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Finite Element Modeling and Validation of a Human Foot through experimental studies

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Abstract. The mechanical experimentation in human beings is practically very difficult due to various laws and procedures. The use of Finite Element (FE) model of the human parts has a significant effect in research. Foot, the most complex structure in human body consists of 26 bones and 33 joints. As reported in the existing literatures, several finite element foot models are developed by imposing simplifications on its anatomy by considering the ligaments as tension free link element, which has a significant variance compared to the experimental results. This paper attempts to develop and validate a realistic finite element model of a normal human foot with bones, muscles, tendons and ligaments mimicking the actual foot using Image Reconstruction Techniques (IRT). The finite element analysis on this model is performed to simulate the balanced standing condition by applying the necessary loading and boundary conditions. Under balanced standing condition, a maximum Von Mises stress of 0.139 MPa is observed in the heel region. For validating the results obtained from finite element analysis, the experimental studies with (i) Moticon insole and (ii) Noraxon's FDM-T SciFit Treadmill is conducted, which provided a variation of 4.3 % and 0.7 % respectively with FE studies.

1. Introduction

Foot is an anatomical structure found in most of the animals and it is the terminal portion of the limb in most cases. The main function of the foot is to support the weight of the body. During locomotion, the foot acts as a lever for propelling the body forward, thereby catering the needs of the vertebrates. The human foot is the complex analytical structure in the lower limb consisting of twenty six bones, thirty three joints, over hundred ligaments, nineteen muscles along with the soft tissues [1-2]. The foot complex with all elements lets one to stand upright and support in performing day to day activities like walking, running, jumping etc. Any deformity in the foot affects the posture and walking pattern of the subject. The Finite Element Modelling (FEM) is one of the tool used for investigating the biomechanical behaviour of foot under different conditions [3-6]. Many researchers developed the finite element foot models by assuming certain simplifications on its anatomy by replacing the ligaments as tension free link elements. This had a significant variance in the results of the finite element analysis as compared to the real/practical values [7-10]. This work aims in developing the finite element model of the human foot with all its components like ligaments, tendons, muscles and soft tissues, which provides realistic behaviour when tested under virtual environment.

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2. Image reconstruction

The subject (Female, 21 years, 60 kg, 170 cm with no foot deformity) selected for this study is taken to SRM Medical College Hospital and Research Centre, where the Computed Tomography (CT) scan of the subject's foot is taken using multi-slice SOMATOM® Spirit® scanner, with a resolution of 0.5 mm and slice intervals of 0.75 mm. The Computed Tomography images of the foot in Digital Imaging and Communications in Medicine (DICOM) format captured in Somatom Spirit scanner is then imported to Medical Imaging and Segmenting software called Materialise Interactive Medical Image Control System (MIMICS 14.0).

The preliminary step in developing 3D image from 2D DICOM data is the segmentation which is used to section the region of interest. The thresholding classifies the pixels based on Hounsfield range. The different bones in the foot are segmented, by setting an upper and lower threshold limits. After thresholding, the various components of the foot like bones, muscles, ligaments, tendons etc., can be separated by “masking” technique. The noise (floating debris or left over images) are removed by “Region Growing”. Further refinement in the mask is done by “Edit Mask” feature. . Any noise or disturbance, present outside the bounding region of the mask is segmented using “Crop Mask”. Further, for transforming the 2D images into 3D model, “Calculate 3D” is used.

In addition to the bones, the other components like ligaments, plantar fascia, and the Achilles tendon, are also segmented. The STL file of the segmented model, generated from MIMICS, is then exported to reverse engineering software (Geomagic Design X, Research Triangle Park, NC, USA). Geomagic Studio, a product of Geomagic Design X is used in converting the 3D point cloud data into highly accurate surface, polygon and native 3D CAD models, which is used for further studies. The “Wrap” command converts the point cloud data into polygons. The “mesh doctor” is used to identify and rectify the errors (non-manifold edges, self-intersection, creased edges, Spikes) in the model. The developed model of the bones, ligaments, Achilles tendon, after smoothening is saved in IGES file format for further processing. Figure 1 represents the refined model obtained from Geomagic Design X.

