A Finite Element Analysis of a Human Foot Model to Simulate Neutral Standing on Ground

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Abstract

The objective of the paper is to perform finite element analysis of a human foot model to study the dynamic behavior and the internal loading conditions during neutral standing on the planar ground. The foot structure is simulated to assist in the design of an instrumented shoe insole. Finite element model of a human foot was generated and the loading condition during neutral standing was used to evaluate the stress distribution. The comprehensive stress distribution of the human foot model subjected to several loading conditions can be specified by a computational model. The method of the research is by using computational tomography data of the bone and soft tissue structures of a human foot in developing a 3-D finite element foot model. An analysis was conducted to simulate the loading condition of human foot during neutral standing. A commercial CAD software package was used to generate the boundary surfaces and the solid models of all model components. The numerical stress analyses for the neutral standing of the foot model was done using a commercial finite element software package. Peak pressures were seen at the first metatarsal, fifth metatarsal, and under the heel. The foot plantar deformation of the neutral standing foot model was seen similar to the finite element foot model in previous literature. The present study offers a prior computational model, which is capable of estimating the comprehensive plantar pressure and is intended to aid researchers in investigating foot plantar pressure as well as to develop custom-made insoles.

Keywords: Foot modeling; plantar pressure; finite element; force distribution

1. Introduction

The standing posture is important for human motor abilities and to master the controls of it is a vital requirement for daily physical activities in life. Postural control is an exceptionally complex system that contains the integrations of several sensory and motor components. For one to stand in balance, information from three sensory systems, which are visual, vestibular, and proprioceptive, are necessary [11].

One way to analyze standing postural is by using a sensor-embedded insole worn during physical activities. The sensor-embedded insole is flexible and its means of measurement is the interface between foot plantar and shoe. Because of its flexibility, it has become a portable foot plantar sensor which allows a wider range of studies with different gait task, footwear design or terrain.

Previous research shows a lot of sensor-embedded insoles have been developed and commercialized based on different sensing technologies [2]. For example, the F-Scan system uses the force-sensing resistor (FSRs) [14], the ParoTec system applies piezo-resistive sensors [16], and the Pedar system assigns embedded capacitive sensors [17]. Even though all these systems have shown their capability and practicability in gait analysis applications, several limitations were shown, such as [4][9][10][15].

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• The flexible contact surface can deform randomly, which cause the sensor's response to vary
• The output value may be altered because of the heat inside the shoe when load is subjected for long period of time
• Lack of measurement accuracy caused by the calibration done with different subjects

Different level of postural stability is required by different sports disciplines to produce the specific balance control strategies to maintain steadiness [3]. Studies have uncovered that standing balance during upright stance of elite shooter athletes outshines that of amateur athletes [1]. However, there are a small amount of studies done to investigate the postural stability in archery. It is a static sport where to achieve high scores requires archers to have high postural stability, body segments coordination, and high concentration of attention at the moment when the shot is executed.

The objective of this work was to compare and validate the plantar pressure distribution during neutral standing with other foot models from different kinds of literature to acquire the most accurate location for the placement of pressure sensor on the insole. The method of the paper is to construct finite element model of a human foot and evaluate the plantar force distribution acting on the foot model. The static structural analysis in ANSYS 15.0 was used and all of the parameters and definitions of the model were set so that it is suitable for the on-going main research. The study described in this paper is an on-going work on the development of a sensor-embedded insole foot pressure distribution monitoring system.

Nomenclature

FE finite element

2. Methods

2.1. Solid body model preparation

The 3D foot model was first acquired in .STL format and its volume was generated into a solid model. It was then converted into ANSYS compatible file format (.STEP) and imported to ANSYS for meshing. And then, the muscle tissue and bony structure FE model of the foot was developed. The .STL file was converted to .STEP using SOLIDWORKS, but then it was found that SOLIDWORKS could only process surface model with maximum 20000 facets.

