Computer Modeling of the Stress-Strain State of the Cervical Spine Segment

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Abstract. The article presents the results of the calculation of the stress-strain state of the C3-C4 segment of the cervical spine at flexion forward. The results of the calculations showed that there is the change in the deformation behavior of the segment and the change in the localization areas of the largest tensile and compression stresses at the increase in the elastic modulus of the intervertebral disk.

1. Introduction
Nowadays medicine is increasingly faced with the problem of optimal selection of an implant that can restore lost body functions. 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. 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 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, thus enhancing the development of recommendations on creation of implants replacing the whole organ or its part and effective methods for correction of the system in general.

The aim of this study is investigating of the stress-strain state of the cervical spine segment.

2. Model of the cervical spine segment
A vertebra geometrical model was built based on the literature data about experimentally obtained dimensions [6].

The simulation algorithm for the vertebra geometrical 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 geometrical model of the cervical spine segment. The geometrical model includes the vertebrae C3 (1) and C4 (2), intervertebral disc (IVD) (3), facet joints (4), interspinous ligament (5), vertebral arches (6), spinous processes (7), transverse processes (8), and articular processes of vertebrae (9).
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 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 [8,9], which in reality results from the water content reduction in the disc [10].

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 pressure 1000 N. The bending moment 7.5 Nmm [11] 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 correspond to physiological flexion of the cervical spine segment.

3. Results of calculations
Figure 3 shows the stress fields $\sigma_z$ in the segments of the spine with different heights and the Young's modulus of the intervertebral disc.

It can be seen from the figure that the compressive and tensile stresses are realized at segment flexion. At the value of the elastic modulus of the disk is 2.5 MPa the maximum absolute compressive stresses and maximum tensile stresses are localized at the sites of attachment of the legs of the C4 vertebra to the articular processes (Figure 2 (a, b)). With an increase in the elastic modulus of the disc, the maximum tensile stresses are localized in the upper part of the lateral surface of the vertebral body C3, and the maximum absolute compressive stresses in the central part of the upper surface of the vertebra C3 (Figure 2 (c, d)).

Such a change in stress localization is associated with a change in the character of the deformation of the cervical spine segment at increase the elastic modulus of the intervertebral disk (Figure 3).

Figure 3 shows the displacements fields in the Z axis direction together with the deformed shape of the segment.
Figure 2. The stress $\sigma_z$ distribution (MPa) in the segment C3-C4 of the cervical spine (a) $h=4.3$ mm, $E=2.5$ MPa; (b) $h=6.0$ mm, $E=2.5$ MPa; (c) $h=4.3$ mm, $E=98$ MPa; (d) $h=6.0$ mm, $E=98$ MPa

It can be seen from Figure 3 that under the 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 greatest stretching is observed in the spinous process of the vertebra C3. As the Young's modulus of the IVD increases, the greatest compression region shifts toward the center of the upper surface of the vertebra C3. Decreasing the IVD 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.

4. Conclusion
Studies of the stress-strain state of the C3-C4 segment of the cervical spine at flexion forward showed that the increase in the Young's modulus of the intervertebral disc entails a change in the regions of localization of the greatest tensile stresses and the greatest absolute compressive stresses, which is associated with a change in the axial character of the spine segment deformation.
Figure 3. Displacements UZ (mm) and deformed shapes of the C3-C4 cervical spine segment
(a) h=4.3 mm, E=2.5 MPa; (b) h=6.0 mm, E=2.5 MPa; (c) h=4.3 mm, E=98 MPa;
(d) h=6.0 mm, E=98 MPa

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