BIOMECHANICAL EVALUATION OF SURGICAL PLANTAR FASCIA RELEASE EFFECTS

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Abstract

Abnormal foot structures are known to influence tension stresses carried by the plantar fascia. An excessive arched foot structure may lead to plantar fasciitis. When conservative treatment fails, surgical intervention called plantar fascia release is often used for reducing chronic heel pain. A finite element structural model for mechanical analysis of the human foot during standing was developed and applied to the investigation of plantar fascia release biomechanical effects. The model integrates a system of five planar structures in the foot rays directions. It includes linear and non-linear elements representing different foot tissue types as well as inter-linking elements. A detailed normal foot structure was obtained using the newly developed advanced MRI technique, called Open MRI. The model was validated by comparing its resulted ground reactions with foot-ground pressure measurements and its predicted displacements with radiological tests. Simulation of fascia release (partial or total) was performed by gradually removing parts of the plantar fascia in the model. Results show that fascia release cause large sagging of the arch. Tension stresses carried by the long plantar ligament increase significantly. As the plantar fascia contribution to foot load bearing capabilities is of major importance, its release should be obviously carefully considered, and the model may be used to help surgeons decide about the degree of release.

Introduction

The plantar fascia functions are mainly to maintain the arched structure of the foot in order to absorb dynamic forces during gait. It also reduces, together with other ligamentous structural components of the foot, deformations under body-weight while standing and during locomotion. As body-weight tends to flatten the arch of the foot, exerted moments are balanced by the stiffness of the bones and joints, and by tension forces which are generated in the plantar ligaments/fascia. These ligaments are able to store part of the strain energy and return some of it in a quasi-elastic recoil. Abnormal foot structures such as excessive arch height are known to influence the tension stresses carried by the plantar fascia. The arched foot structure may lead to plantar fasciitis, an injury shared by athletes involved in different sports. It is an inflammatory condition that results from micro-tears in the plantar fascia. Conservative treatment of plantar fasciitis usually consists of icing the painful and inflamed area and reducing the repetitive weight-bearing stresses to the plantar fascia by using appropriate footwear, heel pad or orthosis. In more severe cases, oral anti-inflammatory medication and physical therapy are used. In the worst cases, when conservative treatment fails, a surgical intervention called plantar fascia partial or total release is performed to release the plantar fascia and reduce the chronic heel pain. However, the biomechanical effects of this procedure on the load bearing characteristics of other foot components are not yet clear. A 3-D finite element (FE) model was developed and applied to study the influence of Plantar Fascia Degree of Release (PFDR) on foot structure behavior and to enable biomechanical assessment of the partial/total release results before surgery. A number of attempts were made over the last years by foot investigators to develop structural models for clinical applications. Nakamura et al. (1981) used a 2-D FE model of the foot in an attempt to predict the stress states within the plantar soft tissues for different shoe conditions. In this work, the complex bony structure of the foot with its articulated joints was represented by a single elastic body (with the exception of a low Young modulus about the metatarsal heads to permit forefoot flexibility). The plantar soft tissue is represented by a non-linear elastic material. Simkin (1982) developed a model of the foot, which is both quantitative and representative in the 3-D structure of the foot, using matrix structural analysis. Structural linear elastic members replaced the bones and ligaments of the foot. The element properties, spatial arrangement and connections were expressed in matrix forms. Computer analysis of the displacements, forces and ground reactions in the structure was performed using a set of rules (equilibrium of forces, compatibility of displacements, and minimum potential energy). The model of Simkin (1982) was a major breakthrough. His model described the general three-dimensional structure of the foot, measured on cadaver feet using X-ray photogrammetry. The flexibility coefficients of the joints were found experimentally, on fresh specimens obtained from human
cadavers. As some joint geometrical misrepresentation could not be avoided when using matrix structural analysis, the resulted reduced accuracy in the field of displacements did not allow a complete validation of the model\textsuperscript{11}. Patil et al. (1993, 1996) used a 2-D FE model of the foot to study the regions of high stress during the three phases of gait in normal and disordered feet\textsuperscript{9,10}. Although the work of Patil et al. is an important step towards the ability to predict stress concentrations in normal and disordered feet, their 2-D approach and inaccurate X-ray geometry are limiting the model validity. Hence, it was decided to develop an advanced model to investigate fascia release effects. The model, which was built according to geometrical data obtained from the human foot, provides a realistic 3-D representation of its structure and includes non-linear soft tissue effects\textsuperscript{4}. The aim of the present study was to apply the model, validated by Foot-Ground Pressure Pattern (FGP)\textsuperscript{1,2,4} and radiological measurements\textsuperscript{4}, for structural stress analysis of the foot when considering a partial/total fascia release surgery.

