FINITE ELEMENT MODEL OF THE HUMAN FOOT-ANKLE JOINT COMPLEX VALIDATED WITH PATIENT-SPECIFIC DATA

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Introduction: The essential biomechanical factors underlying pathologies of many foot disorders have been associated with abnormal stress and strain distributions or loading transfer in the foot and ankle joint complex [1]. Limited by current experiment approaches to measure the internal stress and strain of foot during gait, theoretical analysis using finite element (FE) modeling has so far prevailed. Currently, most of the existing human foot FE models are incomplete, either analyze the partial foot [2], simply to 2-D [3], or are subjected to inaccurate geometry [5] and oversimplified foot skeletal interaction in 3-D analyses [6]. We have developed an improved 3-D FE model of the foot and ankle joint complex with comprehensive skeletal and soft-tissue components. To validate the FE predictions from the model, an experimental study by using F-scan system was also performed for patient-specific plantar pressure measurements. The validated FE model was subsequently applied to determine the internal stress and stain distribution in the foot and ankle joint during static standing.

Materials and Methods: The 3-D geometry of the soft tissue-skeletal foot and ankle joint complex was created based on the coronal computer tomography (CT) scan of the right foot of a male adult who was free of any foot abnormalities and pathologies. Foot structures such as articular cartilages, ligaments and plantar fascia that could not be reconstructed from CT were determined through magnetic resonance (MR) imaging and histological observations. 30 bony parts with articular cartilages, including sesamoids, were created individually and then were enveloped into a mass of foot soft tissue in which the muscular constitutions were not separately identified. A total of 5 sub-bands of plantar fascia and 134 major ligaments (Ligs) were also incorporated into the model to passively stabilize the cartilage-mediated bony joints: 14 ankle Ligs, 11 talocalcaneal Ligs, 14 talonavicular Ligs, 9 calcaneocuboidal Ligs, 13 navicucuneiform Ligs, 27 tarsometatarsal Ligs, and other 46 short Ligs.

In order to simulate the joint interactions among the tibia, fibula, calcaneous, talus, navicular, cuboid, cuneiforms, and metatarsals, 15 pairs of ABaQUS/Con tact conditions were defined accordingly, which allow bones to slide frictionless over one another. Since the joint surfaces were all wrapped with articular cartilages, the governing stiffness during contact was set to be 1.01MPa which is consistent with the compressive material properties of the foot joint cartilage. Both the bony structures and soft-tissue were meshed with 4-noded tetrahedral elements, while the ligaments and plantar fascia were represented by 2-noded tension-only truss elements. A second-order polynomial hyperelastic material model was applied to incorporate the nonlinear properties into the pad soft tissue. Other structures were assumed to behave in linear isotropic manners. During static standing, an estimated ground reaction force of 325 N (half of the BW) was applied to the foot model through uniformly distributed pressure. An estimated gastrocnemius-soleus muscle force of 162 N acting through Achilles tendon to the calcaneous was also applied by using force vectors [7], and the superior part of tibia, fibula and soft tissue were all fixed by all degree of freedom. In addition, a frictional contact interaction was established between the foot plantar surface and the ground.

Results: During static standing, the FE model predicted similar patterns of plantar pressure distribution as compared to the F-scan measurements (Fig. 2), the FE predictions were also found to agree with the F-scan measurements in terms of center of contact pressure (COP), peak contact stress (PCS) and total contact area (TCA) (Table 1), especially true for the COP and PCS predictions. Table 1. Comparison of FE predictions and F-scan measurements

<table>
<thead>
<tr>
<th></th>
<th>Comparison basis</th>
<th>COP</th>
<th>PCS (MPa)</th>
<th>TCA (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-scan data</td>
<td>Half center-bounced</td>
<td>0.150</td>
<td>10.390</td>
<td></td>
</tr>
<tr>
<td>FE predictions</td>
<td>Half center-bounced</td>
<td>0.178</td>
<td>7.522</td>
<td></td>
</tr>
</tbody>
</table>

The internal peak von Mises stress (PVMS) in the soft tissue was found near the region of the third metatarsal head with a magnitude of 1.51MPa. The PVMS in bony structures was located at the contact surface inside the talocalcaneal joint, while the Ligaments that constrained the talonavicular and navicucuneiform joints were the most stretched ligaments during standing since the largest ligaments were found there. As to the internal loading transfer, contact force transferred through the talocalcaneal joint was 120.4 N which is much larger than that transferred through the ankle joint.

Discussion: The current study validates the robustness of a comprehensive FE modeling of a human foot-ankle joint complex by directly comparing the simulated results with the F-scan measurements from a subject. The validated FE model provides valuable information in understanding the internal stress and strain distributions in soft tissue, bones and ligaments, and could provide surgeons with a biomechanical rationale in deciding their treatment options. This model has potential to become a useful tool to predict risk of tissue damage or injury in various disorders of pathologies of the foot. Hence, our future research focuses on the parametrical study using the current FE model to investigate the patient specific effects of foot-ankle surgery or ligament dysfunction, contributions of muscular forces, and contact mechanics of foot bony joints such as talocalcaneal joint.


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