Stress Distribution of the Foot During Mid-Stance to Push-Off in Barefoot Gait: a 3-D Finite Element Analysis

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Introduction
The objective of this research was to establish a preliminary 3-D finite element model of a normal foot, and to estimate the stress distribution in the foot during mid-stance to push-off phase during barefoot gait. In the finite element foot model, major bones and soft tissues of the foot were identified based on the computed tomographic (CT) sectional images. Quasi-static loading condition simulating barefoot gait during mid-stance (starting from heel-off) to push-off was applied and the stress distributions both in the plantar region and the interior bones were quantified. Experimental plantar pressure results from previous literature for normal barefoot gait were compared with the results from our finite element analysis for validation purpose.

Methods
CT scan images of the right foot of a 24-year-old male subject without any foot pathology were obtained in order to provide geometric information of the foot. A series of 136 scans at 2-mm interval was made in the frontal plane direction. The parallel contours for the bones and soft tissues for each CT scan were determined and used for the generation of the finite element model. The bones in the five phalanges were modeled to be five integrated parts and the rest of the metatarsals and tarsal bones were modeled with two rigid columns (medial and lateral). The medial column consisted of the first three metatarsals, three cuneiforms (medial, intermediate, and lateral), navicular, talus, and tibia. The lateral column consisted of the fourth and fifth metatarsals, cuboid, calcaneus, and fibula. The joint spaces between each of the five phalanges and its connective metatarsal bones were modeled with cartilage elements to simulate the metatarsophalangeal joints. Also the joint space between the medial and the lateral columns representing the metatarsals and the tarsal bones was also modeled with cartilage elements. The tetrahedral finite element models for each of the bone and cartilage parts were shown in Fig. 1(a). The soft tissue elements were generated and merged with the bone elements into a complete foot model as shown in Fig. 1(b). All materials were assumed to be linear, elastic solids. The material properties (modulus of elasticity, Poisson’s ratio, cross-sectional area) used for the bone, ligament, cartilage, and soft tissue elements were assigned with values adopted from previous literature.

In the current study we only considered the normal barefoot gait during mid-stance to push-off phase. Instead of direct application of the load on the foot, an alternative approach for the loading condition was used in this study. We assumed the foot to be steady and the floor to be a rigid plane moving towards the foot in the same relative linear and angular velocities as the foot. The kinematic parameters of the foot with respect to the floor was obtained from gait analysis using a Vicon 370 Motion analysis system. The 3-D linear and angular displacements, velocities, and accelerations of the foot with respect to the ground were determined from the kinematic data of the two markers on the foot. Only the dorsi-plantar flexion
motion of the foot in the sagittal plane was considered in this study. The varus-valgus and inversion-eversion motions were neglected for simplicity. A rigid plane simulating the floor was created and set to be moving relatively with respect to the foot model at a constant linear velocity of 20 mm/sec and an angular velocity calculated from the kinematic data obtained during gait. The foot was assumed to be a deformable contact body while the floor was assumed to be a rigid plane. In the finite element analysis, a quasi-static loading scheme was used and the linear and angular velocity control of the rigid plane was employed instead of the often-used load control. In this study, we only simulate gait from mid-stance (starting from heel-off) to push-off phase (total loading time is 0.12 sec). The displacements of all the nodes on the proximal tibial surface of the foot model were constrained in all directions as boundary condition. A finite element analysis package – MARC K.7.2 (MSC/MARC Corp., Los Angeles, CA, USA) on an HP SPP/2000 supercomputer at the National Center for High-Performance Computing (NCHC, Hsinchu, Taiwan, R.O.C.) was used to perform the analysis.

Results & Discussion

Following the analysis, we chose to display the normal stress at the plantar surface and the von Mises equivalent stress at the skeletal parts of the foot at four different loading instants (0.03, 0.06, 0.09, and 0.12 sec). The stress distributions of the plantar surface (normal stress) and the bones (von Mises stress) at the 0.12 sec analysis instant were shown in Fig. 2 for demonstration purpose. The gray scales representing stress levels displayed in the figures are selected to be 0 to -1 MPa (1000 kPa).

In order to compare the magnitudes of the peak normal stress in the plantar surface of the foot at different instants, the peak stress at the plantar surface under the first metatarsal (1MT), second metatarsal (2MT), and other metatarsals (other MT) were recorded. At t=0.03 sec, the peak stress occurred at the plantar surface under the second metatarsal with a magnitude of 374 kPa. At t=0.06 sec, the peak stress occurred at the same region with a magnitude of 549 kPa. At t=0.09 sec, the peak stress occurred under the other metatarsals (3rd to fifth) with a magnitude of 689 kPa. While at t=0.12 sec, the peak stress occurred at the plantar surface under the other metatarsals with a magnitude of 1003 kPa.

For the bone stress, the von Mises equivalent stress was chosen for display. The von Mises stress distributions in the bone at different instants were found and the results for instant 0.12 sec was shown in Fig. 2(b) and the gray scales representing stress levels displayed in the figure are set to be 0 to 10 MPa. We compared the peak von Mises stress at each of the metatarsals (1MT, 2MT, 3MT, 4MT, and 5MT) at four different instants. The maximum stress at each instant all occurred at the third metatarsal bone with magnitudes of 2.12 MPa (t=0.03 sec), 3.94 MPa (t=0.06 sec), 5.29 MPa (t=0.09 sec), and 6.91 MPa (t=0.12 sec), respectively.

The present study provides a preliminary computational model that is capable of estimating both the plantar foot pressure and the stress in the bone. Although many assumptions were still inevitable in the current model, it can provide quantitative analysis of normal and pathological foot and ankle motion. In the future, when this preliminary model is further improved, it would be possible to identify areas of increased pressure and correlate the pressure with foot pathology. Potential applications can be used in the study of foot deformities, such as hallux valgus, claw and hammer toes, flat foot, etc. Also, the biomechanical effects of other structural factors, such as soft tissue thickness, metatarsal length, and arch
length on the alteration of foot stress distribution can be investigated by properly modifying the current model. Moreover, it can predict the effects of footwear or surgical intervention on the alteration of stress distribution in the plantar surface and the bone. It may assist pre-treatment planning, design of pedorthotic appliances, and predict the treatment effect of foot orthosis.

Fig. 1. (a) The exploded view for each of the bones and cartilage in the foot bone model. (b) The complete finite element model of the foot bones, cartilage, ligaments and soft tissues.

Fig. 2. At analysis time 0.12 sec, (a) the normal stress distribution on the plantar surface, and (b) the von Mises stress distribution of the bone. (unit: Pa)

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