The foot surface model was then imported into MESHLAB where it has a tool to simplify and re-mesh, which enabled the surface model's facets to be reduced to 20000, as shown in Fig. 1. The original surface model had 138376 number of facets. The downside of this is that the meshed surface model quality has dropped. The re-meshed foot model was imported into SOLIDWORKS and exported into a .STEP file.

2.2. Properties of the FE model

The FE model of the human foot, as shown in Fig. 2, consists of 28 bony segments; the tibia and fibula, and 26 other foot bones such as talus, calcaneus, cuboid, navicular, 3 cuneiforms, 5 metatarsals, and 14 phalanges components embedded in a volume of soft tissue [7].

The FE model was meshed in ANSYS. ANSYS have quite a range of solid elements packages which can be used to model the foot and ankle structures. Although the meshing routines suitable for 3D model is hexahedral elements, they are not as robust and may not always work with complex models [18]. The analysis that is going to be done offer a high accuracy solution using a complex geometry structure with large allowable deformation. The hexahedral elements are likely to be applied in the foot structure mesh [19]. However, hexahedral element's meshing accuracy only shines when simulating material with linear
behavior material. Also, a great fine mesh is needed near the location of a complex shape where stress and strain gradients are present [20]. Since the soft tissue and bones model experience nonlinear behavior and fairly complex shaped models, tetrahedral elements were used, as shown in Fig. 3.

![Fig. 2. the overview of the FE model with ground support.](image)

ANSYS automated surface-to-surface contact algorithm was used to simulate the interaction of the surfaces of the bony structures. The lubricating nature of the partition surfaces of the bones demonstrated that the contact behavior between the bones surfaces can be treated as frictionless [6].

Next, a neutral standing condition was simulated with a horizontal support block used to set up a foot-ground interaction, as shown in Fig. 4 [5]. Hexahedral elements were used when meshing the horizontal ground. The foot-ground contact was simulated using the same contact modeling algorithm as the surface between bones. The frictional contact behavior between the foot-ground interface was modeled as an additional frictional property. The coefficient of friction between the foot and the ground was set as 0.6 [7]. It is very important that a minimum number of one facet of the foot model have to be in contact with the ground block because the static structural analysis function in ANSYS only simulate one model in one environment. This means that if there are multiple models involved in the simulation, which in this case, soft tissue mode, bones model, and ground support, all models need to be connected into one system.

![Fig. 4. Horizontal block support placement acting as ground.](image)
2.3. Material Properties of the FE model

As shown in Table 1, the bony structures were set to have the value of Young’s modulus and Poisson’s ratio of 10000 MPa and 0.34 respectively [12]. The soft tissue of the FE model was characterized as hyperelastic [8]. From a variety of literature, the Ogden-form hyperelastic constitutive model is generally used as the material property for foot plantar tissue because of its excellent non-linear curve-fitting capacity [6]. The Ogden hyperelastic properties were chosen from the ANSYS library. The support block properties were set as structural steel, which also selected from the ANSYS library.

Table 1. Material properties of the FE model and ground support.

<table>
<thead>
<tr>
<th>Components</th>
<th>Element types</th>
<th>Young’s Modulus, E (MPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bones</td>
<td>3D-tetrahedral</td>
<td>10000</td>
<td>0.34</td>
</tr>
<tr>
<td>Soft tissue</td>
<td>3D-tetrahedral</td>
<td>1.15</td>
<td>0.49</td>
</tr>
<tr>
<td>Ground</td>
<td>3D-hexahedral</td>
<td>2000000</td>
<td>0.29</td>
</tr>
</tbody>
</table>

2.4. Loading condition of the FE model

A downward pressure acting on the face generated on tibia and fibula was chosen as the representation of the downward force of human weight [13]. A force distribution over the area of the face of tibia and fibula was set to 300N, assuming the average weight of a normal male person of 60kg, divided evenly on each foot, as shown in Fig. 5.