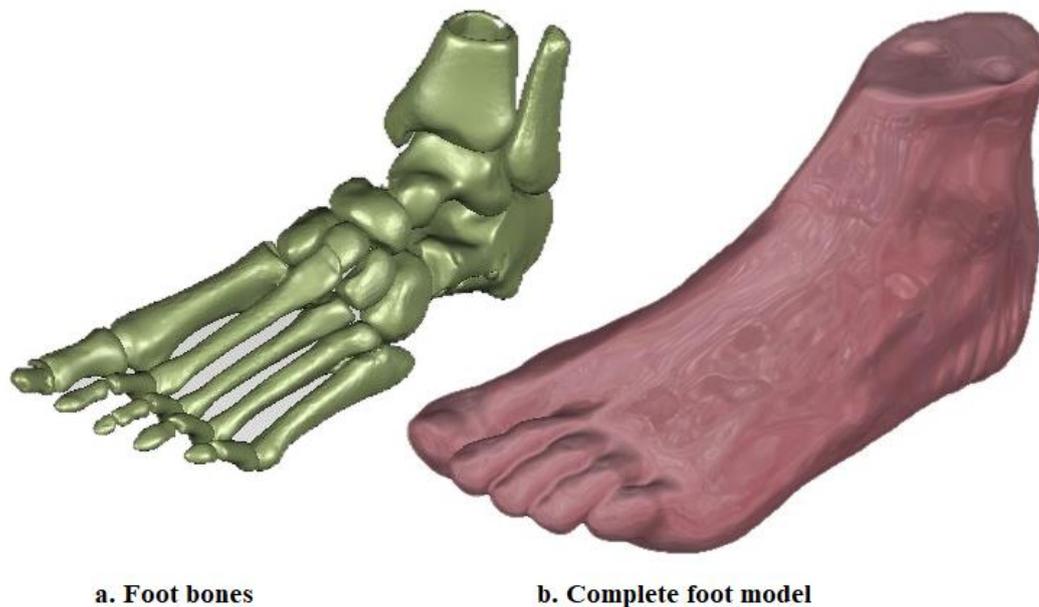


Figure 1. Refined 3D model of the foot[3].

3. Finite element analysis

The 3D model of foot bone and soft tissues is then imported in HyperMesh for meshing. HyperMesh is a finite element pre-processor that delivers excellent performance. Complex geometry like biological models or any other largest 3D models can be imported and processed to deliver the meshed model, which can be used for finite element analysis in various conditions. Solid 45 element is selected to mesh the model as it provides accurate results for the models with complex profiles. The meshed model is assigned with the material properties selected from established literatures [11-16] and listed in Table 1, to mimic the biological behaviour.

Table 1. Material properties of the human foot.

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

During stance phase, i.e., normal standing position, entire body weight is equally shared by each foot. Hence for the subject of weight 600 N, selected for this study, force vectors corresponding to 300 N (half of the body weight) is applied as the reaction force. In addition to this at the posterior extreme of the calcaneus, reaction force acting on the Achilles tendon of magnitude 150 N is represented by five equivalent force vectors [15]. Five axial connector elements inserted in the foot are used to define the contraction forces brought about at these points due to the tension in the Achilles tendon. The convergence study is then performed with different mesh sizes with the displacement in the foot as the primary criterion with the tolerance level under 5%. During the finite element analysis, the top surface of the foot comprising of distal tibia and fibula is fixed, as shown in figure 2. At the same time, point of load application at the center of pressure is constrained to move only in vertical direction.

