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BIAXIAL MECHANICAL CHARACTERIZATION AND CONSTITUTIVE MODELING OF HUMAN MENISCUS

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SUMMARY

Structure-function correlations are crucial for understanding meniscal tears, creating novel meniscal repair techniques, and predicting tissue behavior through computational models. A challenge for modelling structure-function correlations of the meniscus is the complex heterogeneous microstructure, which contributes to region and layer-specific material properties.

In this study, we implement a novel constitutive model that incorporates collagen fiber orientation using experimentally derived data from multi-photon microscopy and biaxial tensile testing.

Key words: *menisci, biaxial tension, mechanical properties, constitutive modeling*

1 INTRODUCTION

Tears in the meniscus are one of the most prevalent knee injuries. The study of the mechanical behavior of the meniscus is fundamental for studying meniscus tears and repair techniques. The biomechanical properties of the menisci must be accurately captured in order to simulate their mechanics. This is particularly problematic due to its intricate microstructure and the lack of a comprehensive experimental characterization of the material properties. This necessitates a thorough experimental characterization of human menisci for identifying the region- and layer-specific material properties and structural constitutive modeling incorporating the collagen fiber orientation.

The meniscus is a fibrocartilaginous structure that acts as a weight-bearing medium as well as a friction-reducing component during movement. Each human knee joint has two menisci: a lateral and a medial meniscus. The anatomy is divided into three regions in the top view: the anterior horn, the mid-body, and the posterior horn, each contributing one-third of the circumferential length. Besides this, the menisci can be divided into three layers based on their fiber orientation in cross-section: the superficial layer, the lamellar layer, and the central main layer [1]. This complex material composition leads to region and layer-specific biomechanical properties. The characterization of site-specific biomechanical features of the human meniscus has been described in only a few publications [2, 3]. Their research, however, is confined to a width-wise characterization.

The objective of this study is to develop a new constitutive model for the human meniscus. This study is described in three-fold: (i) Experimental characterization of region specific information in the lateral meniscus using in-situ biaxial testing (ii) Multi-photon microscopy examination of collagen fiber morphology (iii) Incorporation of these two data into the constitutive model using the material parameters. This study contributes to our knowledge of the structure-function correlations in the human meniscus, which is useful for studying meniscal tear mechanisms, designing meniscal repair procedures, and simulating existing or innovative arthroscopic meniscal repair techniques.

2 METHODOLGY

2.1 Sample preparation

The menisci were harvested from the knee joints of six human cadavers, and cadaver specific information such as age, gender, and health condition were recorded. These menisci were kept at $-28°C$ until the experiment. The menisci were thawed at room temperature in a phosphate buffered saline (PBS) solution prior to the experiment. Square samples with a dimension of 10 to 12 mm and a thickness of 1 to 3 mm were taken from the anterior horn, mid-body, and posterior horn of the lateral and medial menisci of knee joints to evaluate region-specific property variation. Special attention was made to slice the two samples through the thickness of each of these regions in order to evaluate layer-specific property variation.

2.2 Biomechanical testing

A custom-built biaxial test bench was used for mechanical testing. As shown in Fig.1, the sample was attached to the testing equipment with four barbless hooks (Ahrex, Denmark) and surgical gore-tex sutures on each side, while remaining submerged in PBS for the entire duration. The temperature of the PBS bath was maintained at 36.5^oC to mimic in-vivo conditions. Prior to performing the actual test, the sample was loaded with three preconditioning cycles up to 40% of strain in each loading direction. The samples were deformed at a strain rate of $0.1mm/sec$ once a satisfactory outcome was attained after preconditioning.