![Fig. 5. loading definition of the FE model.](image)

3. Results

In this investigation, a three-dimensional FE model of the human foot was developed. The developed FE model consisting 28 in-contact bony structures and the plantar fascia embedded in a volume of soft tissue. The developed model also took into attention considering nonlinear, material properties, large deformation, and interfacial slip and friction conditions.

The FE model developed enables the stress distribution to be predicted from the neutral standing position. In the analysis, the planar pressure was examined and the planar pressure on the plantar surface of the soft tissue was obtained from the FE model considering neutral standing. For the validation of the model, the acquired planar pressure of the made FE model was compared with the FE results given literature, as shown Table 2.
Table 2. Comparison of the force distribution from FE analysis and various literatures.

<table>
<thead>
<tr>
<th>Plantar pressure from FE analysis</th>
<th>Plantar pressure from literatures</th>
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<tbody>
<tr>
<td></td>
<td>Qui et al., 2011</td>
</tr>
<tr>
<td></td>
<td>Tao et al., 2009</td>
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<tr>
<td></td>
<td>Cheung et al., 2005</td>
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<tr>
<td>Peak 1.6x10^{-3} MPa</td>
<td>Peak 1.98x10^{-1} MPa</td>
</tr>
<tr>
<td>Peak 1.45x10^{-1} MPa</td>
<td>Peak 1.70x10^{-3} MPa</td>
</tr>
</tbody>
</table>

As seen in the table, the position and peak value of planar pressure are comparable and are in good agreement. It is seen that the peak planar pressure which is about 0.16 MPa, occurred at the heel part, first metatarsal, and fifth metatarsal of the foot.

From the shape and density of the plantar pressure resulted from this investigation, the position of the three sensors can be concluded, as shown in Fig. 6. The selection of these positions was based on the peak value of pressure across the foot plantar.

4. Discussions

Planar pressure and force distribution on the plantar foot is one of the most popular method of analysis body stability and postural sway. Usually, researchers studied the kinematics of human foot reaction to the ground using FE analysis first so that their parameters are validated and verified before proceeding to the actual experiment. Recent studies showed that the use of insole in investigating human body stability and postural condition have become popular. The insole will be embedded with the pressure sensor. So, to eliminate future complications since the higher number of sensors require more complicated circuitry, the minimum but the accurate quantity of sensors need to be used. And also to make sure that the sensors capture the exact amount of the force acted by the foot, the precise location of the sensors placement is significant. Thus, the current study will assist in the location of the sensor’s placement on the insole.

The material properties of the bone structures and plantar fascia were assumed to be linear and behave elastically. For the validation of the FE model, all current material properties were selected by referring to literature. Static loading conditions were considered in the analysis. Some simplifications on the geometry and material properties were done in order to reduce the complexity of the model. The intrinsic and extrinsic muscle forces were not simulated.

The predicted planar pressure distribution of the foot is in good agreement with the other FE model and experimental results of neutral standing in the literature. For example, Cheung et al. have predicted relatively higher planar pressure at the middle part of the foot, with 7.94 MPa at the third metatarsal and 4.47 MPa at the second metatarsal. However, the planar pressure distributions obtained are in good agreement with the literature.
5. Conclusions

The current method is way cheaper and easier than the real-life measurement techniques for analyzing foot pressure distributions. The geometry and material properties of the foot FE model can be changed to investigate different biomechanical effects of the human foot. Some simplification of the geometry, material properties, and loading condition of the bones and soft tissue were made to reduce the complexity of the model. These simplifications may affect the estimated pressure results. However, the planar pressure distributions and values showed good agreement with previous measurement results from literature.

The concluded position for three sensors method of analyzing foot plantar pressure will assist future research application of plantar pressure since the time and effort taken to re-simulate foot plantar pressure when neutrally standing can be dispersed. However, three sensor position acquired in this investigation only applied to a normal condition human foot.

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References