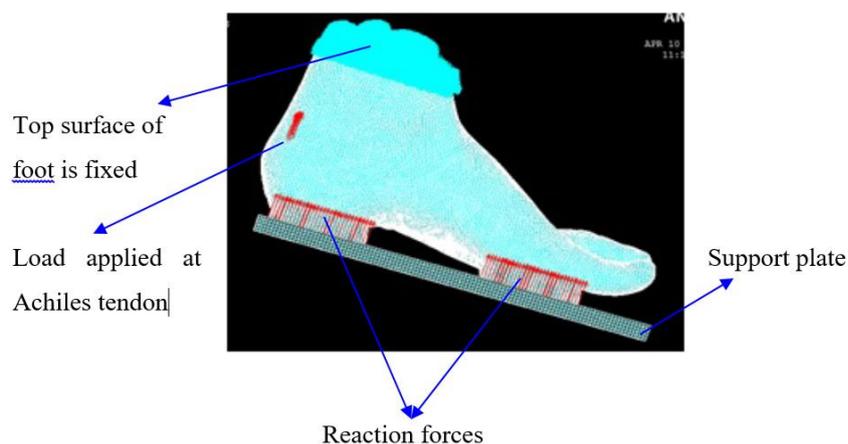


Figure 2. Loading and boundary conditions.

The finite element analysis is performed in the foot model under balanced standing condition otherwise termed as Stance Phase. During the stance phase, each foot will equally share the entire body weight. On applying the necessary loading and boundary conditions the stress distribution in the foot is observed, as shown in figure 3. The maximum Von Misses stress of 0.139 MPa is observed in the heel and metatarsal region of the foot.

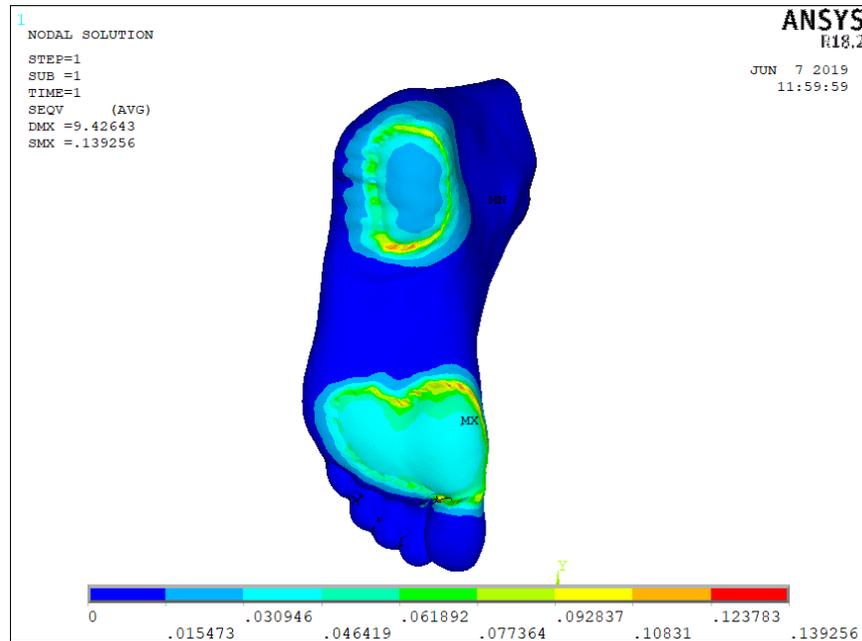


Figure 3. Stress distribution in MPa, during stance phase.

4. Experimental validation with Moticon insole

The finite element model of the subject's foot thus developed by image reconstruction techniques is validated through an experimental analysis, performed under balanced standing condition, on the selected subject, using Moticon insole. The insole consists of 13 capacitive pressure sensing pads and a 3-D accelerometer to measure the different motion parameters. Considering the size, weight and comfort, Moticon insoles are used instead of the standard insoles. This fully integrated sensor insole, powered by a thin lithium battery, allows precise, accurate and natural data collection. As per the recommendations of Roger James [17] six trials are made to measure the maximum stress in the foot. Figure 4 shows the 2D and 3D plots of the stresses developed in the foot under the specified test conditions.

