Computer modelling of the mechanical behaviour of the cervical spine segment and intervertebral disk prosthesis

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Abstract. The article describes the model of intervertebral disc prosthesis and the results of study of mechanical behavior of the cervical spine segment. The results show that degenerative changes in the intervertebral disc lead to a change in the location of the regions of maximum Mises stresses in cervical spine segment. The presented geometric model of the intervertebral disc prosthesis is based on the experimental sample of a ceramic endoprosthesis developed at the Institute of Strength Physics and Materials Science SB RAS.

1. Introduction

One of the most important constructions of the human body is the spine. Its structure allows to perform the functions of support and movement. The spine is divided into cervical, thoracic, lumbar and sacral regions [1]. The cervical spine moves most of all. An intervertebral disc (IVD) separates each vertebra, except in the upper cervical spine (C1 & C2), and in the sacrum and coccyx, where the vertebrae are fused together [2]. The discs resist spinal compression, permits limited bending, twisting, and sliding between vertebral bodies [1].

Degenerative changes of the intervertebral discs are the major cause of pain in the spine and neck in those of the middle and elder age [3]. A radical method of treatment in such cases is the replacement of the intervertebral disc with an implant. Adequate development and individual selection of implants play a decisive role in the treatment of a person. Improper selection of materials and design of implants can lead to deterioration of the bone tissue and the functioning of the spine as a whole. The problems of mechanics arising in the creation and selection of implants of biological tissues are solved on the basis of studying the structure, mechanical behavior and properties of the biological tissues themselves and their interaction with implants. The use of computer modeling methods makes it possible to more deeply understand the patterns of functioning of the spine in norm, at pathologies, at interaction with the implant, which facilitates the selection of a suitable prosthesis for a particular individual.

In this paper, the mechanical behavior of the model cervical spine segment at flexion forward is analyzed and a model of the intervertebral disc prosthesis is presented.

2. Model of the cervical spine segment

A geometric vertebra model was built based on the literature data about experimentally obtained dimensions [4].
The simulation algorithm for the geometric vertebra model was developed and implemented in the ANSYS system with the use of the APDL language. This algorithm allows an automatic rebuilding of the model when input parameters are changed.

Figure 1 shows the geometric model of the cervical spine segment. The geometrical model includes the vertebrae C3 (1) and C4 (2), IVD (3), facet joints (4), interspinous ligament (5), vertebral arches (6), spinous processes (7), transverse processes (8), and articular processes of vertebrae (9).

![Figure 1. Geometrical model of cervical spine segment: (a) lateral view, (b) sectional lateral view.](image)

The presence of the cortical and cancellous tissue in the vertebrae was taken into account. In Fig. 1b, the cancellous tissue is marked by 10, a thin layer of the cortical tissue [2] covers vertebral bodies. It is considered that vertebral arches and processes of the vertebrae fully consist of compact bone tissue. The Z axis of the coordinate system is located along the segment axis. The X axis is directed in the anteroposterior direction of the spinal segment.

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. Degenerative changes of the IVD were simulated through a reduction of the disc height (h) from 6 to 4.5 mm and an increase of Young’s modulus (E) from 2.5 to 98 MPa according to the previous research data [5,6], which in reality results from the water content reduction in the disc [3].

The task was resolved within linear theory of elasticity. The stress-strain state of cervical spine segment was calculated with the help of ANSYS software using the finite-element method. The lower surface of the vertebral body of C4 was rigidly fixed. The upper surface of the C3 vertebra was loaded by the force of 1000 N. A bending moment of 7.5 N·mm [7] was applied to the central point of the upper surface of the C3 vertebral body in the negative direction of the X axis in flexion of the spine segment. Specified load corresponds to physiological flexion of the cervical spine segment.

3. Study of mechanical behaviour of the cervical spine segment

Figure 2 shows the Mises stress fields in the segments of the spine with different heights and the Young's modulus of the intervertebral disc.

