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Biomechanical Modeling of Human Foot using Finite Element Methods

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Abstract

Objective: Studies involving in vivo experimentation in human beings requires ethical clearance, and it is cumbersome due to existing laws and procedures. This research aims at developing a 3D anatomically realistic model of the ankle joint and the foot. **Methodology:** The Computed Tomography (CT) images of the human foot were captured. Using image reconstruction technique, the outer surface of the various components of the foot including the 26 bones, plantar fascia, Achilles tendon and other ligaments were developed. **Findings:** Applying the necessary boundary and loading conditions on the mechanical model, the internal stress distribution under different conditions of the foot were calculated and compared with published literature. **Applications/Improvements:** Upon validation, this model can be used to study the behavior a deformed/diabetic foot by altering suitable material properties of the foot. Further, the detailed study on the design of custom foot orthoses may be performed to counter effect the foot deformity.

Keywords: Finite Element (FE) Model, Human Foot, Image Reconstruction

1. Introduction

The in-vivo study on testing of implants, prostheses and other fixation devices in human requires the ethical approval. In some cases, the experiments are done in animals to provide the physiopathological response in living bodies[1]. These results cannot be directly used to solve human behavior since the properties of the tissues and its functions are different. To overcome the above challenge, a musculoskeletal model of the human body has to be developed which would act as a powerful tool to study its biological structures[2]. Many researchers[2-6] are working in developing the finite element model of the human joints which enables to study the biomechanical interactions of each part and the internal displacement of the components with reference to the external stimulus. This study attempts to develop a finite element model of the human ankle-foot complex. The input for the finite element model were obtained from the medical imaging techniques like Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). These methods are used to capture the anatomical structure of the humans. Though both MRI and CT offer the advantage of capturing the soft tissues like tendons and ligaments in the foot as well as the hard bony structures, generally CT is preferred over MRI as it is economical[7-10].

The foot is a multi-bone structure with many joints and movements. It combines mechanical complexity and structural strength. Anatomically the human foot contains 26 bones, 33 joints, 107 ligaments and 19 muscles[11,12]. All these components must work in unison to provide support, balance, and mobility. A structural deformity or any malfunction of the foot results in the development of problems elsewhere in the body; similarly, an abnormality in any other parts of the body leads to problems in the feet[13,14]. The common foot abnormalities in humans are the flat foot, weakened transverse arch, hallux valgus, hammer toe, talipes, pescavus, hump foot, hollow claw foot[12]. The structural arrangement of the healthy human foot is depicted in Figure 1.

Study on the effects of structural characteristics of the bones in the foot on plantar pressure distribution and

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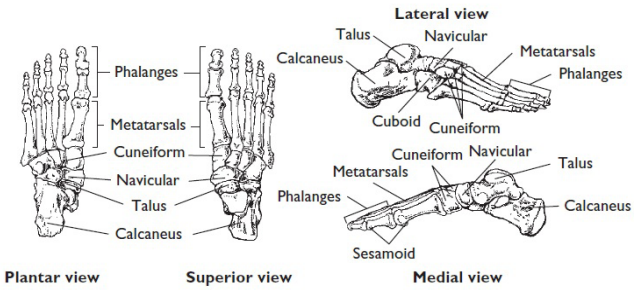

Figure 1. Anatomy of foot.

stress concentration in the bones are very much required for individualized treatment for various foot deformities[15]. As the body propels forward during locomotion, one of the legs acts as a support enabling another leg to proceed forward for a new location[16]. Then the roles of legs will be reversed that assists in locomotion. The gait cycle starts when one foot makes contact with the ground and ends when that same foot contacts the ground again. Few[17-22] has performed human foot analysis based on experimental work using pressure sensors, pedobarograph and gait analysis setup. These experiments do not well support the lack of technological advancement in the experimental measurements, the mechanism for load transfer and stress in the inner cross section of the bones. In tune with this problem, many researchers[23-26] are working in developing a virtual model of biological systems, with which the finite element analysis can be performed on these models to study its behavior in the given loading conditions. In addition to the stress distribution in the foot complex, the stress-strain relation and the deformation or growth pattern of the foot can be studied.This study aims at developing a comprehensive finite element model of the foot by reconstructing the CT images. In addition to the 26 bones of the foot, the Achilles tendon, plantar fascia, and few ligaments were also modeled. This model would help us in finding the effect of the change in stiffness of the soft tissues on internal stress distribution and mechanism of load transfer in the foot.