**Methods**

The model integrates a system of five planar sections of the foot, in the directions of the five rays (Fig. 1). It was built using the ANSYS FEA software, according to geometrical data measured from MRI sections of a normal foot, using the newly developed advanced Open MRI technique. By using inter-linked elements and a realistic loading method, a representation of the 3-D structure of the foot is obtained. Each component of the model represents a planar section comprising several elements of the foot. The model elements belong to the following five types: a) bones, b) joints cartilage, c) plantar fascia, d) ligaments, e) soft tissues. The material properties of the model tissues are based on experimental measurements taken from the literature. Bone cartilage and ligaments are idealized to linear, perfectly elastic, and isotropic materials, while soft tissue is considered as a non-linear material. For the bone, cartilage and ligaments, the values of the Young modulus and Poisson ratios had to be selected from the literature. The Young modulus for bones was taken from Nakamura et al. (1981), as 7300 [MPa] (average value between cortical and trabecular bones). The Poisson ratio for bones was taken from the same work as 0.3. These values are frequently used for bone modeling in the literature\textsuperscript{8}. For the cartilage, the Young modulus and Poisson ratio were taken from Patil et al. (1993, 1996), as 10 [MPa] and 0.4 respectively\textsuperscript{9,10}. The value of Young modulus and Poisson ratio for the plantar fascia were taken from Chu et al. (1995) as 11.5 [MPa] and 0.4 respectively\textsuperscript{3}. The value of the Young modulus for the ligaments was taken as 150\% of the value for the plantar fascia (i.e. 17.25 [MPa]). This value, which was obtained in a convergent process of calculating the model stress state and correcting the Young modulus satisfies the following condition: under loading, no tensile forces are taken by the cartilage. The stresses, which pass through the cartilage, are all-compressive or (nearly) zero, just as in reality. The Poisson ratio for the ligaments was also selected as 0.4. It was determined to include the non-linear behavior of the soft tissue which pads the bony structure of the foot, since it goes through large deformations while transferring the ground reaction forces. Nakamura (1981) et al. studied the material properties of the plantar soft tissue. They obtained the compression stress-strain curve of a specimen taken from the heel of a fresh cadaver\textsuperscript{8}, which was subsequently used in the present work for the soft tissue model; the Poisson ratio for the soft tissue (0.49) was also taken from the same work. The total load carried by the foot model was determined to be 400 [N]. The external force system, representing the body load on each of the five sections of the model in the standing posture, was applied by weighting the loads to the five rays as follows: 25\%-19\%\%-19\%-19\%-18\% for the first through the fifth ray. This distribution is based on the results of Simkin (1982) who, as part of his work, investigated the body load distribution on the five rays of the foot\textsuperscript{11}. In addition to the body-weight...
surface load, a concentrated force is applied on the calcaneal posterior aspect to represent the effect of the Achilles tendon. Simkin (1982) evaluated this force as 50% of the body load\(^{11}\). By assuming that the Achilles tendon load divides equally between the five sections, a force of 40 [N] is applied to the Achilles tendon insertion point in each of the sections. The proposed model provides the distribution of stresses and displacements among the anatomic components of the foot, under static loading of the body weight, in an upright standing posture. The reaction forces (contact stresses) predicted by the model were validated for a normal foot, in comparison to the experimentally obtained foot-ground pressure pattern (FGP) of the subject from whom geometrical data were acquired. The model displacements were also checked by comparing them to lateral X-rays of the subject’s foot\(^4\). Simulation of plantar fascia partial and total release was performed by gradually removing parts of the plantar fascia in the model, as discussed in the following part of the present paper.

