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MECHANICAL BEHAVIOR OF THE LAMELLAE ANNULUS FIBROSUS IN FINITE ELEMENT MODEL

M. Żak*, J. Słowiński, C. Pezowicz*****

Abstract: *The composite construction of annulus fibrous stems from the specific arrangement of collagen fibers in the individual lamellar. Structural differences in collagen fiber connections within a single lamellar of annulus fibrosus determine the nonlinear mechanical properties of the intervertebral disc. This structure of annulus fibrosus facilitates the transfer of loads acting on the spine while ensuring stiffness and strength in intervertebral disc. The aim of this study was to build numerical model of single lamellar annulus fibrosus on the basis of experimental research. In next stages, the information about the directional mechanical properties obtained from numerical simulations would allow explain the mechanism of damage in the intervertebral disc.*

Keywords: Intervertebral disc, Annulus fibrosus, Mechanical properties, Numerical simulations.

1. Introduction

Annulus fibrosus consists of a hierarchically organized tissue structure, which is characterized by high deformability while transferring loads by the spine. Simultaneously forming part of annulus fibrous collagen fiber network, determines the anisotropic mechanical properties in the entire structure (Pezowicz et al., 2005, Pezowicz et al., 2006, Fujita et al., 2000). Based on the above, the aim of this work was to develop a numerical model of single lamellar intervertebral disc according to the directional mechanical properties. The study included the impact of collagen fibers orientation, as the factor determining the functioning of the intervertebral disc.

2. Material and Methods

The numerical model of a single lamellar annulus fibrosus was developed on the basis of experimental study in animal models. 6 anterior parts of nondegenerate intervertebral disc taken from lumbar spine of pigs at 9 months of age were used in the experimental study. Blocks of annulus fibrosus were cut in the plane of outer lamellar sections in nominal thickness 40÷50 μm. An uniaxial tensile test at a constant speed of 0.06 mm/s, until rupture, was carried out on the special microtensile device. Specimens were kept in NaCl medium in order to preserve comparable conditions tests (Żak et al., 2013).

Numerical model was generated in several steps. In the first step a rectangular area measuring 2.63 mm long and 1.76 mm wide was created. These values are averaging real sample dimensions. Then the area was cut into tens of areas by making a series of cuts parallel to the short edge of the area. Distance between each cuts was varied randomly within a certain range. Number of cuts was selected experimentally and was a result of a compromise between accuracy and the time necessary to carry out a simulation using the developed model. A component of vertical lines obtained as a result of first cutting operation simulate the main fibers system (Ir) in a single lamellar of annulus fibrosus. In the second cutting every area was cut into tens of subareas by making a series of cuts routed at an angle in the range

* M.Sc. Eng. Małgorzata Żak: Department of Biomedical Engineering, Mechatronics and Theory of Mechanisms, Wroclaw University of Technology, ul. Lukasiewicza 7/9, 50-371 Wroclaw, Poland, malgorzata.a.zak@pwr.wroc.pl

** Jakub J. Słowiński, PhD.: Department of Mechanics and Materials Science, Wroclaw University of Technology, ul. Smoluchowskiego 25, 50-370, Wroclaw, Poland, jakub.slowinski@pwr.wroc.pl

*** Prof. Celina Pezowicz: Department of Biomedical Engineering, Mechatronics and Theory of Mechanisms, Wroclaw University of Technology, ul. Lukasiewicza 7/9, 50-371 Wroclaw, Poland, celina.pezowicz@pwr.wroc.pl

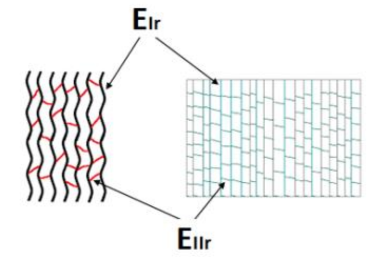
of 95 to 105 degrees relative to the main fibers. A component of lines from second cutting operation simulate short fibers system (IIr).

Arrangement of the main fibers (Ir) in the sample were defined as a random variable in the range ± 30% of the distance between the fibers, assuming that all the fibers are evenly distributed. In IIr fibers oriented transversely to the main fiber and includes the random distribution and angle. A random arrangement of fibers Ir and IIr in numerical model gives larger regularity of the fibers as opposed to the actual model of the lamellar annulus fibrosus.

All lines from both components were discretized using 2-nodes link element. This type of element is used in the case of uniaxial tension test, no bending of the element is considered. A component of areas obtained during both, first and second, cutting operation simulate an annulus ground substance in which the fibers are immersed. Discretization of the areas was carried out using 4-nodes shell element.