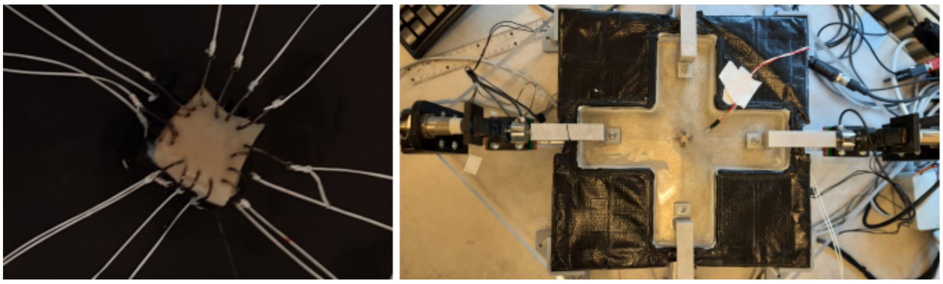

Figure 1: Biaxial tension test setup showing the sample mounted with barbless hooks and sutures.

2.3 Multi-photon microscopy

Multi-photon microscopy (MPM) images of the tissue layers were obtained using a second harmonic generation (SHG) setup, which consists of a mode-locked Ti:Sapphire laser (Chameleon Vision; Coherent, Santa Clara, CA) and an inverted optical microscope. The average excitation power at the sample was $40\,mW$ with an excitation wavelength of $890\,nm$. The acquired image covered an area of $512 \times 512\,\mu m^2$ and was integrated over two frames to improve the signal/noise ratio. The step size between slices was typically set at $0.5 - 5\,\mu m$ depending on the thickness of the sample. The total scan time for a single z-stack was less than 30 minutes.

2.4 Model formulation

Based on the findings of MPM imaging and biaxial mechanical testing, a structural constitutive model for the human meniscus is presented, which includes the collagen fiber morphology.

The general continuum description of deformation stated here as in [4]. The stretch λ of the material in any given direction represented by a unit vector e is expressed as $\lambda^2 = e : C : e$. Here, $C = F^T F$ is the right Cauchy-Green tensor, and $F = \partial x/\partial X$ represents the standard deformation gradient tensor, where X is reference configuration and x is deformed configuration. The multiplicative decomposition of F into dilatational ($J^{1/3}I$) and distortional parts ($J^{-1/3}F = \bar{F}$) is generally established; where $J = det\ F(X)$ is the local volume ratio, also called the Jacobian of the deformation. The modified counterpart of C with the invariant $I_1 = tr\ C$ can be written as $\bar{C} = \bar{F}^T\bar{F}$ with the invariant $\bar{I}_1 = tr\ \bar{C}$.

In order to characterize the anisotropic, hyperelastic material behavior of the meniscus, it is assumed that the strain energy can be represented as a superposition of the elastic contribution of the isotropic matrix (ψ_{iso}) and an anisotropic potential for each fiber family (ψ_{fi}) [5].

$$\psi = \psi_{iso} + \sum_{i=1,2} \psi_{fi} \tag{1}$$

The isotropic part of the strain energy function is defined as,

$$\psi_{iso} = C_1(\bar{I}_1 - 3) \tag{2}$$

where C_1 is a stress like parameter similar to the shear modulus of the material. The anisotropic contribution of each fiber family is defined as,

$$\psi_{f1} = \frac{k_1}{2k_2}[exp(k_2\bar{E}_1^2) - 1] \qquad ; \qquad \psi_{f2} = \frac{k_3}{2k_4}[exp(k_4\bar{E}_2^2) - 1] \tag{3}$$

where $k_i{}'s$ are material constants and $\bar{E}_i$ is an invariant based on the material structural tensor defined as,

$$\bar{E}_i = H_i : C - 1 \qquad ; \qquad H_i = \gamma * I + (1 - 3\gamma)(\mu_i \otimes \mu_i) \tag{4}$$

where I is the 2nd order identity tensor, μ_i is the mean orientation of the fiber family, and γ is the fiber dispersion parameter; which is related to the von-Mises concentration parameter through the equation: $\gamma = 0.5 - \frac{I_1(a)}{2I_0(a)}$, where I_0 and I_1 are modified Bessel functions of first kind with order 0 and 1 respectively. Thus the strain energy function proposed for the human meniscus with two fiber families described by:

$$\psi = C_1(\bar{I}_1 - 3) + \frac{k_1}{2k_2}[exp(k_2\bar{E}_1^2) - 1] + \frac{k_3}{2k_4}[exp(k_4\bar{E}_2^2) - 1] \tag{5}$$

3 RESULTS AND CONCLUSIONS

A series of biaxial tests with 60 to 80% strain were performed on samples collected width-wise and depth-wise using the custom-made biaxial test bench. The force-displacement curve of samples cut within the top one-third depth of the meniscus from the anterior horn, mid-body, and posterior horn is shown in Fig 2.