![Figure 2](image)

It can be seen from the figure that the maximum stresses are localized in the areas of joints of the vertebra legs with articular processes of the vertebra C4 at Young's modulus of 2.5 MPa (Figure 2 (a, b)). The increase in Young's modulus of the disc leads to the localization of the maximum stresses in the areas of attachment of the vertebra legs to the bodies of the vertebrae C3, C4 and in the central part of the upper surface of the vertebra C3 (Figure 2 (c, d)). The change in the regions of localization of maximum Mises stresses in the segment is associated with a change in the character of the deformation of the segment at increase in the modulus of the intervertebral disc, as evidenced by the distribution of displacements along the axis of the segment, shown in Figure 3.
Figure 2. Mises stress distribution (MPa) in the segment C3-C4 of the cervical spine: (a) \( h=4.3 \) mm, \( E=2.5 \) MPa; (b) \( h=6 \) mm, \( E=2.5 \) MPa; (c) \( h=4.3 \) mm, \( E=98.0 \) MPa; (d) \( h=6 \) mm, \( E=98 \) MPa.

It can be seen from Figure 3 that under Young's modulus of the disk \( 2.5 \) MPa, the greatest compression in the direction of the Z axis is observed in the anterior part of the vertebral body C3, affecting the upper part of the intervertebral disc, and stretching in the spinous process of the vertebra C3. As Young's modulus of the MTD increases, the greatest compression region shifts toward the center of the upper surface of the vertebra C3. Decreasing the MTD height, as well as increasing its Young's modulus, leads to a decrease in the degree of compression and stretching of indicated regions in the direction of the Z axis.
Figure 3. The displacement fields UZ (mm) of segments: (a) h=4.3 mm, E=2.5 MPa; (b) h=6 mm, E=2.5 MPa; (c) h=4.3 mm, E=98.0 MPa; (d) h=6 mm, E=98 MPa.

4. Model of the intervertebral disc prosthesis

The algorithm for constructing the geometric model of the intervertebral disc prosthesis is developed in the ANSYS programming language APDL. The geometric model of the intervertebral disc prosthesis is based on the experimental sample of a ceramic endoprosthesis developed at the Institute of Strength Physics and Materials Science SB RAS [8].

Figure 4 shows the geometrical model of the intervertebral disc prosthesis built in ANSYS. The Z axis is directed along the axis of the prosthesis (spine axis), the Y axis in the anteroposterior direction, the X axis in the lateral direction. Geometrical model includes two opposing plates: upper plate and lower plate. The upper and lower plates contain elements forming a pair of conjugation (Figure 5). It is assumed that the upper plate of the prosthesis will be attached to the lower surface of the upper vertebra, and the lower one to the upper surface of the lower vertebra respectively.

5. Conclusion

The following results and conclusions are obtained.

The increase in the Young's modulus of the intervertebral disc entails a change in the regions of Mises stress localization, which is associated with a change in the axial character of the deformation of the spine segment. The increase in the modulus of elasticity of the disc leads to the localization of the maximum stresses in the areas of attachment of the vertebral legs to the vertebral bodies C3, C4 and in the central part of the upper surface of the vertebra C3. An algorithm for constructing the geometric model of intervertebral disk prosthesis in the ANSYS programming language APDL is developed. The
A geometric model of the intervertebral disc prosthesis is based on the experimental sample of a ceramic endoprosthesis developed at the Institute of Strength Physics and Materials Science SB RAS. The constructed computer model is designed to study the behavior of the prosthesis in the segment of the spine under physiological loads and to study its effect on the stress-strain state of the spinal segment.

![Figure 4. Geometrical model of the intervertebral disc prosthesis (front view).](image)

![Figure 5. Geometric models of the structural components of the model prosthesis of the intervertebral disc: (a) the upper plate of the prosthesis, (b) the lower plate of the prosthesis.](image)

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