


# Bio-Numerical Analysis of the Human Ankle-Foot Model Corresponding to Neutral Standing Condition

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## ABSTRACT

**Background:** The foot is the most complex body's structure; it is highly susceptible to disorders because of its loading pattern. The complexity of the foot structure geometry implies the use of reverse engineering tools to obtain a model that can accurately mimic the biomechanical behavior of the foot.

**Objective:** The objective of this study is to establish a state-of-the-art ankle-foot finite element (FE) model with anatomically realistic geometry and structure in order to get the model that will suit all cases for future studies on stress injuries and foot insole designs under different loading conditions.

**Material and Methods:** In this analytical study, tomography images were imported in DICOM format, after that, the object was exported in the form of three-dimensional structures in STL file format to define and assemble the structures. After that, the computer simulation on numerical model was done. One-way Analysis of variance (ANOVA) test was performed, and a threshold ( $p < 0.05$ ) was used to indicate the significance of results.

**Results:** The results showed no significant differences ( $P > 0.05$ ) between the values of the plantar pressure corresponding to neutral standing condition with other foot models in literature. The stresses transferred to the bone structure show that the relatively higher stress was located in the fifth, fourth and third tarsometatarsal, where the maximum von Mises stress in the bone structure was 2155.4 kPa.

**Conclusion:** The state-of-the-art ankle-foot FE model with anatomically realistic geometry and structure will be very helpful for future studies on stress injuries and foot insole designs under different loading conditions.

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## Keywords

Methods; Ankle; Foot; Stress Distribution; Neutral Standing

## Introduction

The standing posture is significant for human movement abilities to master the controls of it, which is a vital requirement for different daily physical activities [1]. However, the foot is an anatomically complicated structure with many movements and joints [2], where the foot contains 26 bones, 19 muscles, 33 joints and 107 ligaments. This constitutes 12% of the human body bones. These components work efficiently together to provide the human body with balance, support and mobility [3]. The foot is the most complex body's structure, and highly susceptible to disorders because of its loading pattern. The complexity

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of the foot structure geometry implies the use of reverse engineering tools to obtain a model that can accurately mimic the biomechanical behavior of the foot [4].

It is worth pointing up that a sensor-embedded insole, wearing during physical activities, has been used to analyze standing postural because of its property degradation during physical activities. Previous research showed that many sensor-embedded insoles have been developed based on various sensing technologies [5]. For instance, the ParoTec system uses piezo-resistive sensors, the F-Scan system employs the force-sensing resistor (FSRs), and the Pedar system applies embedded capacitive sensors.

All of these systems have shown their practicability and capability to analyze standing postural. Nevertheless, these techniques suffer from some technical difficulties that could affect the measurement accuracy. In fact, the value of output may change due to the heat inside the shoes when the load is applied for a long period. In addition, the flexible contact surface could deform, resulting in a variation in the sensor's response [6-8].

Hence, the objective of this study is to establish a state-of-the-art ankle-foot FE model with anatomically realistic geometry and structure, and to compare the plantar pressure distribution corresponding to neutral standing condition with other foot models in literature in order to get the model that will suit all cases for future studies on stress injuries and foot insole designs under different loading conditions.

## Material and Methods

### Modeling and meshing

In this analytical study, building a three-dimensional computer model based on computed tomography scans is the most accurate way to maintain the dimensions of the geometric studied structure without distortions or changes. The three-dimensional model of the

compounding area was carried out according to the following stages that are summarized in Figure 1(a): Tomography images were imported in DICOM format. The minimum threshold was set at -325 HU and the upper at -1000 HU. The foot area was then specified and the rest of the image was removed based on a region-growing algorithm, after that, the object was exported in the form of three-dimensional structures in STL file format. The numerical foot model was then exported to Autodesk®Inventor™ software to define and assemble the structures. After that, Ansys®Workbench™ software was used to perform computer simulation on numerical model.

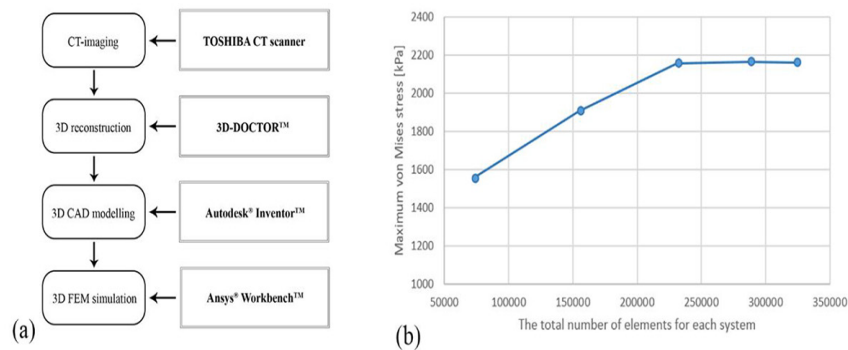
The model was then subdivided into elements by volumetric meshing, where elements for FEA were tetrahedrons. The mesh was refined and accepted when the relative errors were less than 1% [9-11], as shown in Figure 1(b). Before refining, the mesh consisted of 131268 nodes and 72675 elements as shown in Figure 2(a). After refining, the mesh consisted of 403308 nodes and 230887 elements as shown in Figure 2(b).

