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Structural modelling of the annulus fibrosus - an anisotropic hyperelastic model approach at the lamellar level

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SUMMARY

This work was aimed at developing a first approach to produce structural models of the Annulus Fibrosus, i.e. constitutive models of individual lamellae. Parameters of Holzapfel's model were fitted using literature data on the behaviour of tissue components. Used on sample-specific or simplified geometries, the effect on the whole annulus deformation of the fibre angles, inter-lamellar behaviour, and incompressibility was analysed to assess their role in the disc mechanics.

Key Words: *annulus fibrosus lamellae, anisotropic hyperelasticity, finite element analysis.*

1. INTRODUCTION

The annulus fibrosus is the fibrous avascular outer part of the intervertebral disc (IVD). It is composed of a series of circumferential layers called the lamellae [1]. Each lamella is composed of collagen fibre bundles embedded into a ground matrix. Secondary structures such as bridges across the lamellae or surrounding elastin walls are also present. In each lamella, the fibres are quasi-uniformly oriented in one direction at an angle of 20° to 50° with the transverse plane. This angle alternates between adjacent lamellae. The inner part of the IVD, surrounded by the annulus, is a gel-like substance called the nucleus pulposus.

The IVD is a permanently loaded environment. It acts as a joint between two adjacent vertebrae and gives the spine its flexibility. It is subjected to compressive loads, bending and shear. In particular, the annulus withstands internal pressure due to the nucleus hydrostatic compressive stress. As the annulus bulges, the tissue is extended, making tension an important mode of loading for the annulus fibrosus [1]. A realistic virtual model of the IVD can give insight into the significance of deformation patterns and is a help for the design of novel treatment approaches.

As such the understanding of the mechanical properties of the different constituent tissues and their role in the IVD mechanics is of greater importance. In the last decade, many constitutive models of the annulus fibrosus have been proposed, most of these considering an annulus constituted of two sets of fibres with different orientations and an isotropic elastic matrix [2,3], with some accounting for the cross-links between adjacent lamellae [4]. To our knowledge no previous model has accounted for fibres and matrix of individual lamella, the inter-lamellar behaviour and the cross-bridges. This study took the first step towards such a model. The approach was focused on the structural aspects and did not account for viscous or damage effects.

2. METHODS

Considering the nonlinear behaviour of the collagen fibres and the structural aspect the model has to represent, an anisotropic hyperelastic model was chosen for the lamellar behaviour. Such a model allows consideration of separate energy density functions for the matrix and the fibres, including their specific orientation. It also allows the consideration of incompressibility for the lamellae. In particular, Holzapfel's constitutive model [5], developed mainly for arterial walls, was used in this work. It assumes a linear shear behaviour of the ground matrix (neo-Hookean model) and a non-linear exponential behaviour of oriented fibres, that bear load only in tension.

First, 1D analytical stress-strain curves for each component of Holzapfel's model were fitted against experimental data for a single lamellae extracted from the literature. Details of mechanical tests on lamellar samples prepared in such a way that the fibres would not bear loads, and thus representative of the matrix behaviour, are available in [6]. Data from shear tests were used to characterise the ground matrix mechanical behaviour. Single lamellar tension tests performed along the fibre direction [3,7,8] were used to characterise the fibre behaviour.

The constitutive model with the fitted parameters was then used in a sample-specific finite element (FE) model. The geometry was acquired from a micrograph of a sample cut through the annulus width in the radial direction [9]. Segmentation and tetrahedral mesh generation were performed using ScanIP 5.1 (Simpleware Ltd). This FE model was used to assess the relevance of an anisotropic hyperelastic model versus a neo-Hookean model with equivalent shear stiffness.

Finally, the constitutive model was used in a finite element model of the whole annulus fibrosus represented as a simplified cylindrical geometry. This model consisted of 12 concentric perfectly circular lamellae subjected to internal pressure. It was used to analyse the effect of inter-lamellar behaviour on the annulus bulge as well as the effect of the site-dependency of the fibrous behaviour, the fibre orientation, and the incompressibility.

