Mechanical Behavior of the Spine Segment

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Abstract. The article presents the model of intervertebral disc, that takes into account the presence of a nucleus pulposus and an annulus fibrous containing collagen fibers with direction at angles ±45° and ±30°. The influence of the percentage of layers of the annulus fibrous with different directions of collagen fibers on the stress-strain state of the intervertebral disc was investigated.

1. Introduction

The spine is one of the most important structures of the human body. Its structure allows to perform the functions of support and movement. Degeneration of the intervertebral discs is a major cause of pain in the spine and neck in those of the middle and older age people. A radical method of treatment in such cases is the replacement of the intervertebral disc with an implant. Apart from biological and chemical compatibility with the body, implants should also have compatible mechanical properties.

Improper selection of implants can lead to deterioration of the bone tissue and impair the functioning of the spine as a whole. Despite the variety of modern materials, specialists whose professional activities is related to the development of methods for correction of human organs and structures and the creation of implants give their preference to ceramic materials. This is due to the fact that ceramics are identical to the inorganic bone matrix in the type of chemical bond [1-5].

The use of computer modeling methods makes it possible to research patterns of mechanical behavior of the spine in more depth, which will guide the development of recommendations for the creation and selection of individual prostheses that are mechanically compatible with the body.

The intervertebral disk (IVD) is a composite material with a complex organization of its elements at each structural level. Two main structural components of the intervertebral disk can be distinguished: nucleus pulposus and annulus fibrosus [6]. The annulus fibrosus is formed by a set of concentric plates consisting of collagen fibers parallel to each other, embedded in a homogeneous matrix formed by a watery gel of proteoglycans. The direction of the fibers in each plate varies from ±30° in the outer to ±45° in the inner layers of the annulus [6].

There are many models that take into account the structural organization of the intervertebral disc and studies of the mechanical behavior of spinal segments under going physiological activity [6–9]. However, there is no information about how of changes in the direction of collagen fibers in the structural layers of the intervertebral disk affect its stress-strain state. The aim of this study is therefore to investigate how the percentage of layers of the fibrous annulus with aligned collagen fibres affects the stress-strain state of the intervertebral disk during axial compression of the lumbar spine segment.
2. Geometric model of the middle section of cervical spine

The geometric model consists of 3 structural components: two halves of adjacent vertebrae C3 and C4 (Fig.1) or L4-L5 (Fig.2), including cortical (compact) bony tissues (Fig.2 № 1) and trabecular (spongy) bony tissues (Fig.2 №2), hyaline endplates (Fig.2 №3), and an intervertebral disc itself. There is a nucleus pulposus (Fig. 2 №4) and an annulus fibrous (Fig.2 №5) which consists of layers.

Figure 1. Geometrical model of the middle path of the cervical spine segment

Figure 2. The geometric model consists of three structural components: two halves of adjacent vertebrae, 1 - cortical(compact) bony tissues, 2- trabecular (spongy)bony tissues, 3- hyaline endplates, 4- nucleus pulposus, 5- annulus fibrosus.

The geometric model was build in accordance with real size of vertebrae and intervertebral discs of a lumbar and a cervical spine [10-13].

Materials of the cortical and cancellous tissues of the vertebral bodies, materials of the intervertebral disc, facet joints, interspinous ligament, vertebral arches, and processes of vertebrae are considered as isotropic linear elastic materials.

The layers of an annulus fibrous ring with collagenous fibres arranged at an angle of +45°, +30° or –45°, -30° have anisotropic properties. These two layers were considered as one symmetrically armored orthotropic layer for calculations. Mechanical properties of the layers were estimated using the mechanics of composite materials, based on data on the mechanical properties of collagen and proteoglycan [14].
The calculations were carried out with ANSYS software by using the finite element method. The task was performed within the linear elastic theory.

The upper surface of the upper vertebra half was put under an axial compressive force $\sigma_z=1.9$ MPa, the bottom surface of the bottom vertebra half was fixated. The applied pressure is equivalent to what a human experiences daily while walking [15].

