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Jacob, S.; Patil, K.M.; Braak, L.H.; Huson, A.

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STRESSES IN A 3D TWO ARCH MODEL OF A NORMAL HUMAN FOOT

Shanti Jacob, K.M. Patil, L.H. Braak and A. Huson
Department of Applied Mechanics, Indian Institute of Technology, Madras, India and Department of Fundamentals of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands

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Introduction

The weakness or paralysis of foot muscles as occurring in leprosy or diabetes is found to alter the pattern of internal stresses in the foot skeleton. Direct measurements of the internal stresses are not possible in vivo. However, these stresses can be predicted using an appropriate mathematical or numerical model of the foot skeleton acted upon by the important muscles. It is necessary to model a normal foot to establish the normal stress distribution in the foot before calculating the stresses in a leprotic foot. Available foot models that can be used for stress analysis are two dimensional models [1, 2]. In the first two dimensional model [1], the foot skeleton is simplified as a single bone while considering the shape variation of the bones and forces due to muscles triceps surae and tibialis anterior and ankle joint force are taken into account to find the possible regions of high stresses. In the second model [2], the earlier foot model is modified by introducing cartilages and ligaments between the bones talus and navicular, navicular and cuneiform, cuneiform and metatarsals and metatarsals and toes and the effect of these on stress distribution are studied. Modeling of the foot confronts inherently a three dimensional problem, one to which results from two dimensional analyses cannot necessarily be directly extrapolated. The stresses developed in the foot depend upon the geometry of the foot, and magnitude and insertion points of the muscle forces. Hence it is necessary to model the foot in all the three dimensions of geometry to make a more realistic representation. Therefore, in this study, a three dimensional model of the normal foot skeleton with cartilages and ligaments which enable simulation of articulations (joints) is developed in the mid-stance phase of walking and stress analyses are carried out using finite element technique. Estimation of the regions of high stresses in the normal foot could help in understanding the factors contributing to disintegration of tarsal bones in leprosy or diabetic patients.
Methodology

The three dimensional geometry of the foot is obtained from medio-lateral and antero-posterior radiographic measurements of a normal foot and by measurements on a cadaver foot (Fig. 1). One approximate method of treating dynamic loading during walking is in a quasi-static fashion by adding inertia forces to the body weight. The present model is developed taking into account the inertia forces from literature. The finite element method became the logical choice for the analysis of the present model due to its unique capability to analyze structures of complex shape, loading and material behaviour where the focus is on the internal stress distribution. The aim of this study is to develop a model of the foot and carry out the stress analysis of the foot model using an available well tested finite element software known as NISA (Numerically Integrated Elements for System Analysis), developed by EMRC, USA.

Huiskes and Chao [3] have reported that in the case of quasi-static loading both cortical and trabecular bones behave linear elastic by approximation. Under short term or instantaneous loading, some useful information can be gained by modeling the cartilage as a linear elastic material, reported by Clift [4]. In this study, the foot bone material and the cartilages are assumed to be homogeneous, isotropic [2] and linear elastic. Young's modulus of the bone is taken as 7300 N/mm² and Poisson's ratio 0.3 [5] and that of the cartilage is taken as 10 N/mm² and 0.4 [6] respectively. The stiffness of the ligaments is taken as 1500 N/mm [2].

![A schematic diagram of the foot skeleton, (a) dorsal view (b) medial view](image-url)
Foot Model

In the present work, a three dimensional foot model (Fig. 1), consisting of the two arches namely, medial arch and lateral arch, is developed to simulate the mid-stance phase. The medial arch consists of the bones, talus, navicular, three cuneiforms, three metatarsals, three toes and the cartilages between them. The lateral arch consists of calcaneus, cuboid, two metatarsals, two toes and the cartilages between them. In both medial arch and lateral arch, the bones in the medio-lateral directions are combined together. The bones with their respective cartilages are constrained to move by the respective longitudinal ligaments modeled both on dorsal and plantar sides and these ligaments are distributed as per anatomical data [7,8].

The complex cartilage between calcaneus and talus is also introduced with medial, lateral, cervical and interosseous ligaments. Ligaments are provided connecting the medial arch and lateral arch in their respective places [7, 8 & 9] in addition to the above ligaments and these ligaments are also distributed over a large area as found in the anatomy of the foot [7, 8 & 9]. Thus the model consists of totally eight cartilages between the bones each of them with their respective ligaments (Fig. 1). The predominant muscle forces acting on the foot are taken into consideration as per literature [10, 11] and the points of insertion of the muscles on the model are decided considering the anatomical data [7, 8 & 9]. The foot model is idealized as an assemblage of eight noded isoparametric solid brick elements representing the bones and cartilages and two noded spring elements representing the ligaments. The elements have three translational degrees of freedom per node. The meshes used are fine at areas of high stress gradients.

