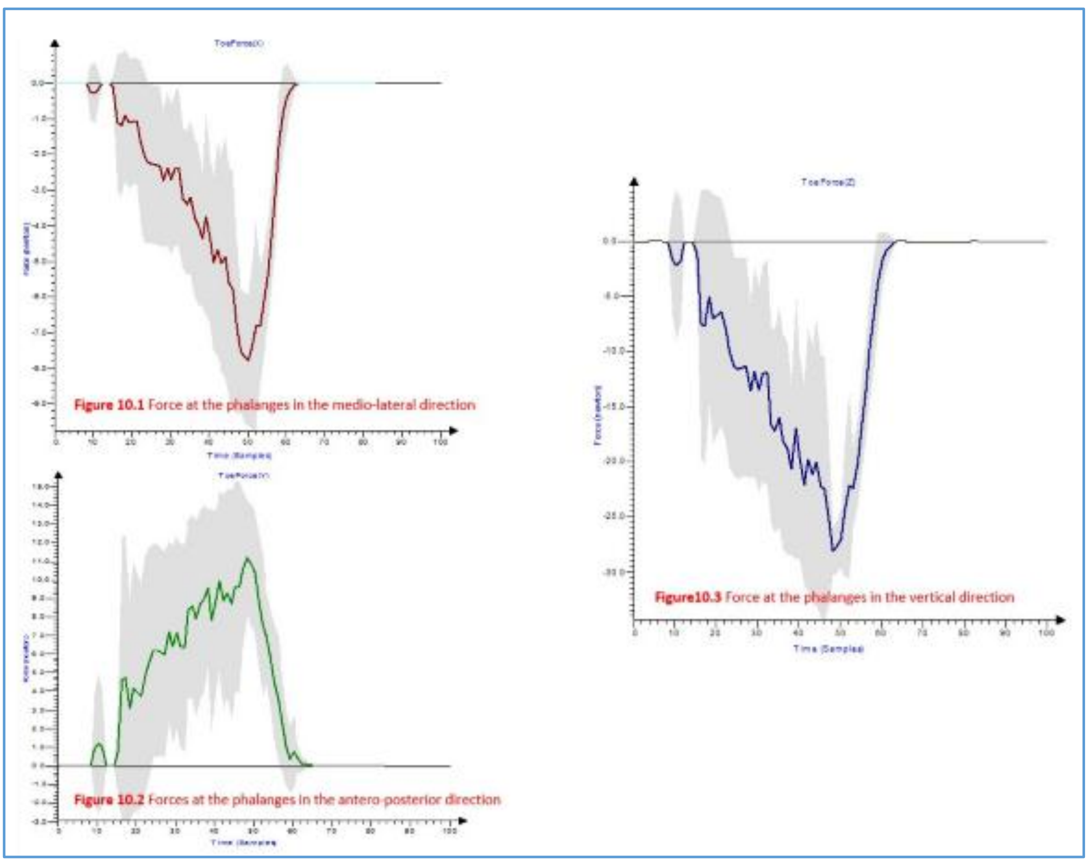


Figure 10.1 Force at the phalanges in the medio-lateral direction

Figure 10.2 Forces at the phalanges in the antero-posterior direction

Figure10.3 Force at the phalanges in the vertical direction

Figure 10.1 Forces at the Phalanges in the Medio-Lateral Direction
Figure 10.2 Forces at the Phalanges in the Antero-Posterior Direction
Figure10.3 Force at the Phalanges in the Vertical Direction

DISCUSSION

The goal of the present study was to calculate the foot joint angles during walking to validate the model and finally if established to discuss the possibility of application of the model in clinical applications. During the heel-strike for the initial 10% of the stance phase, the ankle is in plantar flexion and begins to dorsiflex at the single stance phase. At the toe-off, the ankle is in plantar flexion as well. This pattern was similar to earlier studies.[7] There is not much of movement taking place at the ankle in the frontal and transverse planes. The pattern of the angles in the sagittal plane showed that the tarsometatarsal joint is in dorsiflexion for almost 50% of the cycle. The joint goes into plantar flexion at the late stance phase, and at the toe-off. In the frontal plane, there is not much movement taking place at the tarsometatarsal joint. There is a lateral movement at the joint in the initial phase, which becomes medial by around 50% of the cycle. There is a minimal average angle of 17° in the transverse plane and the pattern of movement is similar to the movement in the frontal plane. The metatarsophalangeal joint angles attain maximum dorsiflexion during the toe-off. During the first 40% of cycle in the mid-stance phase, the angles remain constant. The forefoot is in plantar-flexion initially and dorsiflexes during toe-off. Initially, the forefoot rotates laterally, but by the end of the stance phase it rotates medially in the transverse plane. In the frontal plane, there is progressive eversion at the metatarsophalangeal joints.

The forces at the ankle joint were acting in vertical, horizontal and transverse planes. Major force at the ankle and calcaneum was transmitted in the vertical direction. The calcaneum takes the major amount of force during the initial 20% of the cycle at the heel strike.

There was not much force acting on the calcaneum during the rest of the stance phase until the next heel strike. In the horizontal plane, the force at the calcaneum was larger than the force acting at the ankle, because during heel strike the calcaneum plays a major role at the initial contact to bear the load. The force at the ankle was transmitted throughout the stance phase. The ankle joint force curves in the pedobarographs show that force was acting for almost 60% of the stance phase. Major force through the ankle is transmitted in the vertical direction. The force at the ankle in the medio-lateral and antero-posterior planes is almost similar. The forces at the metatarsals were not much at heel strike during the initial 10% and at 60% of the cycle showing that the force mainly acts on the calcaneum and ankle during the heel strike. The force at the metatarsals was maximum in the vertical direction and present for almost the remaining of the stance phase. The force acting was slightly larger in the antero-posterior plane compared to the medio-lateral plane. The force at the toes was maximum at the late stance phase as expected, because the toes take the major load only during toe-off. During toe-off, the force was transmitted through all the toes. The force on the toes was not significant during the first-half of the stance phase. The results obtained from this study suggest that the graphs from the analysis of the data were identical to the pattern of walking and the movement of the joints of the foot and ankle. The force data obtained suggests the exact patterns of loading on the foot and ankle during various stages of stance phase. The results of the present study suggests that the Wang-foot model is a simple tool to calculate the foot joint angles and force. This model can be used as a new tool to assess the foot and ankle joint movements and forces for patients, sportsmen and normal people. This is advancement with additional functions over the Plug-in-Gait model.

Shortcomings of Our Model and Suggestions

Our model considers the lower limb and foot as a 5 segment structure. If the lower limb and foot can be modelled into more segments, the details of individual joints of the foot can be obtained. However, if we consider more segments, the number of markers will increase. As the number of markers increases, more difficult it is to collect the data.

The difficulties we came across during our study in collecting the complete trajectories for the markers could be overcome by positioning the camera system around the volume to be collected, around the force plate. Further studies should be considered to model the foot and ankle into more segments with smaller size markers. The models in future should be designed to collect the pressure and the force data together.

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