STRESSES IN A SIMPLIFIED TWO DIMENSIONAL MODEL OF A NORMAL FOOT - A PRELIMINARY ANALYSIS

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(Received 25 February 1992; accepted for print 23 September 1992)

Introduction

The loss of motor functions of the foot muscles in leprosy or diabetes changes the pattern of internal stresses in the foot skeleton. This may provoke local foci of relatively high stresses. In those cases where osteoporosis and cystic degeneration has weakened the mechanical strength of the bones, these excessive stresses may eventually lead to a local breakdown of bone. A finite element analysis of a foot model indicates those regions of high stresses. Before proceeding the analysis of stresses in the foot of a leprosy patient, it is essential that an estimate is made of the stress patterns in a normal foot. The foot is a complex structure with a number of bone segments, cartilages, ligaments and muscles. But, it is difficult to represent all the complex geometries and muscles in the first model. Therefore, in this paper, a simplified two-dimensional model of the foot is chosen and the predominant muscle forces acting (as per literature) are taken into consideration. The simplified model is used to study the regions of high stresses during three simulated, quasi-static equilibrium positions: mid-stance, heel strike and push off positions. The result of this analysis can serve as guidance in devising a model with next-higher level of complexity.

Model forming

The medial arch system of a human foot seems to be the most interesting system to be modelled first. The geometry of the simplified single bone model is taken from an X-ray of a normal foot. The foot is modelled as a two-dimensional membrane of equal thickness, with in-plane loading (Figure 1). The loads in the model are from two tendons of long muscles, one inserting at the calcaneous (simulating the triceps surae) and the
other at the combined cuneiform-metatarsal bones (simulating (2) the tibialis anterior muscle). The foot bone material is assumed to be homogeneous, isotropic and linear elastic; Young's modulus is equal to 7300 MPa and Poisson's ratio is taken as 0.3 [1]. The model is divided into 16 grids; one grid is divided into triangular three-noded membrane elements, the others into four-noded quadrilaterals, the finite element analysis is done by using the GIFTS program developed at the University of Arizona.

In the mid-stance phase the foot is supported at the heel and at the forefoot. From EMG muscle recordings [2,3] it can be observed that only the triceps surae muscle is active (Figure 2a). The ankle joint load is simulated by 2 times the body weight [4] of a normal subject having a weight of 800N, applied vertically downwards.

The heel strike phase is characterized by a $30^\circ$ inclination of the foot sole (Figure 2b). Only the tibialis anterior muscle is active [2,3]. The ankle joint force is simulated by 2.25 times body weight [4].

The push-off phase, from gait recordings [3,4], is characterized by a $45^\circ$ inclination of the foot sole (Figure 2c). From EMG recordings [2,3], it is obvious that only the triceps surae muscle is active. The ankle joint force is simulated by 3.5 times body weight $W$ [4].

In all load cases the directions of the forces are taken from anatomical considerations [5]. The magnitudes of the forces, expressed as multiples of
the body weight $W$, are shown in Table 1. In each of the three phases, the ankle joint force is in equilibrium with muscle forces and ground reaction forces.

**FIG. 2a**
The finite element mesh during mid-stance phase

**FIG. 2b**
The finite element mesh during heel strike phase

**FIG. 2c**
Finite element mesh during push-off phase
TABLE 1

External loads on the foot model in different positions

<table>
<thead>
<tr>
<th>Model phase</th>
<th>Ankle joint force</th>
<th>Triceps surae</th>
<th>Tibialis anterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-stance</td>
<td>2W</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Heel-strike</td>
<td>2.25W</td>
<td>0.77W</td>
<td></td>
</tr>
<tr>
<td>Push-off</td>
<td>3.5W</td>
<td>2.02W</td>
<td></td>
</tr>
</tbody>
</table>

W - body weight of a normal person, here stated as 600N

Results

In the Figures 3a, 3b and 3c the von Mises stress contours are plotted for each of the three calculated positions of the foot. In the mid-stance phase, it is observed that the anterior part of the tibio-talar joint region is the highest stressed region. In the heel strike position, it is the posterior part of the ankle joint which shows the highest stresses, whereas in the push-off position the talocalcaneonavicular boundary region is the highest stressed region. In Table 2, the values of high stresses are summarized and represented as a percentage of the yield stress of the bone material.