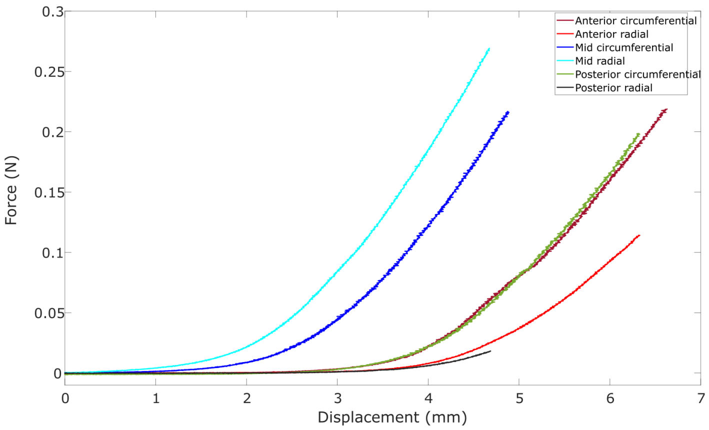

Figure 2: Force-displacement curves obtained from biaxial tensile testing from the upper one-third depth of the anterior horn, mid-body and posterior horn of the lateral meniscus

The circumferential direction of the fibers was evident to the naked eyes throughout the dissection. As a result, the orientation distribution of the collagen fibrous network in the circumferential-radial plane was focused in order to analyze the structural organization of the fibrous structure. To eliminate artifacts and improve the contrast of the fibers, the images were preprocessed in ImageJ. The illustration in Fig 3 shows the collagen fiber orientation in the anterior horn, mod-body, and posterior horn of the lateral meniscus.

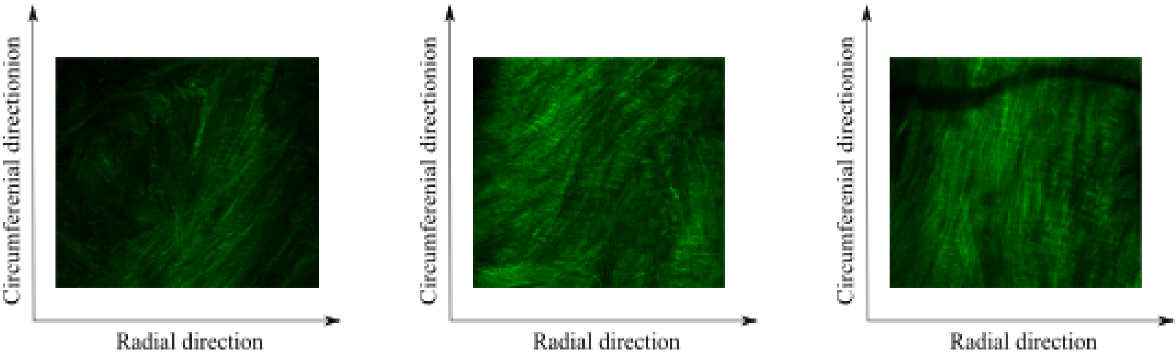

Figure 3: Collagen fiber orientation in anterior horn, mid-body and posterior horn of the lateral meniscus

The relevant quantitative information regarding orientation, waviness, and volume fraction is analyzed using a custom python script based on the FFT (Fast Fourier Transform) principle, and an orientation histogram is computed. The structural parameters of the constitutive model will be determined using this information, as well as region-and layer-specific biaxial tensile test results. This constitutive model formulation is appropriate for future numerical studies of the human meniscus for analyzing tears, repair techniques, and simulating arthroscopic surgical procedures.

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