All finite element analyses were performed using the implicit finite element software Abaqus 6.12 (Dassault Systèmes) with linear tetrahedral or hexahedral elements.

3. RESULTS

Data available in [6] clearly shows the ground matrix shear behaviour is non-linear. However a linear model that characterises the shear behaviour of the neo-Hookean model can be fitted (r^2=0.982) up to 30% shear strains (Figure 1, left). The non-linear behaviour of the fibres depends on the fibre location around the annulus (Figure 1, right - dots). An exponential behaviour as in Holzapfel's model can be fitted (Figure 1, right - lines) for each experimental test (r^2 between 0.986 and 0.999) over the whole available stretch range.

The longitudinal force (radial in terms of the IVD geometry) needed to stretch a radial cut through the annulus, for two material models (Holzapfel's model or a neo-Hookean model), is shown on Figure 2 (right). As the elongation is perpendicular to the fibre stretch, the neo-Hookean model, being isotropic, necessitates a higher force (20% greater at 20% strain).

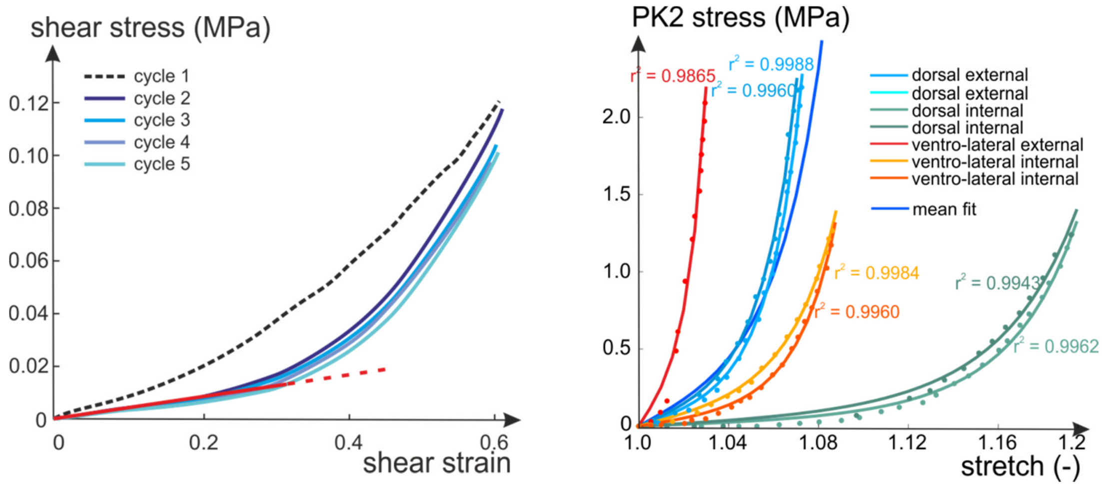

Figure 1- Results of a parameter fit: Left: a neo-Hookean model of the ground matrix (exp. data from [6], linear fit in red); Right: an exponential behaviour of the collagen fibres (exp. data from [7,8]).