2. Image Reconstruction

As per the approval from the Institutional Ethics Committee vide clearance number 965/IEC/2016, a female subject (21 years, 136 cm and 600 N) with no history of foot deformities is selected for this study. After The subject is explained about the process and after obtaining the consent form, Computed Tomograms (CT) of the left foot were acquired using a SIEMENS Somatom Spirit with a slice thickness of 1 mm as shown in Figure 2.

Figure 2. SIEMENS Somatom Spirit Scanner.

The digitized CT images were imported into image processing software MIMICS v10 (Materialise, Leuven, Belgium) for reconstruction and to obtain the skeleton boundary and the surface of the soft tissues as shown in Figure 3.

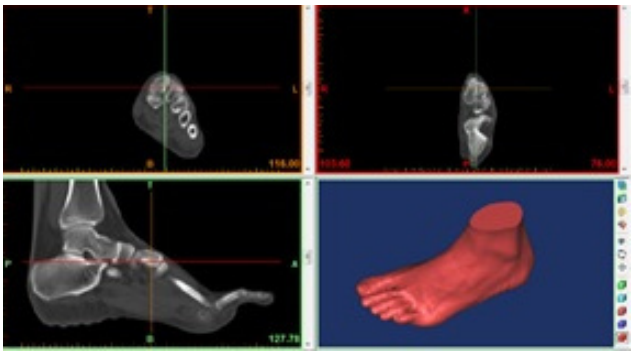

Figure 3. CT images imported in Mimics.

Based on threshold values, the surface model of the individual bones in the foot are generated using windowing and segmentation. The bones in the hindfoot, midfoot and forefoot are differentiated by providing different colors for better visualization as shown in Figure 4.

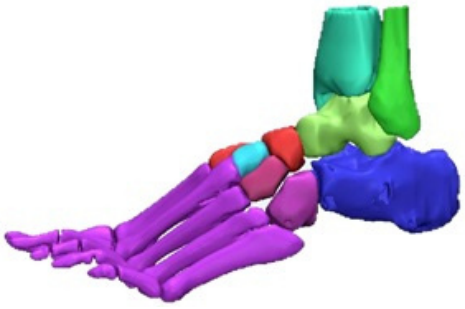

Figure 4. Individual bones of the foot.

The contours of the various entities in the foot like the bones, Achilles tendon, plantar fascia, inferior tibiofibular ligaments, posterior ligaments and soft are gathered by adjusting the threshold values. These entities are edited to smooth out its complex profile. Smoothing operations were performed to remove the stacks due to 1 mm cut in CT images. Each layer is edited with reference to its adjacent layer and the solid model thus obtained is shown in Figure 5. This process preserves the anatomical features of the various components of the foot. By treating the outer

Figure 5. Complete model of foot.

surfaces of the skeleton and soft tissues, the solid of the foot including all the bones were modeled.

3. Finite Element Modeling

The model thus developed by image reconstruction was imported and processed in the FE package ANSYS 15. The solid model of the foot, as shown in Figure 5 contains 28 bones including the distal segments of tibia and fibula and the 26 bones of the foot. The phalanges were connected by the cartilage and other connective tissues.

The contact surfaces were defined between the various bones in the foot, and it allows the relative articulating movement. The contact between the joint surfaces are assumed to be frictionless and are represented using the surface-to-surface contact in ANSYS. The Achilles tendon, talo navicular ligament, deltoid ligament and the plantar fascia were meshed with 3D tetrahedral elements as shown in Figure 6.

