Mechanical Behavior of Human Gastrocnemius

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Mechanical Behavior of Human Gastrocnemius

INTRODUCTION

- Muscles, such as the gastrocnemius (one of the largest human calf muscles) exhibit large deformation without experiencing permanent damage because of their visco and hyper-elastic behavior.
- Constitutive equations, such as the Yeoh strain energy function are used to describe the nonlinear and hyper-elastic behavior of muscles.

BACKGROUND INFORMATION

- The Yeoh strain energy function is a constitutive equation for hyper-elastic and fully incompressible materials (which is the assumption when investigating muscle tissues).
- The Yeoh strain energy function can be described as a one, two, or three term function:

\[ \Psi = c_1(l_1 - 3) + c_2(l_1 - 3)^2 + c_3(l_1 - 3)^3 \]

Where, \( \Psi \) is strain energy function
\( c_1 \) is the first material constant
\( c_2 \) is the second material constant
\( c_3 \) is the third material constant
\( l_1 \) is the first strain invariant

OBJECTIVE

To describe the mechanical behavior of human gastrocnemius by using finite element analysis (FEA) to simulate uniaxial tensile tests and find the total strain, energy, deformation, stiffness, and normal strain.

METHODOLOGY

Experimental Testing:
- The experimental data (e.g., maximum load, deformation, engineering stress, and strain) were obtained from the literature (Shan et al., 2019).
- The gastrocnemius were cut into thin (thickness < 1 mm) rectangular specimens (width 10-40 mm and length 20-40 mm) and subjected to uniaxial tensile testing until the specimen elongated by 0.48-1 mm (Shan et al., 2019).

Modeling:
- SolidWorks was used to model the rectangular specimens and grip of the tensile testing machine.
- SolidWorks was also used to assemble the tensile testing set-up, using the rectangular specimen and grip of the tensile testing machine.

Mathematical Modeling:
- A two- and three-term Yeoh strain energy function in terms of Cauchy stress and stretch ratios was used to describe the material behavior of gastrocnemius.
- The two term Yeoh strain energy function:

\[ \Psi = c_1(l_1 - 3) + c_2(l_1 - 3)^2 \]

Cauchy stress equation:

\[ \sigma = -p I + 2 \frac{\mathbf{F}}{\mathbf{I}_2} \]

Where, \( \sigma \) is Cauchy stress
\( p \) is pressure
\( I \) is the identity matrix
\( \mathbf{F} \) is the left Cauchy stress tensor

FEA:
- The assemblies of the testing set-up were imported into the Ansys workbench.
- In the Ansys workbench, the experimental data was imported and curve-fitted to a two term Yeoh strain energy function to describe the material behavior of the specimen.
- Ansys Mechanical was used to simulate the uniaxial tensile testing and predict the mechanical behavior of gastrocnemius from total strain energy, deformation, and normal strain.

RESULTS

Descriptive Measurements:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum Load (N)</th>
<th>Deformation (mm)</th>
<th>Normal Strain (mm/mm)</th>
<th>Total Strain Energy (mJ)</th>
<th>Stiffness (MPa)</th>
<th>Young's Modulus (MPa)</th>
<th>Shear Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average ± Standard Deviation</td>
<td>63.363 ± 38.853</td>
<td>0.087 ± 0.288</td>
<td>0.0404 ± 0.0152</td>
<td>20.964 ± 17.832</td>
<td>71.403 ± 37.988</td>
<td>179.568 ± 82.872</td>
<td>59.856 ± 27.624</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FEA Predicted Results:</th>
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<td>Maximum deformation and strain were experienced towards the top of the specimen.</td>
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</tbody>
</table>

DISCUSSION/CONCLUSION

- The large standard deviation for some mechanical properties occurred because the specimens varied in age and activity level.
- The literature shows that mechanical properties deteriorate with age and increase with moderate activity levels (LaCroix et al., 2013).
- However, using a three term Yeoh model may improve results because some specimens' material behavior could have been expressed as a cubic function.
- In conclusion, based on relatively high stiffness the human gastrocnemius is a hyper-elastic biological tissue and shear modulus shows that the human gastrocnemius is also a visco-elastic material that can deform without experiencing permanent damage.

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REFERENCES