3. The results of the intervertebral disc in stress-strain state research

The influence of fibre position $\pm 30^\circ$ and $\pm 45^\circ$ on stress-strained state of IVD in annulus fibrosus (AF) was investigated. The results with percentage ($0\%, ~20\%, ~60\%, ~80\% ~100\%$) of layers content $\beta \pm 45$ with fibre disposition $\pm 45^\circ$.

Figure 3 layers distribution with different mechanical properties, corresponding to fibre directions in the model IVD with 10 layers of an annulus fibrosus. The layers with $\pm 45$ direction are marked black color, with $\pm 30^\circ$ are bright grey.

$$\beta_{\pm 45^\circ}=20\%; ~\beta_{\pm 30^\circ}=80\%$$

$$\beta_{\pm 45^\circ}=60\%; ~\beta_{\pm 30^\circ}=40\%$$

$$\beta_{\pm 45^\circ}=80\%; ~\beta_{\pm 30^\circ}=20\%$$

**Figure 3.** Distribution of layers with the direction of the fibers at an angle of $\pm 45^\circ$ (black color) and $\pm 30^\circ$ (grey color) in the cross sections of YZ annulus fibrosus

Figure 4 shows graphs of the axial stress $|\sigma_z|$ and of the axial strain $|\varepsilon_z|$ with values at the anterior point (fp) (Fig. 4, a) and midpoint (ave) (Fig. 4, b) of the lumbar (marked by gray color) and cervical (marked by black color) segments intervertebral disc (IVD) depending on the elastic modulus of the nucleus pulposus.

The value of stress at the anterior point of the intervertebral disc of the cervical segment at $\beta_{\pm 45^\circ}=0\%$ and $60\%$ is approximately 1.2 times higher than the values of the anterior point of the disc of the lumbar segment, at $\beta_{\pm 45^\circ}=100\%$. 1.4 times. of the intervertebral disc of the cervical segment regardless of $\beta_{\pm 45^\circ}$ by 1.5 times higher than the values of the midpoint point of the disc of the lumbar segment. The value of deformations at the anterior point of the intervertebral disc of the cervical segment at $\beta_{\pm 45^\circ}=0\%$ and $60\%$ is approximately 1.2 times higher than the values of the anterior point of the disc of the lumbar segment, at $\beta_{\pm 45^\circ}=100\%$ by 1.4 times. The value of deformations at the midpoint of the intervertebral disc of the cervical segment regardless of $\beta_{\pm 45^\circ}$ by 1.5 times higher than the values of the midpoint point of the disc of the lumbar segment. Figure 7, b shows that the nucleus pulposus with values an elastic modulus of 0.0045 MPa and 0.5 MPa has the same strain value.

4. Conclusion

The values of stress and of deformations at the anterior point of the cervical segment of the IVD with the percentage of layers of the annulus fibrosus with the direction of collagen fibers at an angle of $\pm 45^\circ$ equal to $0\%$ and $60\%$ are approximately 1.2 times higher than the values of the anterior point of the disk of the lumbar segment. The values of stress and of deformations at the anterior point of the IVD of cervical segment with the percentage of layers of the annulus fibrosus with the direction of collagen fibers at an angle of $\pm 45^\circ$ equal to $100\%$ 1.4 times higher than the values of the anterior point of the disk of the lumbar segment. For the middle point of the cervical segment disk, regardless of the percentage of layers of the annulus fibrosus with the direction of collagen fibers at an angle of...
±45º, stress are 1.4 times higher and deformations are 1.5 times higher than for the lumbar segment. The nucleus pulposus with an elastic modulus of 0.15 MPa has the highest deformation.

Figure 4. Distribution of axial stress \(|\sigma_z|\) and axial deformation \(|\varepsilon_z|\) at the anterior points (a) and midpoints (b) of IVD, depending on the elastic modulus \(E_{pn}\) of the nucleus pulposus at different percentages of layers of the annulus fibrosus with fiber direction ±45º (β±45º)

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