Figure 6. Meshed model of the foot.

4. Material Properties

Even though the properties of foot vary along different location, for simplicity, the homogeneous property is assumed for all its components. Linear and elastic solid elements were selected for the components. The material properties of various elements of the foot were adopted from the published literature[27-30] and are listed in Table 1.

Table 1. Material Properties

Component	Modulus of elasticity (MPa)	Poisson's ratio	Element type
Bone	7300	0.3	3D tertahedron
Soft tissue	0.15	0.4	3D tertahedron
Cartilage	1	0.4	3D tertahedron
Ligament	260	0.4	3D tertahedron
Plantar Fascia	350	0.4	3D tertahedron
Ground support	20000	0.1	3D brick

5. Loading Conditions

For the different ambulatory activities of the foot the loading conditions are very complex, hence, in this study the standard bare foot gait during stance phase is considered. The motions in the varus-valgus and inversion-eversion angles were not considered as it is very small compared to the dorsi-plantar flexion angle. For performing the finite element analysis, the top surface of the ankle joint comprising of distal tibia and fibula along with the soft tissues were fixed. During Balanced Standing (BS) phase of the Gait cycle, the ankle joint is assumed to be in neutral position. A vertical force of 300 N representing half of the body weight is applied on each foot[31-33]. In addition to this load, 150 N is applied to Achilles tendon during balanced standing[34]. This force is represented by five equivalent vectors at the posterior extreme of the calcaneus. The loading condition of the foot is depicted in Figure 7.

6. Results and Discussion

For performing element analysis of the human foot, a 3D anatomical model is developed by image reconstruction. Under the stated loading and boundary conditions, the model thus developed can be

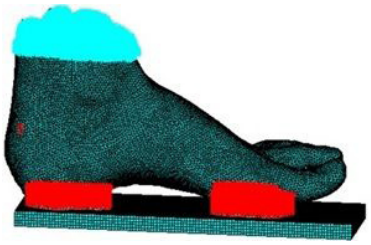

Figure 7. Loading conditions in human foot.

used for studying the stress distribution in the foot. Figure 8 depicts the Von Mises stresses in the foot during balanced standing.

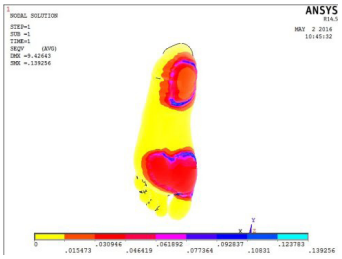

Figure 8. Von Mises stresses in the foot.

A peak stress of 0.139 MPa is observed in the heel region and the metatarsals experiences stresses ranging from 0.015 to 0.07 MPa. Similar FE analysis is performed for heel strike and toe-off phases, and the results are listed in Table 2 and depicted in Figure 9.

Table 2. Internal stress from FEA

Conditions	Stress (kPa)
Balanced standing (BS)	139
Heel strike (HS)	53
Toe off (TO)	210

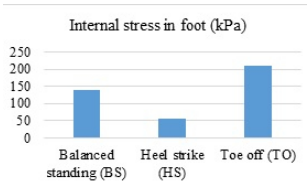

Figure 9. Internal stress in foot.

7. Conclusion

A 3D finite element model of the human foot which replicates/resembles the actual foot was developed in this study by stacking the CT slices by image reconstruction technique. The various components including the 26 bones, deltoid ligament, plantar fascia and achilles tendons were modeled which would be a new milestone achieved in this topic of interest. The subject-specific model is generated based on their geometry, and the corresponding loading conditions were applied to study the internal stress distribution in the foot for Balanced Standing (BS), Heel Strike (HS) and Toe-off (TO) phases during locomotion. The results conclude that the stress gradually increases from the HS (53 kPa), BS(139 kPa) and TO (210 kPa) respectively.

This model can be further validated by comparing the internal stress distribution calculated by experimental testing with the use of insoles or force plates for different phases of human locomotion.

8. Acknowledgement

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