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Jugular and Saphenous Venous Valve tissue Behavior comparison via Phenomenological Modeling

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Introduction and Background

Motivations :

- Valves ensure unidirectional flow, preventing reflux of blood preventing CVI and varicose veins.
- Veins (ubiquitous throughout the body) affected by numerous diseases like CVI, Thrombosis; used in valve replacement, vein reconstruction .etc., but without any proper study.
- Material Properties are not known.
- Highly Non-Linear Stress-Strain behavior Mechanical Anisotropy, Large Deformations, Viscoelastic nature of both tissue materials.
- Use of SV valves as replacement valves is an ongoing area of research.

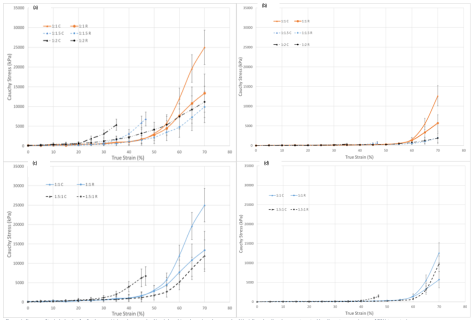


Figure 1: Stress vs Strain behavior for Saphenous Vein valve samples (1a, 1c) and Jugular vein valve samples (1b, 1d) under diusplacement control loadin upto a maximum of 70% true strain.

Focus :

I. To compare the mechanical behavior of SV and JV valve tissue under displacement control loading.
II. To determine suitable phenomenological strain energy based constitutive relation for SV valve tissue.
III. Determination of material parameters required to implement the model numerically in FEM environment.

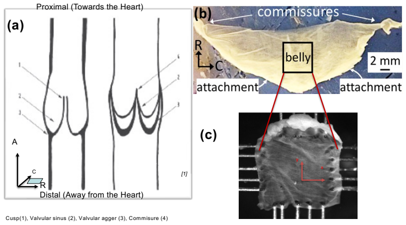


Fig. 2: Schematic showing the position of the tissue used for experimental tests: (a.) Position of the valve tissue. (b.) Position of the valve tissue sample from the belly region. (c.) Valve sample mounted on the biaxial testing apparatus with hooks attached for holding all 4 sides with no in plane shear.

Methods and Results

Mathematical Preliminaries and Strain Energy based Constitutive Relation :

- For Hyperelastic Tissues at finite strains : $S = 2\frac{\partial W}{\partial C} + pC^{-1}$
- Factoring Incompressibility, In plane Stress, and a strain energy function of the form $f(I_1, I_4)$:

$$\sigma = 2F.\{W_1 I + W_4 a_0 \otimes a_0\}.F^T - 2W_1 C_{33}.I$$

- Choice of material specific strain energy expression is based on the material behavior when subjected to constant Invariant testing.
- Constant α and Constant I_1 Tests for 8 Saphenous valve samples were conducted to study the behavior of strain energy derivatives.
- Response curves (Fig. 3) were plotted based on the experimental data.
- The SV response curves were found highly similar to JV response curves qualitatively.
- Same Strain energy expression selected for SV as was used for JV.

$$W = c_0\{\exp Q - 1\} \qquad Q = c_1(I_1 - 3)^a + c_2(\alpha - 1)^b \qquad \alpha = I_4^{\frac{1}{2}}$$

- Strain energy derivatives hence can be written as (a=2,b=4):

$$W_1 = \frac{\partial W}{\partial I_1} = ac_0c_1(I_1 - 3)^{a-1}\exp Q$$

$$W_4 = \frac{\partial W}{\partial I_4} = \frac{bc_0c_2}{2\alpha}(\alpha - 1)^{b-1}\exp Q$$

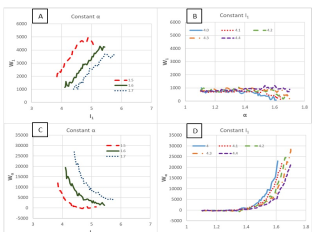


Figure 3: Response curve for Saphenous vein valve sample generated from Constant Invariant testing. The curves shows the behavior of Strain energy derivatives with respect to Invariants.

Material Model Parameter estimation :

- Using Powell's Method Algorithm to minimize the square of residuals between experimental and model predicted stress value.

$$\chi^2 = \sum_{i=1}^{N}[y^i - t^i]^2$$

- Model predicted stress values are given by:

$$\sigma_{11} = \{2ac_0c_1(I_1 - 3)^{a-1}(\lambda_1^2 - \lambda_3^2) + \frac{bc_0c_2}{\alpha}(\alpha - 1)^{b-1}(\lambda_1^2\cos^2\theta)\}\exp Q$$

$$\sigma_{22} = \{2ac_0c_1(I_1 - 3)^{a-1}(\lambda_2^2 - \lambda_3^2) + \frac{bc_0c_2}{\alpha}(\alpha - 1)^{b-1}(\lambda_2^2\sin^2\theta)\}\exp Q$$

- Data from equibiaxial and off biaxial displacement-controlled testing (with a maximum strain of 70%) was used for parameter estimation.
- 5 different protocols were used to collect data at 1Hz with 8 cycles of tissue preconditioning.
- c_1 and c_2 are dimensionless in the model whereas, c_0 has the units of MPa for SV and kPa for JV.

Sample	c_0	c_1	c_2
Jugular Vein Valve Tissue	112.281	0.059	1.09

Sample	C_0 (in MPa)	C_1 ($\times 10^{-2}$)	C_2 ($\times 10^{-2}$)
Saphenous Vein Valve Tissue	7.68	1.40	20.85

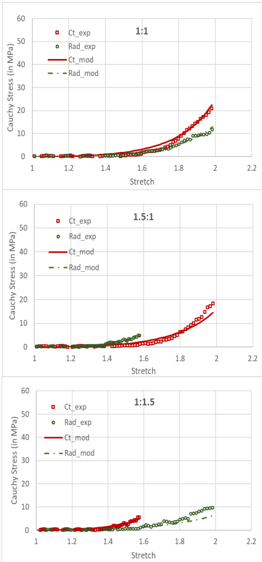
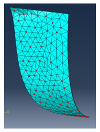
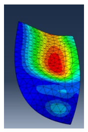


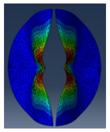
Figure 4: Predicted vs experimental Stress vs Stretch Values for a Saphenous Valve Sample.

Conclusion & Future Work

- Material models presented for the SV valve tissue were able to emulate the behavior of tissue under experimental testing, evident from high correlation coefficients.
- SV valve tissue is stiffer in nature, smaller and experiences higher stresses compared to JV counterpart.
- The study also provides investigators with representative material parameters to be used in computer simulations
- Additionally, it can be of great help during the primary stages of bio prosthetic designs, valve-replacement surgeries, and when investigating valvular diseases.
- FEM Simulations implementing the material model are currently under work.







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