### Boundary conditions

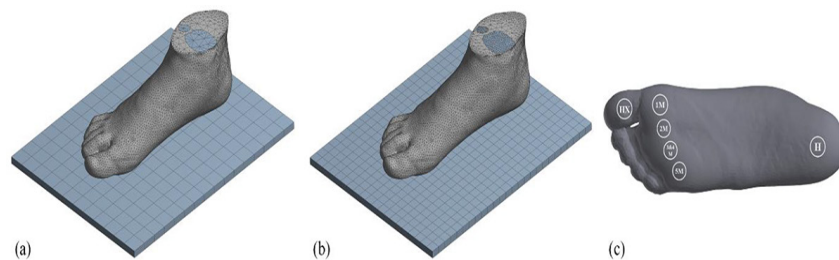
The patient details are given as follows: his gender is male with 29 years old having a body weight of 80 kg and a height of 180 cm. The right foot is considered in this investigation with a length of 26.9 cm. To simulate static standing conditions, the ground plate was bounded in all directions. The coefficient of friction between the plantar surface and ground was 0.6 [12]. The static loads have been applied on the plantar discrete locations [13]: hallux (HX) 594.5 kPa, metatarsal 1 (1M) 527.1 kPa, metatarsal 2 (2M) 469.3 kPa, metatarsal 3&4 (3&4M) 392.2 kPa, metatarsal 5 (5M) 271.6 kPa, heel (H) 567.6 kPa as shown in Figure 2(c).

### Material properties

All the materials were idealized as isotropic and linear-elastic except for the soft tissues, defined as hyperelastic. The Young's



**Figure 1:** (a) The stages of 3D finite element (FE) model design, (b) Mesh sensitivity results in terms of the maximum von Mises stress.



**Figure 2:** (a) 3D Mesh before refining, (b) 3D Mesh after refining, (c) Plantar discrete locations that subjected to standing loads.

modulus was defined as 7300 MPa, 1 MPa, 350 MPa, 260 MPa, and 17000 MPa for the bony structure, cartilage, plantar fascia, ligament, and ground, respectively. The Poisson's ratio was defined as 0.3, 0.4 and 0.1 for the bony structure, cartilage and ground, respectively. The cross-section area was 58.6 mm<sup>2</sup> and 18.4mm<sup>2</sup> for the plantar fascia and ligament. The parameters of encapsulated soft tissue of the finite element model were defined as  $C_{10}=0.0855$ ,  $C_{01}=-0.0584$ ,  $C_{20}=0.0390$ ,  $C_{11}=-0.0231$ ,  $C_{02}=0.0085$ ,  $D_1=3.6527$ . All the reference values were taken from the literature [14-20]. Non-linear biaxial, shear and uniaxial mechanical behavior of the encapsulated soft tissues are shown in Figure 3.

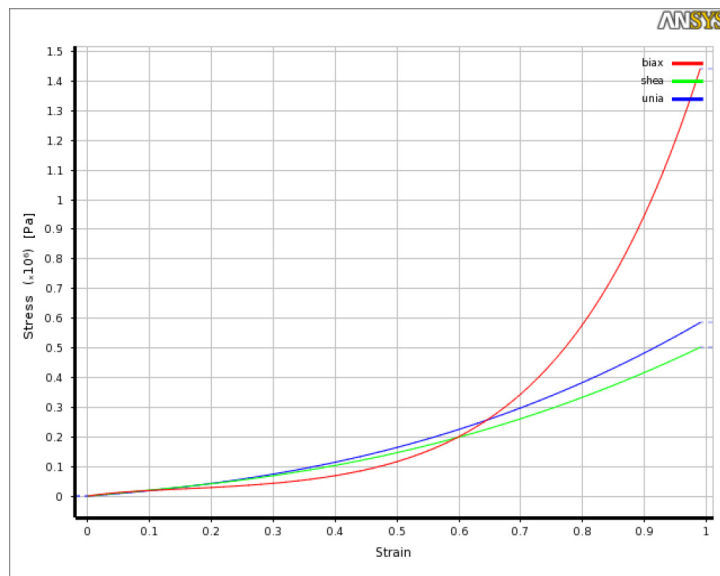
#### Statistical analysis

The plantar pressure values corresponding to neutral standing condition in comparison with other foot models in literature were used to assess the variability of the results. One-way

