MICROMECHANICAL MODELING OF NONLINEAR VISCOELASTIC BEHAVIOR OF MITRAL VALVE CHORDAE

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INTRODUCTION

Biological tissues, such as heart valves, consist of stiff fibers embedded in a soft matrix. Most computational analyses of the highly non-linear mechanical response that results are based on the concept of a continuum in which a constitutive model is postulated for an averaged volume. In order to more accurately model the specific interaction of tissue constituents, we have applied a micromechanical modeling approach, in which the macroscopic behavior emerges from the mechanical interaction of the internal microstructure. Our vision is to associate subgrid mechanics based on measured tissue microstructure with macroscopic computational models in order to resolve stress at the physiologically relevant scale.

METHODS

Micromechanics Model and Geometry

We have implemented a high-fidelity modeling system that uses the generalized method of cells to represent the viscoelastic response of periodic materials with continuous reinforcement along the X1 direction. The model is characterized by a repeating unit cell with an arbitrary microstructure in X2-X3 plane [1]. The micromechanics analysis of the periodic multiphase material is based on approximating repeating unit cell by a rectangular grid (Fig.1).

Microscopic Constituents

The microstructure of mitral valve chordae was assumed to be composed of nonlinearly viscoelastic, crimped collagen fibrils, embedded in a nonlinearly elastic matrix. The nonlinear elastic response of both phases was modeled as a Mooney-Rivlin material, whose strain energy function (W) is:

$$W = c_{10}(I_1-3) + c_{01}(I_2-3) \quad , \qquad (1)$$

where c_{10} and c_{01} are material parameters. The viscoelastic response of the collagen fibers was assumed to be quasi-linear (QLV). Generally, the elastic response of each constituent is determined from the relationship between the second Piola-Kirchhoff stress $\mathbf{S}^e$ and the right Cauchy-Green deformation tensor [1]

$$\mathbf{S}^e = 2\frac{\partial W}{\partial \mathbf{C}}. \qquad (2)$$

Following the discrete spectrum approximation of Puso and Weiss [2], the time-dependent response is represented as:

$$\mathbf{S}_{(t+\Delta t)} = G_e\mathbf{S}^e_{(t+\Delta t)} + K\sum_{I=0}^{N}\left[\begin{array}{l}\exp\left(\Delta t/v_I\right)\mathbf{H}_{I(t)} + \\ \left(\mathbf{S}^e_{(t+\Delta t)} - \mathbf{S}^e_{(t)}\right)\left[\dfrac{1-\exp\left(\Delta t/v_I\right)}{\Delta t\, v_I}\right]\end{array}\right]$$

$$K = \frac{G_0 - G_e}{Nd+1}; \quad v_I = 10^{I+I_0}; \quad \mathbf{H}_I = \int_0^t \exp\left(-(t-s)/v_I\right)\frac{d\mathbf{S}^e}{ds}ds$$

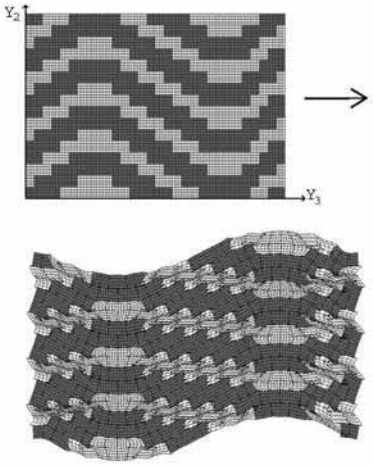

Figure 1: A wavy mesh representing crimped structure of collagen embedded in a nonlinearly elastic matrix: undeformed mesh (top), deformed mesh (bottom). Collagen fibers are in black.

Ge is the equilibrium modulus, G0 is the initial modulus, Nd is the number of decades in the transition and 10Io is the lowest discernable relaxation time. As indicated by Puso and Weiss [2], these four parameters can be determined graphically from a logarithmic plot of G(t). A non-zero deformation was applied in 33-direction ($F_{33}\neq 0$). All tractions other than T_{33} were zero. Deformation was applied for 1.25 s at a strain rate of 40%/sec. From t = 1.25 sec. to t = 3.25 sec., extension was held constant to examine stress relaxation.

RESULTS AND DISCUSSION

The deformation and stress distribution of the unit cell was as expected. Figure 1 shows both undeformed and deformed configurations. Extension of collagen crimp produced a toe region of the stress strain curve. As the collagen begins to bear the load, the stress-strain behavior becomes progressively linear. During the hold phase, stress in the fibers is relaxed.

CONCLUSIONS

The nonlinear, viscoelastic response of chordae results from the interplay of its microstructure. This behavior was simulated in a subgrid micromechanics method. We continue to develop this micromechanical approach, toward the goal of resolving stress and damage on a scale that better inform devise design and clinical understanding.

REFERENCES

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ACKNOWLEGDEMENTS

This study is funded by DHRP Grant No. DAMD17-01-1-0673.