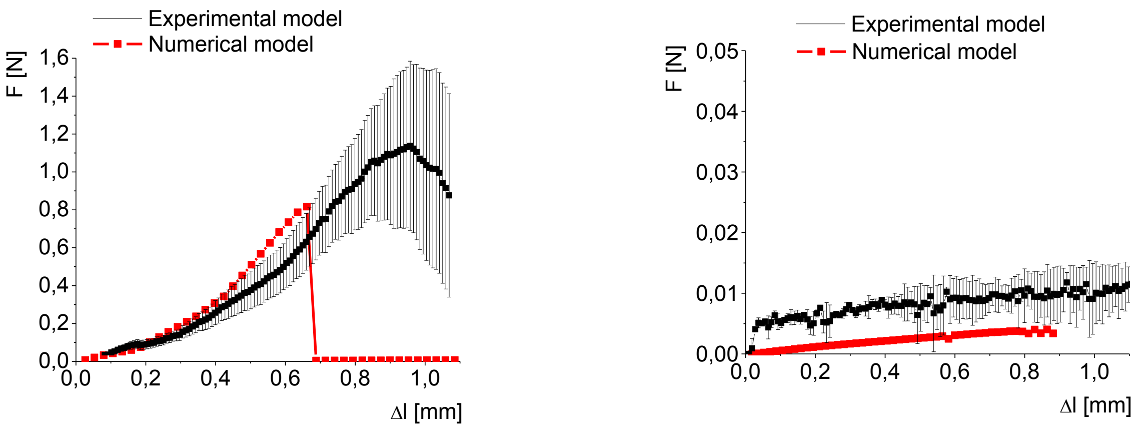
The material properties (Young's modulus and Poisson's ratio) of the fibers and annulus ground substance were determined from experimental study and literature (Tab. 1). Two types of fibers were adopted: the main long fibers (Ir) and smaller short fibers (IIr) contained between the main fibers. The value of Young's modulus of the Ir fiber (E_{Ir}) was adopted on the basis of the average values obtained during the tensile test in parallel direction to orientation of collagen fibers. On the other hand the Young's modulus of the IIr fiber (E_{IIr}) was determined on the basis of the uniaxial stretching in perpendicular direction to orientation of collagen fibers

Tab. 1: The material properties of the fibers and annulus ground substance in a single lamellar of annulus fibrosus model.

				ν [-]
	**Collagen fibers[1]**	**E_{Ir} [MPa]**	**54.37**	**0.45**
		E_{IIr} [MPa]	**0.32**	
	Annulus ground substance [2]	**E_0 [MPa]**	**0.10**	**0.45**

[1] based on their own experimental data
[2] Schmidt et al., 2010

In the numerical simulation, the sample was fixed by taking all the degrees of freedom of the nodes situated on the edge of the model. The nodes located on the opposite shore were loaded by a displacement acting in along or across to long fibers. The procedure of uniaxial tension was carried out iteratively. At each step the displacement of the fibers was increasing. Rupture of the fiber elements occurred when a certain strain exceeded an experimentally determined value (in parallel direction 60% and in perpendicular direction 80%).



a) *b)*

Fig. 1: Comparison of the example F (p) characteristics of a single lamellar annulus fibrosus stretched in: a) parallel direction, b) perpendicular direction to orientation of collagen fibers.

3. Results

Results obtained from numerical simulations of the force - displacement characteristics were similar to the results obtained experimentally, but were varied in terms of these values (Fig. 1).

The mechanical characteristics of physiological single lamellar annulus fibrous showed significant differences due to the orientation of collagen fibers. Characteristic stages of change in the structure of lamellar annulus fibrosus: straightening, tension, loss of cohesion and rupture of collagen fibers (Fig. 2.a) could be identified during stretching in parallel direction of the fibers. Contrary to parallel direction of stretching in a perpendicular direction structure of annulus fibrosus had a tendency to further reorganization and isolating the short fibers with collagen bundles (Fig. 2.b).

