HYPERELASTIC MECHANICAL PROPERTIES OF THE HUMAN SUBCALCANEAL FAT PAD: AN INVERSE FINITE ELEMENT ANALYSIS

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INTRODUCTION
Many previous finite element (FE) foot models assume a single homogeneous, isotropic, hyperelastic generic soft tissue material to represent skin, fat, and muscles [1, 2]. In these models, the material behavior was typically obtained from in vivo heel-pad indentation experiments [3] or in vitro uni-axial dynamic compression testing [4, 5]. The corresponding hyperelastic parameters were calculated from automatic model fitting via commercial FE software [1, 6] or by inverse FE analysis [3, 7]. Failure to distinguish between skin and fat in the indentation tests, lack of shear data, and extensive model simplification leads to biomechanically unrealistic material parameters and poor predictions of the soft tissue response. For example, significant errors (>100%) in plantar pressure prediction were found in a model with generic soft tissue in contrast to small errors (<10%) in a model with distinct skin and plantar fat layers [6]. The purpose of this study is to quantify the hyperelastic material parameters from the compression and shear mechanical testing of the isolated subcalcaneal fat pad by utilizing 3D inverse FE analysis.

METHODS
The dynamic force-displacement data of the isolated subcalcaneal fat pad subjected to compression only loading [5] and shear loading [8] from previous studies were used as target response for inverse FE analysis. A semi-circular FE model of the cylindrical fat specimen consisted of all hexahedral elements (Figure 1). The fat material was modeled as a first order (n=1) and second order (n=2), homogeneous, isotropic, incompressible (Poisson’s ratio = 0.495) Ogden hyperelastic material [9] in compression, shear and multi-objective (optimize compression and shear simultaneously) tests, for a total of six analyses. The material parameters, \( \mu_m \) and \( \alpha_m \), are treated as variables in the inverse FE analysis. No slipping was allowed for nodes that contacted the loading platens. The displacement was prescribed to the bottom platen according to the test protocol (57% in compression only and 85% in shear (with 36% pre-compression)). To ensure model stability, global damping (VALDMP=35), hourglass control (IHQ=4, QM= 0.05) and an automatic time step calculation were utilized. The models were solved in LS-DYNA (V971 R5.1.1). The predicted total force acting on the platen was used in an inverse FE analysis, performed in LS-OPT (V4.1 R66374), which iteratively adjusted variables, \( \mu_m \) and \( \alpha_m \), until the optimum mean square error (MSE) between the model and target force-displacement response was achieved.

RESULTS AND DISCUSSION
Although the inverse FE analysis is still in progress, several trends were observed in the data generated to date. First, the analysis found different material parameters between the compression and shear optimization (Table 1). Using the first order Ogden hyperelastic material, the root mean square error (RMSE) was 5.5% from the peak force for compression (Figure 2) and 8.6% from the peak force for shear. Modifying the hyperelastic model to the second order yielded a better fit with an RMSE of 2.6% from the peak force in compression. By performing multi-objective optimization, higher RMSE for both compression and shear were found. Future work includes: shear and multi-objective analysis using second (or higher) order Ogden model and incorporating material anisotropy.

Table 1: Hyperelastic parameters from inverse FE analysis

<table>
<thead>
<tr>
<th>Analysis (n=order)</th>
<th>Ogden parameters</th>
<th>RMSE (% max force)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression (n=1)</td>
<td>( \mu_1 = 0.214 \text{kPa}, \alpha_1 = 7.64 )</td>
<td>5.5</td>
</tr>
<tr>
<td>Compression (n=2)†</td>
<td>( \mu_1 = 4.95E-13 \text{kPa}, \alpha_1 = 55.3 )</td>
<td>2.6</td>
</tr>
<tr>
<td>Shear (n=1)†</td>
<td>( \mu_1 = 2.154 \text{kPa}, \alpha_1 = 1.18 )</td>
<td>8.6</td>
</tr>
<tr>
<td>Multi-objective (n=1)</td>
<td>( \mu_1 = 82.5 \text{kPa}, \alpha_1 = 0.57 )</td>
<td>8.43 comp</td>
</tr>
<tr>
<td></td>
<td>( \mu_1 = 0.045 \text{kPa}, \alpha_1 = 16.1 )</td>
<td>25.7 shear</td>
</tr>
</tbody>
</table>

† work in progress

Figure 2: Compression force-displacement response of the optimized model compared to the target response.

REFERENCES

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