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MECHANICAL CHARACTERISATION OF AORTIC VALVE TISSUES

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Introduction

Because of their high prevalence in degenerative valve diseases, aortic valves (AVs) have been widely studied during the last decades. In particular finite element analysis is becoming increasingly popular to support the design of enhanced prostheses with mechanical properties as close as possible to those of natural tissues.

The mechanical behaviors of the AV leaflets under a wide range of physiological biaxial loading conditions have been already investigated in the literature [1].

AVs have an oriented network of collagen fibers embedded in an elastin matrix, which is responsible for their hyperelastic and anisotropic behavior. Non-linear transverse isotropic constitutive equations are often used for their modeling, as far as a macroscopically preferred fiber direction can be identified. Dozens of mechanical tests with various loading conditions must generally be carried out to identify those parameters.

In this study, a method is proposed in order to simultaneously estimate relevant material and structural characteristics of AV while reducing the number of experiments. An inverse analysis procedure based on the finite element computation of biaxial tensile tests coupled with full-field measurements was used to set up this reduced protocol. In a second time, this protocol was applied to porcine aortic tissues to identify real parameters.

Methods

Sensitivity analysis: AV leaflet tissue behavior was modeled using a modified hyperelastic transversely isotropic HGO [2] material law. This model was implemented in the finite element code FORGE® using the strain energy function (1):

$$\psi = c_0 [e^{c_1(I_1-3)+c_2(I_4-1)^2} - 1] + p(J-1) \quad (1)$$

where c_i are material parameters, I_1 and I_4 respectively the first invariant and fourth pseudo-invariant of the right Cauchy–Green tensor, J the volume ratio and p a Lagrange multiplier. Biaxial tensile tests with several loading conditions were modeled using an arbitrary set of parameters. Then a sensitivity analysis was performed on the set of curves obtained for each loading condition in order to determine an optimal number of experimental conditions (i.e. by removing unnecessary experiments) that enable to identify accurately the initial set of parameters used for creating the reference curves.

Experimental measurement: Fresh native AV valves collected from porcine hearts were used. Rectangular

samples excised from the center of the leaflets (in the “belly” area) were submitted to optimal biaxial loading conditions that were numerically identified (Fig. 1). The biaxial tensile tests were coupled with full-field measurements in order to get local strain measurements to be compared to numerical sensors.

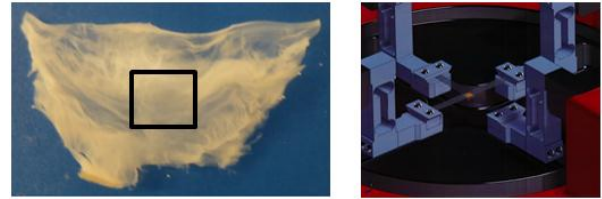


Figure 1: the “belly” area on a AV leaflet (left) and the biaxial tensile device (right)

Parameters identification: Inverse analysis parameters identification was carried out using a metamodel-assisted evolutionary algorithm. A set of material parameters was obtained by comparing experimental reference curves to finite element modeling of the biaxial tensile tests under similar conditions.

Results

The sensitivity analysis carried out on the artificial set of curves showed that both local strain measurements and force/displacement curves obtained with at least two different loading conditions are necessary if one wants to accurately determine structural and material parameters.

This conclusion was assessed and confirmed thanks to the biaxial tensile tests coupled with digital image correlation (DIC) data that were performed on AV leaflets.

Discussion

In this study we considered heart valve samples as monolayer homogenous materials with only one family of fibers. The same fiber orientation is assigned to each element. Second-harmonic imaging microscopy, using a confocal microscope, is planned to assess this assumption and to estimate the error that was made.

References

1. Billar et al, J Biomech Eng, 122:23-30, 2000.
2. Gasser et al, J R Soc Interface, 3:15-35, 2006.

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