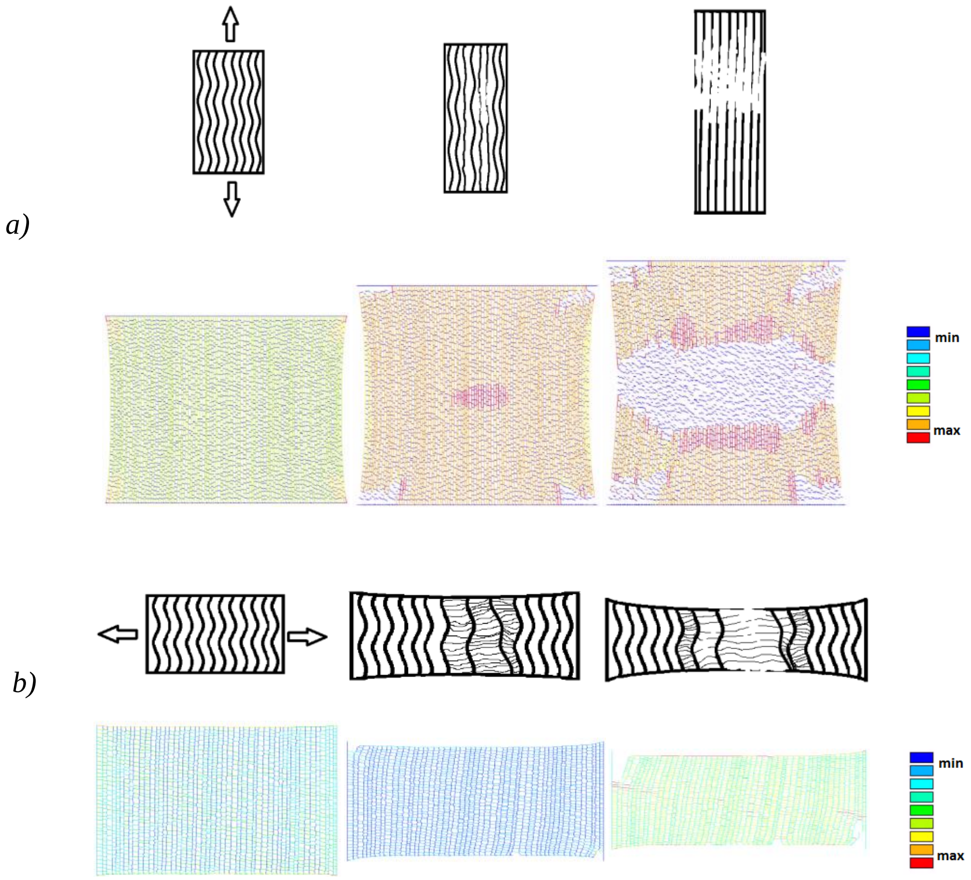


Fig. 2: Stages of structural changes in experimental and numerical model of a single lamellar annulus fibrosus stretched in: a) parallel direction, b) perpendicular direction to orientation of collagen fibers.

On the basis of the force and displacement of the sample in the numerical model the value of the ultimate force (F_{UTS}) was obtained. A stiffness coefficient (k) were determined based on the slope of the curve F(Δl). Then, the obtained parameters were compared with experimental values which are presented in the form of a box-plot graphs and the estimated value of the numerical simulations are marked in blue line (Fig. 3).

The model of sample stretched in parallel direction to the collagen fibers obtained high compliance value of the analyzed mechanical parameters (Fig.3.a). The value of the ultimate force (FUTS) in the numerical model was 13% smaller than the value in real sample (0.95 ± 0.40 N). The stiffness coefficient in numerical model was differed by 12% from the experimental value (1.87 ± 0.73 N/mm).

The value of ultimate force for the perpendicular direction tensile obtained from experiment (14.02 ± 8.26 mN) was 70% higher than from numerical model. In the case of the numerical model stiffness coefficient were 7% smaller than the average of experimental value (4.95 N ± 2.68 mN/mm).

The discrepancy between the experimental and numerical model can be attributed to inhomogenity of the biological material, as the strong scattering of the results obtained in experimental study.

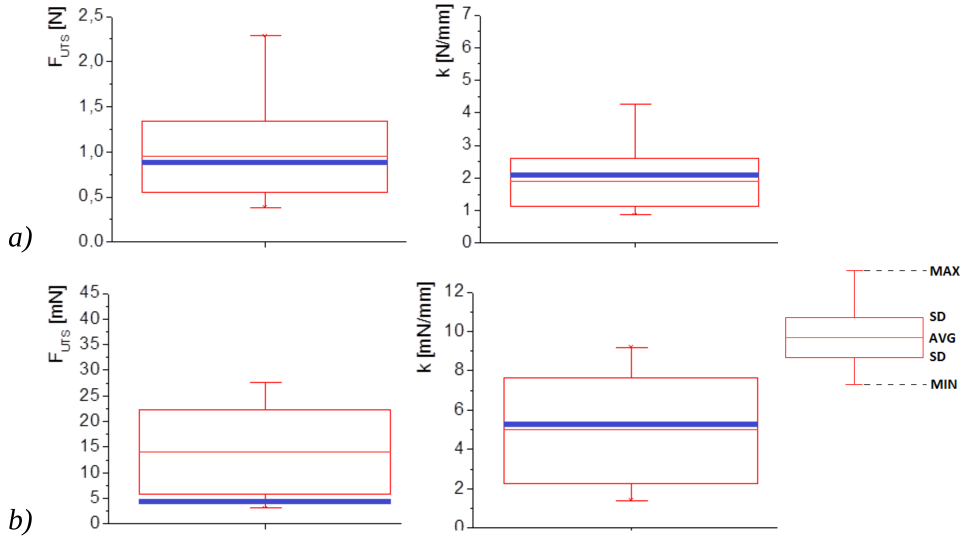


Fig. 3: Comparison of mechanical parameters (stiffness coefficient - k, ultimate force - F_{UTS}) in experimental and numerical model of a single lamellar annulus fibrosus stretched in: a) parallel direction, b) perpendicular direction to orientation of collagen fibers.

4. Conclusions

The knowledge gained from research, have confirmed the anisotropy of annulus fibrosus in animal model and indicated that fiber orientation has influence on the mechanical properties. Detailed characterization of single lamellar annulus fibrosus allows for the preparation numerical model of the multi lamellar fiber structure. In the next stage of the study, presented numerical model will be essential to understand the mechanism of damage in intervertebral disc.

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