**Results and Discussion**

Structural stresses and displacements were calculated for the post-surgery conditions. The displacements in the y direction for a total plantar fascia release are presented in Fig. 2. Comparison of the results for the pre- and post-surgery conditions yields a predicted additional 44% lowering of the arch under body-weight after plantar fascia release (maximal sagging of 0.36 mm in the normal foot compared to predicted post-surgery maximal sagging of 0.52 mm). By decreasing arch height, plantar fascia release reduces the dynamic shock absorbing abilities of the foot. This phenomenon might be connected with clinical studies showing that subjects, who are characterized by flat feet, cannot sustain long marches\(^2,6\). The resulted principal tension stress distributions for plantar fascia total release are presented in Fig. 3. The predicted tension force in the long plantar ligament increases as much as 1.7 times its value before the fascia was surgically released. The deep long plantar ligament in the normal foot model carries average tension stresses of 19 KPa (1\(^{st}\) section). The superficial long plantar ligament in the normal foot model carries average tension stresses of 14 KPa (2\(^{nd}\) section). Plantar fascia surgical total release causes the average tension stresses in both the deep and the superficial long plantar ligament to reach a value of 24 KPa. These amplified tension stresses are transferred to the calcaneus, cuneiform and metatarsal, and exert increased structural stresses. Simulation of a partial plantar fascia release, performed by reducing the plantar fascia sectional area, yields displacements and tension stresses, which are smaller than in total plantar fascia release. The displacements and stresses predicted by the model for a partial fascia release are given in the following table.

<table>
<thead>
<tr>
<th>Plantar Fascia Reduction [%]</th>
<th>Foot Sagging [mm]</th>
<th>Relative Sagging [%]</th>
<th>Deep LPL Tension Stress [KPa]</th>
<th>Superficial LPL Tension Stress [KPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Normal Foot)</td>
<td>0.36</td>
<td>-</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>25</td>
<td>0.38</td>
<td>6</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>50</td>
<td>0.41</td>
<td>14</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>75</td>
<td>0.46</td>
<td>28</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>100 (total release)</td>
<td>0.52</td>
<td>44</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

The results obtained for different partial fascia release degrees, show that both foot sagging and average tension stresses in the long plantar ligaments, increase exponentially (correlation coefficient of \(r^2=0.999\)) with the decrease in the sectional area of the fascia. Calculating the ratio of elastic energy stored in the plantar fascia to the work performed by body load, an estimation of the load sharing between the plantar fascia and the rest of the foot components is obtained. It was found that the plantar fascia carries as much as 18% of the entire loading applied to the normal foot. The rest, 82% of the loading, is maintained by other foot structural components, including other ligaments and the arch. The released plantar fascia model results show that plantar fascia total release cause large sagging of the arch, relatively to its geometry before surgery. Tension stresses carried by the long plantar ligament increase significantly. Hence, when a surgical removal or significant release of the plantar fascia is considered, a decrease in foot structure load-bearing capabilities should be taken into account. The model presented in this work may be further applied to investigate other clinical relevant
foot disorders due to congenital or acquired deformities, or to traumatic injuries. By changing geometrical or material properties of the model, such disorders could be analyzed. Decreasing the ligament stiffness and increasing this way the midfoot-ground contact area, for example, may simulate low arched foot structure (flatfoot). Additional surgical interventions could be studied, by simply removing or adding elements. Alternative old or new surgical procedures may be simulated. Orthotics and supportive devices may be evaluated and their effect on the stress distribution studied. Finally, as the model visualize the structural behavior of the human foot, it may be used by physicians not only for surgeries pre-evaluation, but also to have a better and comprehensive understanding of the load bearing mechanisms in the normal and disordered foot.
References