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Mechanical Behavior of Human Gastrocnemius

Shunafrica C. White
North Carolina Agricultural and Technical State University

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Student: Shunafrica C. White, Department of Mechanical Engineering, PhD Student
Advisors: Matthew B.A. McCullough, Department of Chemical, Biological, and Bioengineering
Paul Akangah, Department of Mechanical Engineering

Cross-Disciplinary Research Area: Biomechanics

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.

Figure 1. Illustration of human gastrocnemius.

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:

$$\Psi = c_1(I_1 - 3) + c_2(I_1 - 3)^2 + c_3(I_1 - 3)^3$$

Where, Ψ 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

I_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 gastrocnemii 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 assembly the tensile testing set-up, using the rectangular specimen and grip of the tensile testing machine.

Mathematical Modeling:

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

$$\Psi = c_1(I_1 - 3) + c_2(I_1 - 3)^2$$

- Cauchy stress equation:

$$\sigma = -p\mathrm{I} + 2\frac{\partial \Psi}{\partial I_1} b$$

Where, σ is Cauchy stress

p is pressure

I is the identity matrix

b 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 gastrocnemii from total strain energy, deformation, and normal strain.

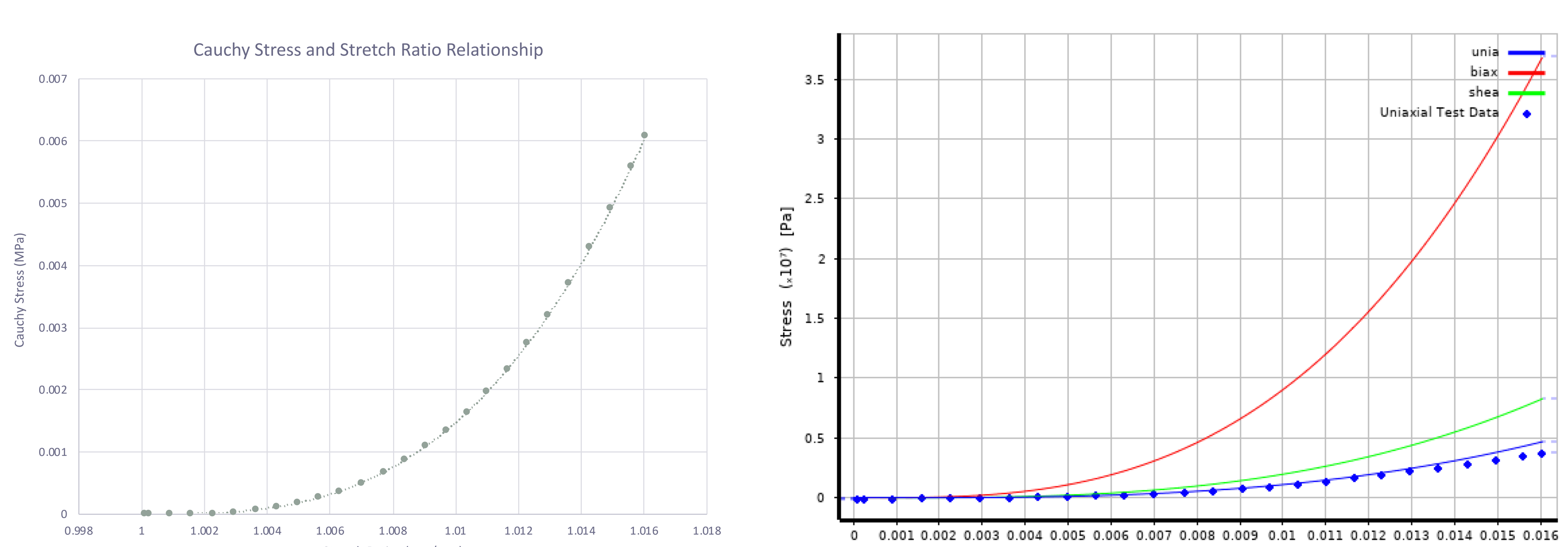

Figure 2. Left: Material behavior of gastrocnemii as defined by mathematical model. Right: Material behavior of gastrocnemii as defined by Ansys Curve Fitting.

Statistical Analysis:

- Descriptive measurements such as mean and standard deviation were used to describe mechanical properties (total strain energy, deformation, stiffness, maximum load, Young's Modulus, shear modulus, and normal strain).

RESULTS

Descriptive Measurements:

Maximum Load (N)	Deformation (mm)	Normal Strain (mm/mm)	Total Strain Energy (mJ)	Stiffness (N/mm)	Young's Modulus (MPa)	Shear Modulus (MPa)
63.363 ± 38.653	0.887 ± 0.288	0.0404 ± 0.0152	20.964 ± 17.852	71.403 ± 37.988	179.568 ± 82.872	59.856 ± 27.624

Table 1. Average and standard deviation of mechanical properties of human gastrocnemius.

FEA Predicted Results:

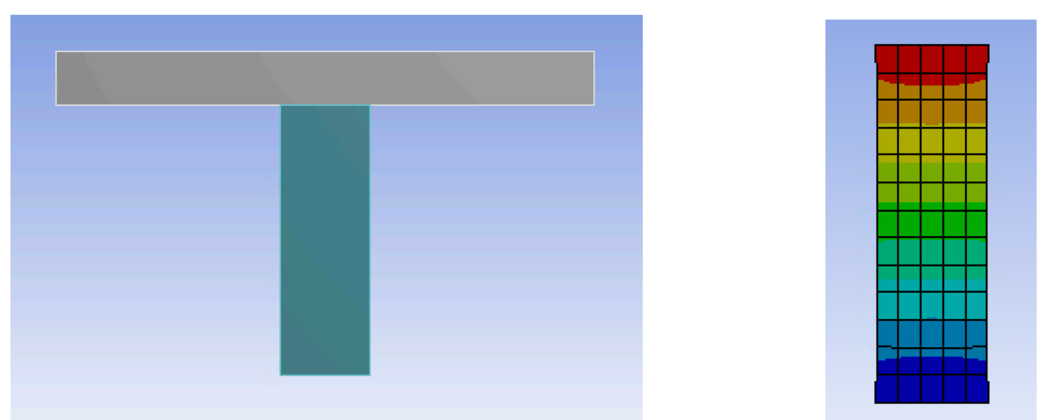

Figure 3. Left: Model of the tensile test set-up prior to deformation. Right: Model of the rectangular specimen after deformation.

- Maximum deformation and strain were experienced towards the top of the specimen.

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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