TABLE 2

Summary of results

<table>
<thead>
<tr>
<th>Model phase</th>
<th>Ground reaction force(N)</th>
<th>Highest von Mises stress contour</th>
<th>Highest principal stress</th>
<th>Failure criterion ++</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>von-Mises</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tresca</td>
</tr>
<tr>
<td>Mid-stance</td>
<td>600</td>
<td>32.5</td>
<td>52</td>
<td>46.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>38</td>
<td>51.7</td>
</tr>
<tr>
<td>Heel-strike</td>
<td>961*</td>
<td>22</td>
<td>24</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>(0.77W)</td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Push-off</td>
<td>904.8+</td>
<td>60</td>
<td>82.5</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>(1.51W)</td>
<td></td>
<td>61</td>
<td>82.5</td>
</tr>
</tbody>
</table>

* acting at an angle of 72° with the negative x direction, + acting at an angle of 73.2° with the positive x direction, W body weight of a normal person, here taken as 600N, All stresses, failure criteria are expressed as percentage of yield stress, ++ based on values calculated in the stress points of the elements.
VON MISES CRITERIA

A 25.00E+00  G  1.750E+01  M  3.250E+01
B 5.000E+00  H  2.000E+01  N  3.500E+01
C 7.500E+00  I  2.250E+01  O  3.750E+01
D 1.000E+01  J  2.500E+01  P  4.000E+01
E 1.250E+01  K  2.750E+01  Q  4.250E+01
F 1.500E+01  L  3.000E+01  R  4.500E+01

FIG. 3a
von Mises stress contours during mid-stance phase

FIG. 3b
von Mises stress contour plots during heel strike phase

FIG. 3c
von Mises stress contour plots during push-off phase
In the figures 4a, 4b and 4c a representation is given of the principal stresses in the elements of the highest stressed regions.

**FIG. 4a**
Distribution pattern of principal stresses on the higher stressed region during mid-stance

**FIG. 4b**
Principal stress distribution in the higher stressed regions of foot model during heel strike

**FIG. 4c**
Principal stress distribution in the higher stressed regions of the foot model during push-off phase
Conclusions

1. The push-off position gives rise to the highest von Mises stress in the model. The ratio of the highest stress in the three positions, heel strike, mid-stance and push-off is $1 : 2 : 3$.

2. The highest stressed region is the lower boundary of the talo-calcaneo-navicular region.

3. Compressive stresses are high in the upper part of the talus posterior to the trochlea during heel strike and in the upper part of the talus anterior to the trochlea during mid-stance and push-off position.

4. Tensile stresses are high at the lower boundary of the talo-calcaneo-navicular region during mid-stance and push-off phases.

Thus, the results of the finite element analysis of a simplified two-dimensional model of a normal foot, are useful in (i) finding the regions of high stresses which according to Orthopaedic surgeons is a possible point, wherein the bone disintegration process in leprosy may start and sometimes arthritis also develops, (ii) finding the relative value of stresses in different phases of the foot, namely, heel strike, mid-stance and push off. The result of this analysis can serve as guidance in devising a model with next-higher level of complexity involving cartilages, ligaments which enable simulations of articulations (joints) and the numerous interactions that take place between the bony segments of the foot.

Acknowledgement

The above study was supported by the financial grant by The Netherlands Foundation for Advancement of Tropical Research (WOTRO / DGIS, nr. W95 - 234.89), The Hague. The authors gratefully acknowledge the grant given by the foundation.

References