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A THREE DIMENSIONAL TWO ARCH MODEL OF A NORMAL FOOT FOR STRESS ANALYSIS

Shanti Jacob*, K.M. Patil*, L.H. Braak†, A. Huson††

* Department of Applied Mechanics, Indian Institute of Technology, Madras, India

† Department of Fundamentals of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands

†† Department of Movement Sciences, Faculty of Health Sciences, University of Limburg, Maastricht, The Netherlands

ABSTRACT

A three dimensional two arch model of the foot skeleton with cartilages and ligaments between bone segments is developed taking into account the predominant muscle forces. The model is used to study the regions of high stresses during mid-stance phase of walking for a normal foot. The stress analyses are carried out using finite element software package NISA. The results of these analyses could possibly help in understanding better the factors contributing to tarsal disintegration in leprosy.

Keywords: 3-D Foot Model, stress analysis, normal foot

INTRODUCTION

Knowledge of stresses that occur throughout normal and abnormal feet under various loading conditions is of fundamental importance in understanding the physiology and pathophysiology of the foot, and can provide important information for the prevention and treatment of diseases like leprosy or diabetes. Leprosy is still a widespread disease in India as well as in many other countries in the world. 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. This may provoke a local foci of relatively high stresses. In those cases where osteoporosis and cystic degeneration has weakened the mechanical strength of the bones, these relatively excessive stresses may lead eventually to a local break down of the bone. These internal stresses cannot be measured *in vivo*, but can be predicted using an appropriate mathematical or numerical model of the foot. It is necessary to model a normal foot before calculating the stresses in a diseased 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 and the effect of these, on stress distribution, are studied.

Modelling 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 feet 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. 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 used to study the regions of high stresses, 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 analyse structures of complex shape, loading and material behaviour where the focus is on the internal stress distribution. The analysis is carried out using NISA (Numerically Integrated Elements for System Analysis) software.

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 modelling 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].

FOOT MODEL

In the present work, a three dimensional foot model, 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 and three toes. The lateral arch consists of calcaneus, cuboid, two metatarsals and two toes. Only one phalanx is modelled. In both medial arch and lateral arch, the bones in the medio-lateral directions are combined together. The cartilages between the bones are also modelled with their respective medial and lateral ligaments both on plantar and dorsal sides. The complex cartilage between calcaneus and talus is also introduced with medial and lateral ligaments and interosseous ligaments. Ligaments are provided connecting the medial arch and lateral arch in addition to the above ligaments. The predominant muscle forces are taken into consideration using anatomical data [7, 8] for the points of origin and insertion points.

The foot model is idealised as an assemblage of eight noded isoparametric solid brick elements representing the bones and cartilages and two noded rod elements representing the ligaments. The brick elements have three translational degrees of freedom per node. The meshes used are fine at areas of high stress gradients and the final mesh is decided based on a convergence study of the maximum deflection of the model.

In the mid-stance phase 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 [9] 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) and flexor digitorum longus (FDL) act predominantly on the foot [10, 11] and the forces in these muscles are obtained from literature [11, 12]. 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. Fig. 1 shows the model acted upon by the muscle forces. The finite element model as shown in Fig. 2 has 1475 brick elements to represent the bones and cartilages and 77 rod elements to model the ligaments.

Fig. 1 Two arch model of the normal foot in mid-stance phase. The muscle forces acting are indicated by numbers 1 through 12. 1- Muscle force in 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 in PB, 6- Muscle force in TP, 7- Muscle force in PL, 8, 9 & 10- Muscle forces in adductor hallucis (AH), 11- Muscle force in FHL and 12 & 13 Muscle forces in FDL.

Fig. 2 Finite element discretization of the two arch model in mid-stance phase

RESULTS

Fig. 3 shows the von Mises stress contour of the two arch model. The stress analysis shows von Mises stress is maximum (8.1 N/mm^2) near the ankle joint. The other high stressed regions are the junction of calcaneus and cuboid (7.5 N/mm^2), medial pulley (6.9 N/mm^2), plantar side of the navicular (6.9 N/mm^2), near the medial metatarsal head (6.9 N/mm^2), plantar side of cuneiform (5.8 N/mm^2) near the junction of talus and navicular. Fig. 4 shows a different view of the foot model with von Mises stress contour. The principal stresses are predominantly compressive in nature at these locations. It is found that the small magnitude

Fig. 3 Von Mises stress contour of the two arch model in mid-stance phase

Fig. 4 A different view of the von Mises stress contour of the two arch model

The high stress regions during the mid-stance phase are found near the ankle joint. The other areas of high stresses are the junction of calcaneus and cuboid, medial pulley, plantar side of the navicular, near the medial metatarsal support, plantar side of cuneiform, near the heel support and at the dorsal side of the talus near the junction of talus and navicular.

The two dimensional analysis [2] gives high von Mises stresses only at the dorsal anterior face of the talus whereas in the present three dimensional study eight 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 the 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 [13], 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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