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MECHANICAL BEHAVIOR OF ANNULUS FIBROSUS TISSUE: IDENTIFICATION OF A PORO-HYPER-ELASTIC MODEL FROM EXPERIMENTAL MEASUREMENTS

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INTRODUCTION

Annulus fibrosus (AF) is the outer tissue of intervertebral disc (IVD) which is a highly specialized element of the spine that provides flexibility and dissipative capacities. When mechanical loads are transmitted along the spine, IVD mainly supports compression and bending stresses. This results in a hydrostatic excessive pressure in the central nucleus pulposus and generates circumferential tensile stresses in the surrounding AF. To hold these large circumferential strains, AF tissue is assimilated to a composite material made of oriented structures of collagen fibers embedded in a highly hydrated (60−70%) matrix [6]. This particular microstructure and biphasic composition confers to AF a non-linear and anisotropic behavior. Many experimental studies have underlined the anisotropic and non-linear mechanical behavior of AF using uniaxial tensile tests [5-7]. However, few authors have experimentally investigated the biaxial behavior [8].

Various models of the AF mechanical behavior have been proposed in the context of fiber-reinforced theory. To account for finite strains, hyper-elastic formulations have been developed which introduce some exponential strain energy functions [5,7]. Thanks to their large degrees of freedom, these models have been successfully employed to curvefit many experimental stress-strain data in different configurations: tension or compression on axial, radial or circumferential samples. Nevertheless, these descriptions fail to represent the hysteresis observed under loading cycles [1,10] that would be related to a viscous component. This behavior is classically described by a poro-elastic formulation and can account for coupling effects between macroscopic mechanical strains and viscous flow through it [9]. In this framework, the porous structure is usually described by an elastic behavior unable to capture non-linearities.

This work aims to couple a poro-mechanical formulation with a hyper-elastic model to account for fluid flows and describe viscous effects.

MATERIALS & METHODS

First of all, an experimental method has been developed [2] to measure simultaneously stress/strain curve and transverse strain fields during a cyclic tensile test with *in vivo* conditions. Strain fields are computed from a digital image correlation (DIC) technique performed on both transverse planes. To avoid mechanical interferences induced by physical markers, the natural tissue pattern is used. This leads to 300 measurement points on both planes.

AF tissue is modeled with an hyper-elastic material which considers the underlying fibers network embedded in an isotropic porous matrix [4]. Thereby, the strain energy function is a combination of three terms:

$$W = W_{iso} + W_{comp} + W_{aniso}$$

Where the first term, W_{iso}, represents the matrix with a neo-Hookean description, W_{comp} controls the material compressibility and W_{aniso} defines the fibers network with an exponential formulation. This leads to:

$$W = \frac{G}{2}\left(I_1 - 3\right) + K\left(J - 1\right)^2 + \frac{1}{2K_2}\sum_{i\in[1,2]} K_{1i}\left[\exp\left\{K_2\left[k I_1 + \left(1-3k\right)I_{4i} - 1\right]^2\right\} - 1\right]$$

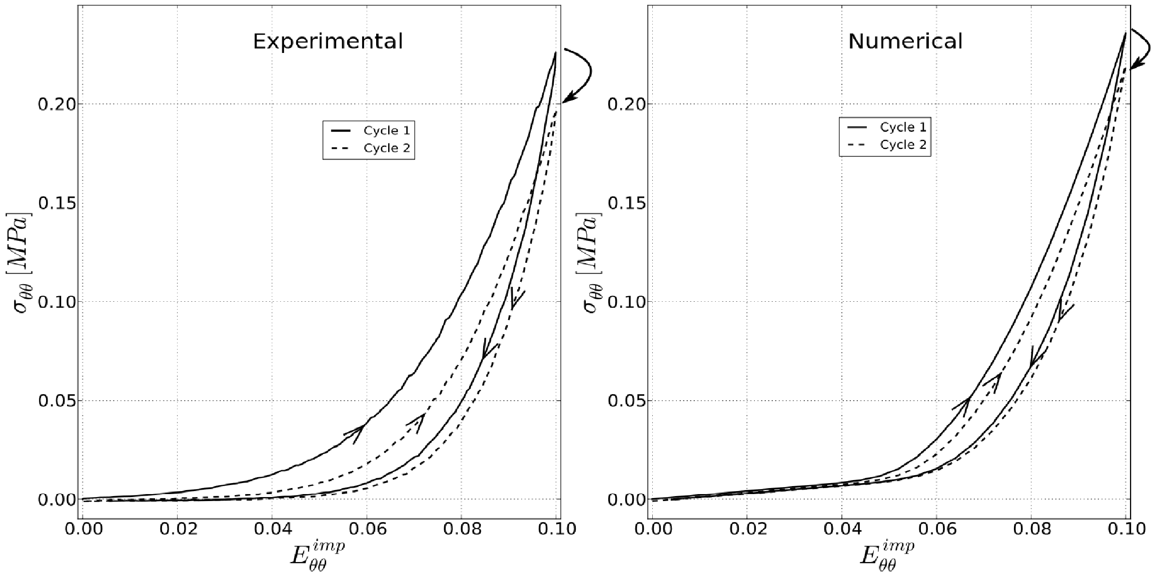

Figure 1: Experimental and numerical stress(Piola-Kirchhoff 1)/strain curves over 2 cycles.

where G is the shear modulus, K_{1i}, K_2 and k the anisotropic parameters, K the bulk modulus and I_1, I_{4i}, and J the right Cauchy strain invariants.