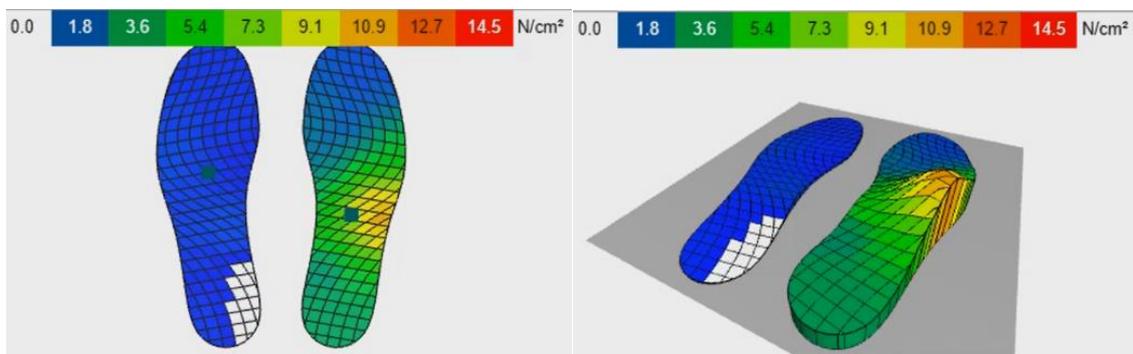


Figure 4. 2D & 3D plot of the stress in the foot.

During balanced standing condition on a plain surface, the maximum foot pressure accounts for 14.5 N/cm² (0.145 MPa) as shown in Figure 4.12 which is 95.7% closer to the FE results of 0.139 MPa. Pressure insoles have been widely used for quantification. Several studies have validated them against standard force sensing systems such as force plates and instrumented treadmills. Hence, a

treadmill test is also performed to ensure the reliability of the test results obtained from Moticon insole study and FE study.

5. Experimental validation with FDM-T SciFit Treadmill

The Noraxon's FDM-T SciFit Treadmill test is conducted with the same subject considered for this study, in idle standing posture, on a plain surface for few seconds, and the stress distribution in both the foot is obtained. The stress distribution in each of the foot, shown in figure 5, depicts the ratio of the weight distribution in forefoot to back foot as 67.26:32.74 and between the right and left foot as 52.00:48.00. The maximum stress in the foot is found to be 14 N/cm² (0.140 MPa) which is 99.3% closer to the results obtained from FE analysis (0.139 MPa).

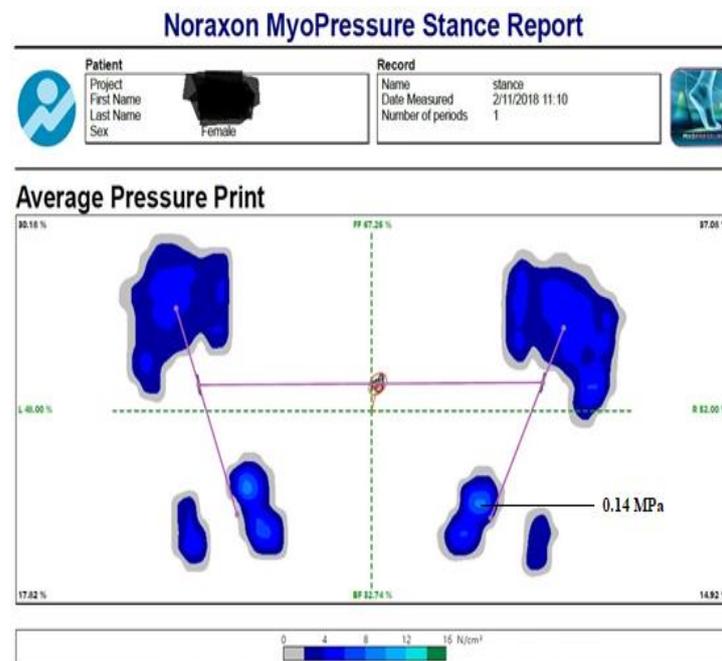


Figure 5. Pressure distribution from treadmill.