The foot model (Fig. 2) represents the mid-stance phase where the foot is supported at the heel and the forefoot. The ankle joint load (FAN) is simulated by 3.5 times the body weight of a normal subject [12] weighing 600 N. During the mid-stance phase the muscles triceps surae (TS), peroneus longus (PL), peroneus brevis (PB), tibialis posterior (TP), flexor hallucis longus (FHL), flexor digitorum longus (FDL) and adductor hallucis act predominantly on the foot [10, 11]. The forces on the calcaneus due to the muscles FHL, FDL and TP as they go around the medial pulley and PL and PB around the lateral pulley are also considered in this model. The force in the muscle TS is taken from literature [11, 13]. The other muscle forces are calculated from the ratio of cross sectional areas of the muscles with respect to that of TS [14]. The values of the muscle forces thus obtained agree well with those reported in literature [14]. Instead of attaching the muscles to single points, these are distributed over an area which is confirming to the anatomy, to remove the stress concentrations at the attachment points of the muscle forces. The ankle joint load is also distributed along both longitudinal and medio-lateral directions. Fig. 2 shows the model acted upon by the muscle forces. The finite element model as shown in Fig. 3 has 1475 brick elements to represent the bones and cartilages and 116 rod elements to model the ligaments. The magnitude of muscles and other forces acting on the model of the foot are shown in Table 1.
Two arch model of the normal foot in mid-stance phase. The muscle forces acting are indicated by numbers 1 through 13. 1- Muscle force due to triceps surae (TS), 2- Ankle joint force (FAN), 3- Reaction on the medial pulley due to muscle forces flexor hallucis longus (FHL), flexor digitorum longus (FDL) and tibialis posterior (TP), 4- Reaction on the lateral pulley due to peroneus longus (PL) and peroneus brevis (PB), 5- Muscle force due to PB, 6- Muscle force due to TP, 7- Muscle force due to PL, 8- Muscle force due to adductor hallucis (AH) in medial arch, 9- Muscle force due to AH in lateral arch, 10- Muscle force due to AH in toe, 11-Muscle force due to FHL, 12- Muscle force due to FDL in medial arch and 13- Muscle force due to FDL in lateral arch.

Finite element discretization of the foot model in mid-stance phase.
TABLE 1

Muscle forces and ankle joint force acting on the normal foot during the mid-stance phase

<table>
<thead>
<tr>
<th>Forces</th>
<th>Magnitude in Newton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle joint force (FAN)</td>
<td>2100</td>
</tr>
<tr>
<td>Triceps Surae (TS)</td>
<td>550</td>
</tr>
<tr>
<td>Peroneus Longus (PL)</td>
<td>132</td>
</tr>
<tr>
<td>Peroneus Brevis (PB)</td>
<td>64</td>
</tr>
<tr>
<td>Tibialis Posterior (TP)</td>
<td>290</td>
</tr>
<tr>
<td>Flexor Hallucis Longus (FHL)</td>
<td>143</td>
</tr>
<tr>
<td>Flexor Digitorum Longus (FDL)</td>
<td>68</td>
</tr>
<tr>
<td>Reaction at medial pulley due to muscle forces FHL, FDL &amp; TP</td>
<td>645</td>
</tr>
<tr>
<td>Reaction at lateral pulley due to muscle forces PL &amp; PB</td>
<td>256</td>
</tr>
</tbody>
</table>

Results and Discussion

The results of the stress analysis are presented here. Figs. 4 and 5 show two views of von Mises stress contours for the 3-D two arch model. Fig. 4 shows the stresses to be maximum (8.97 N/mm²) at the dorsal side of the junction of calcaneus and cuboid. The other high stressed regions (shown in Fig. 4) are lateral side of ankle joint (6.41 N/mm²), medial dorsal side of central part of lateral metatarsals (5.13 N/mm²) and the dorsal anterior side (neck) of the talus (4.49 N/mm²). Fig. 5 shows von Mises stress contours in the medio-lateral view of the foot model with high stresses concentrated in the regions of medial plantar side of navicular (6.41 N/mm²), medial plantar side of medial metatarsal head (6.41 N/mm²) and medial plantar side of medial toes (4.49 N/mm²). The principal stresses are predominantly compressive in nature at the dorsal locations and in metatarsal heads and toe regions, whereas it is tensile at the plantar side of navicular. This is expected since the dorsal side of the foot as well as the points of contact of the foot with the ground undergo compression; the plantar side where spring ligament is attached undergoes tension in the mid-stance phase due to spring ligaments getting stretched, at the high stressed points.
FIG. 4
Von Mises stress contours of the two arch model of a normal foot (lateral view)

FIG. 5
A medio-lateral view of the von Mises stress contours of the two arch model of a normal foot

Conclusion

The highest stress during the mid-stance phase is found near the dorsal side of the junction of calcaneus and cuboid. The other high stressed regions are the medial plantar side of navicular, medial plantar side of medial metatarsal head, lateral side of ankle joint, medial dorsal side of central part of lateral metatarsals.
medial plantar side of medial toes and the dorsal anterior face (neck) of the talus. The two dimensional analyses [1, 2] give high von Mises stresses only at the dorsal anterior face of the talus whereas in the present three dimensional study seven areas as indicated above are subjected to high stresses. This difference in results as compared to two dimensional case could be due to the introduction of the three dimensional geometry and the three dimensional location of insertion points of the muscles thereby forming a more realistic representation of the human foot. These areas of high von Mises stresses are important since it is found from the clinical reports that in certain leprosy patients [15], some of these areas of the bones get disintegrated if subjected to osteoporosis due to decreased mechanical strength of the bone in that region. This investigation could possibly provide an insight into the factors contributing to tarsal disintegration in leprosy.

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References