Meanwhile, the poro-mechanical coupling is described based on Biot model:

$$\underline{\underline{\sigma}} = \frac{2}{J} \underline{\underline{F}} \frac{\partial W}{\partial \underline{\underline{C}}} \underline{\underline{F}}^T - p \underline{\underline{I}}$$

$$\underline{\nabla} \cdot \underline{v}^{f/s} = -\frac{k}{\mu} \Delta p$$

where $\underline{\underline{\sigma}}$ is the Cauchy stress, $\underline{\underline{F}}$ the transformation gradient, $\underline{\underline{C}}$ the right Cauchy strain, p the pressure, $\underline{v}^{f/s}$ the relative fluid velocity, k the permeability and μ the dynamic viscosity of the saturating fluid.

The finite element (FE) software *LMGC90* (University of Montpellier 2) was used for numerical simulations. The Taylor-Hood 20-nodes, fully integrated elements with a quadratic interpolation of displacement fields and a linear interpolation of pore pressure were used with a total implicit formulation. Rectangular experimental samples were used, thus a mesh with average dimensions and symmetric simplification has been designed. It represents a unitary symmetric sample portion of AF (L_{rr} x $L_{\theta\theta}$ x L_{zz} = 1.94 x 1.00 x 2.03 mm^3), with 169 elements.

RESULTS

Experimental results (Fig. 1) exhibit a classical non-linear stiffening behavior with hysteresis under loading cycles. Moreover, a systematic drift is observed along cycles and related to the porous accommodation process. In fact, the first cycle shows a larger hysteresis than the following ones. Furthermore, maximal stress decreases along cycles; this behavior is usually associated with material damage like Mullins effect. However, this process is totally reversible when comparing two consecutive loading cyclic tests separated by a poro-mechanical equilibrium.

The 6 mechanical properties associated with the theoretical model previously presented are identified using a Levendberg-Marquardt algorithm. Results of the inverse procedure are given in Fig. 1. The hyper-elastic part gives the non-linear shape and the porous model accounts for the hysteretic behavior and accommodation along cycles. Nevertheless, these preliminary results with stress/strain curves reveal a large variability of parameters.

DISCUSSION

Uniaxial tensile test is the classical experimental technique to characterize the mechanical behavior of biological tissue. Experimental results bring out the cyclic behavior of a large range of soft biological tissue: cartilage, aneurysm, bladder, and AF tissue [1,3,10,11] which is strongly hysteretic and non-linear. Currently, 19 samples have been analyzed and all of them present similar stress/strain features.

To date, a good agreement is obtained between experimental data and numerical simulation. Only 6 parameters is required to describe this non-linear behavior over multiple cycles. In fact, when dealing with complex anisotropic material, the stress/strain curve does not bring out sufficient data to identify material properties. In our case, transverse results will be used to improve the inverse procedure and decrease the confidence range of mechanical parameters. Finally, this model will be include in a IVD FE model to simulate the global poro-mechanical behavior and better understand fluid flows role in the macroscopic mechanical behavior, issue of main importance when dealing with cell nutrition processes.

REFERENCES

[1] Ambard, D et al., *Ann Biomed Eng*, 37, 11:2256-2265, 2009.
[2] Baldit, A et al., *J Biomech*, 45, S155, Proceed. ESB2012, 2012.
[3] Costalat, V et al., *J Biomech*, 44, 15:685-2691, 2011.
[4] Gasser T.C et al., *J R Soc Interface*, 22, 3(6):15-35, 2006.
[5] Guerin, H et al., *J Ortho Res*, 25:508-516, 2007.
[6] Iatridis, J et al., *J Biomech*, 38, 3:557-565, 2005.
[7] Klisch, S.M et al., *J Biomech*, 32,10:1027-1036, 1999.
[8] O'Connell, G et al., *Biomech & Mod Mechanobio*, 11:493-503, 2012.
[9] Swider, P et al., *J Biomech*, 43:1287-1291, 2010.
[10] Tower, T.T. et al.,*Ann Biomed Eng*, 30:1221-1233, 2002.
[11] Zanetti, E.M et al., *J Biomech*, 45, S74, Proceed. ESB2012, 2012.