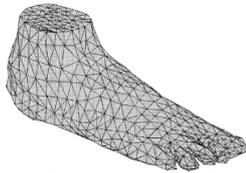
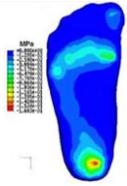
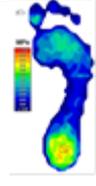
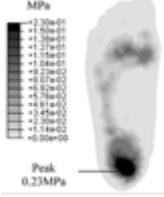
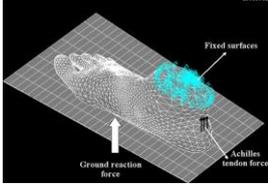
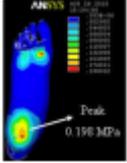
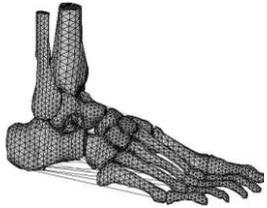
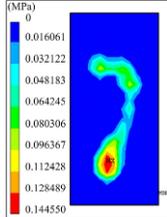
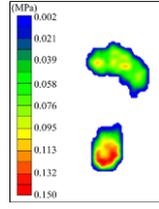
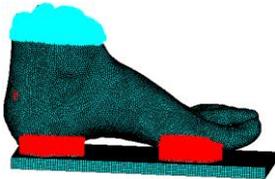
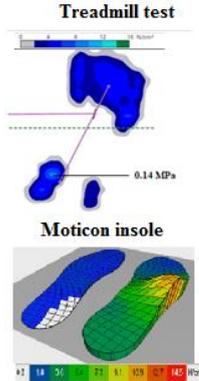
The small % deviation is very likely to be attributed to the modelling of the ligaments using actual material properties, as all other conditions are considered similar to that specified in the literature. The maximum stress and % variation in respect of finite element analysis and experimental studies is tabulated in table 2.

Table 2. Comparison of maximum stress in foot.

Source	Maximum stress (MPa)	Variation in %
Finite element model	0.139	Reference
Moticon insole study	0.145	4.3
Treadmill study	0.14	0.7

From the above it can be safely inferred that the finite element model developed by considering the actual properties of ligaments (in lieu of the 1-D link element) of the foot of the subject, behaves much closer to a real foot and provides realistic behaviour in a virtual environment. Table 3 depicts the comparison of the maximum stress obtained through the current study and those found in published literatures.

Table 3. Comparison of FE model of the foot with published literature.

Literature	Finite element model	Plantar pressure distribution based on		Deviation
		Finite element analysis	Experiment	
Chen WM [13]	 Maximum stress	 0.168 MPa	 0.14 MPa (insole)	16.67 %
Jason TC [14]	 Maximum stress	 0.23 MPa	 0.17 MPa (insole)	26.08 %
Qiu TX [15]	 Maximum stress	 0.198 MPa	Experimentation was not performed	Not Applicable
Tao K [16]	 Maximum stress	 0.144 MPa	 0.15 MPa (insole)	4.17 %
Current study	 Maximum stress	 0.139 MPa	 Moticon 0.145 MPa Treadmill 0.14 MPa	4.3 % for Insole study & 0.7 % for treadmill study

6. Conclusion

In this study an anatomically realistic three dimensional finite element human foot model is developed through image reconstruction techniques. During the image reconstruction there are certain limitations and assumptions. All the elements of the foot are assumed to be linearly elastic and the ligaments and plantar fascia are modelled based on the anatomy of the foot. The material properties and the loading conditions for finite element analysis are selected from the published literatures. The plantar pressures obtained from FE studies were validated with experimental studies and compared with the existing literature. Upon comparison with the literature the FE model developed is very useful and the predicted results are reasonable. As this study is limited to balanced standing, it can be further extended to different phases of Gait cycle to assess the walking pattern and thereby providing necessary suggestions to improve. This model can be used for designing an orthotic device for the subjects.

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