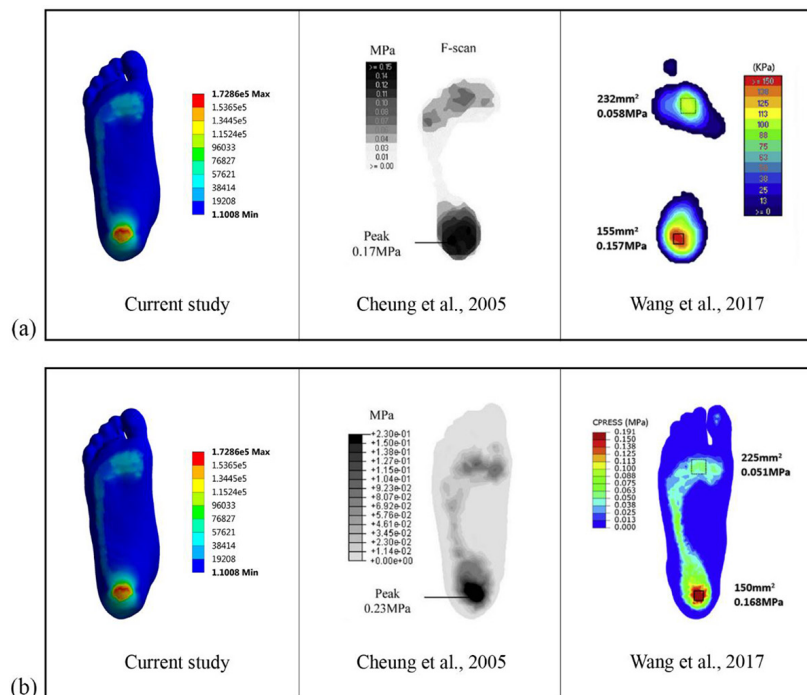
ANOVA test was performed, and a threshold ( $p<0.05$ ) was used to indicate the significance of results using IBM SPSS® Statistics V26 [21].

### Results

The data acquired from the FE analysis can be presented in a map with a color scale, which could help to compare the stresses for the models. For the validation of the ankle-foot model, Figure 4(a) shows that the stress distribution and the peak value were in a good agreement with experimental one reported in the literature, even if relatively higher stresses are located in the forefoot and rearfoot. The stress distribution in current FE model was also compared to those from other numerical data reported in the literature as shown in Figure 4(b), where the comparison shows a good agreement in the patterns of predicted and measured stress distribution and the peak



**Figure 3:** Encapsulated soft tissues biaxial, shear and uniaxial mechanical behavior.



**Figure 4:** Comparison of predicted plantar pressure (Pa): (a) with published experimental data, (b) with published numerical data.

value during balance standing condition.

From Table 1, ANOVA results showed no significant differences ( $P>0.05$ ) between the values of the plantar pressure corresponding to neutral standing condition with other foot

models in literature. The stresses transferred to the bone structure show that the relatively higher stress was located in the fifth, fourth and third tarsometatarsal as shown in Figure 5, where the maximum of von Mises stress in the

**Table 1:** Analysis of variance (ANOVA) results of von Mises stress for the soft tissue.

	Mean	Standard deviation	Standard error
<b>Current model</b>	0.172	0.0028	0.002
<b>Cheung et al. model</b>	0.2	0.0424	0.03
<b>Wang et al. model</b>	0.1625	0.0078	0.0055
<b>F-statistics</b>		1.22184	
<b>P-value</b>		0.40911	

bone structure was 2155.4 kPa.

## Discussion

Planar pressure distribution on the plantar foot is one of the most common method to analyze the postural sway and body stability. Finite element analysis is a useful method to understand the distribution mechanisms of the loads under the foot [22-24]; it can be also a powerful method to understand the foot bio-mechanical behavior and its influence on human comfort generation.

In order to achieve reliable data in current study, three basic verifications were made; first, to ensure about the mesh size, a sensitivity analysis of the mesh was performed, where it was accepted when the relative errors were < 1 percentage as previously mentioned. Second, a comparison with respect to related previous works [16, 25], as we stated in this study. Third, performing an analysis of variance where the results showed no significant

differences ( $P > 0.05$ ) between the values of the plantar pressure corresponding to neutral standing condition with other foot models in literature.

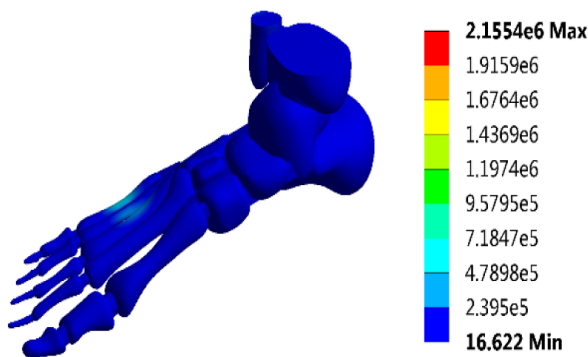
Many researchers studied the kinematics of foot reaction to the ground using finite element analysis first, so that their parameters are verified and validated before going on to the actual experiment. This non-linear finite element model was purposed as a tool for the design optimization process of shoe insoles. Thus, the details of human foot model were generated from computed tomography scan image data using segmentation rebuilding techniques and 3D-CAD modelling. After that, a wide variety of insole materials and geometries can be tested so as to study the comfort behavior through the modification of insole materials definition and/or insole geometrical design.

## Conclusion

The finite element modeling process and method in the current study are satisfactory and practical based on the predicted numerical results for validation of the model. Hence, the state-of-the-art ankle-foot FE model with anatomically realistic geometry and structure will be very helpful for future studies on stress injuries and foot insole designs under different loading conditions.

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**Figure 5:** Stress transferred to the bone structure (Pa).

## Conflict of Interest

None

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