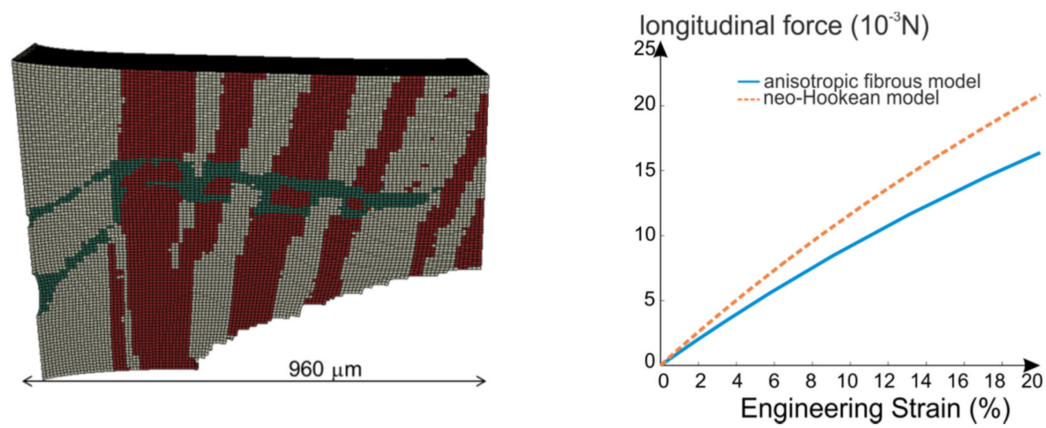

Figure 2 – Left: FE model of 20% applied strain to a radial cut - white: lamellae cut along the fibre direction, red lamellae with sectioned fibres, green: cross-bridges; Right: Force vs. strain for a neo-Hookean model (in orange) and a Holzapfel one (in blue).

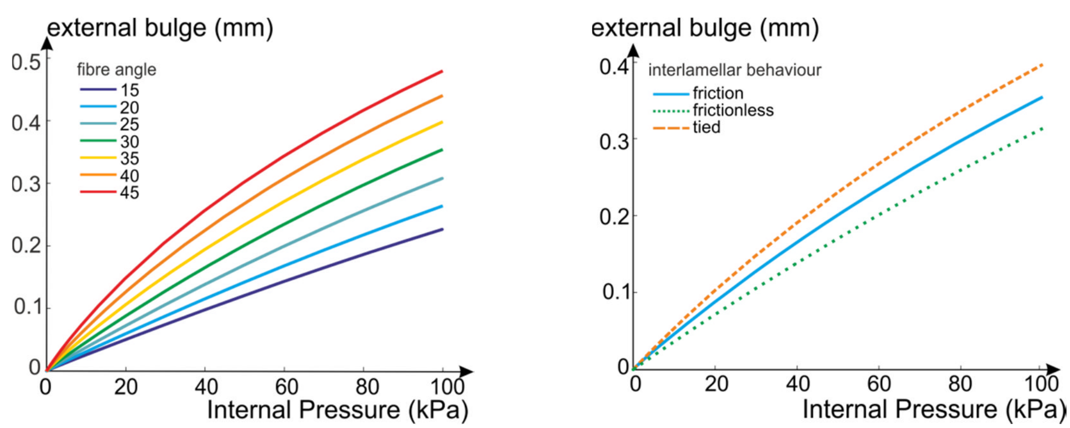

Figure 3 – Results from an FE model of cylindrical annulus under pressure - Left: Change in bulge vs. internal pressure as a function of the fibre angle. Right: Change in bulge vs. internal pressure as a function of the inter-lamellar interaction model.

Finally, the bulge of a cylindrical annulus under pressure is presented in Figure 3. It shows a dependence on the assumed fibre angle (adjacent lamellae have supplementary angles from the transverse plane). It also shows a strong dependence on the assumed inter-lamellar behaviour.

4. DISCUSION / CONCLUSIONS

This work, focussing on a structural model of the annulus fibrosus, showed that the use of Holzapfel's constitutive model with one fibre orientation to represent each lamellae shows promising results. The exponential model of the fibre mechanics is adequate on the whole tested range available in the literature. The linear model of the matrix gives relevant results up to 30% shear strains. This is a limitation at very large strain but not essentially for clinically relevant deformations. A radial stretching model of an actual sample showed that using an anisotropic law rather than a neo-Hookean law is worth the extra-computational cost. When used on a cylindrical representation of the annulus, the model shows not only a sensitivity to the fibre angle but also to the assumed inter-lamellar behaviour. Future work will propose experimental tests to further validate the model of the lamellar components, including the incompressibility and the possible pre-stress. The use of a validated lamellar constitutive model in conjunction with whole annulus experimental data could give insight to the inter-lamellar behaviour.

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