

MATHEMATICAL MODELING OF CHANGES IN LUMBOSACRAL REGION OF THE SPINE–PELVIS KINEMATIC CHAIN IN ILIOLUMBAR LIGAMENT SYNDROME

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ABSTRACT

The pain in the lower back in several occasions can be caused by iliolumbar ligament pathology. At a certain stage of pathogenesis of iliolumbar ligament syndrome recurring microtraumas of its fiber cause to their fibrosis that has an influence on stiffness of injured structure and biomechanics of kinematic chain lumbosacral region of the spine–pelvis. With a view to substantiating pathogenetic role of stiffness increase of iliolumbar ligament in pain formation in the lower back, by us there were made investigations of stress-strain state of kinematic chain lumbosacral region of the spine - pelvis in iliolumbar ligament syndrome.

The investigations were made using finite element model, built on the basis of tomographic 0.5 – 1 slices of lumbosacral region of the spine and pelvis for irregular regions. The ligamentous apparatus also was modeled on the basis of tomographic data taking into account the density of intact or pathologically changed fibers. The model development and calculations were made in the program SolidWorks, the prime load was body weight 700 H. For the assessment of stress state were used von Mises stresses.

The investigations made showed that the increase of ligament modulus of elasticity, which is characteristic of iliolumbar ligament syndrome leads to not only to the increase of stress state level itself, but also to SSS redistribution in L5-S1 intervertebral disc.

Thus, the use of prolotherapy and other methods of lower back pain treatment, which lead to ligament sclerosis is fraught with the development and progression of degenerative changes in L5-S1 intervertebral disc. These changes, in turn, will affect on load redistribution and involvement of all structures of kinematic chain lumbosacral region of the spine - pelvis. Therefore, the concept of treatment of this ligamentopathy must establish incremental recovery of modulus of elasticity of iliolumbar ligament.

KEYWORDS: iliolumbar ligament, mathematical model, stress-strain state.

INTRODUCTION

The pain in the lower back is the most common pathology of human musculoskeletal system. Pain and dysfunction of lumbosacral spine and sacroiliac joints occur in 80% of people throughout life. [Shostak N, 2003]. In Sweden the treatment expenses of patients with lumbar pain represented

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11% of the total value of all causes of disability and 13% of the total number of early disabilities. In 2001 the cost of treatment of such patients reached 1860 million euro, 84% of which were indirect [Ekman M et al., 2005]. Despite the numerous fundamental and clinical researches on the issue, lots of its aspects are still valid today.

The lower back pain (LBP) has multifactorial nature [Panjabi M, 2006; Schleip R, 2007] and can be caused by lumbosacral region ligaments pathology, particularly iliolumbar ligament (ILL) [Mironov

S, 2001]. At a certain stage of iliolumbar ligament syndrome pathogenesis, recurring microtraumas of ligament fiber bring to their fibrosis [Sims J, Moor-man J, 1996; Ammer K, 2001] which has an influence on stiffness (modulus of elasticity) of injured structure and biomechanics of ‘lumbosacral region of the spine–pelvis’ kinematic chain.

There are many works in literature, dedicated to the stress-strain state (SSS) investigation of lumbar spine [Kutsenko V, 2009] ‘lumbosacral region of the spine–pelvis’ kinematic chain [Istomin A, 2002]. There is interesting data in works dedicated to stress-strain state of certain muscle groups and joints in ‘lumbosacral region of the spine-pelvis’ stabilization system [Pel J.J.M et al., 2008], and also the results of investigations of stress-strain state of ‘lumbosacral region of the spine–pelvis’ kinematic chain with account of major muscles of sacroiliac joint [Staude V et al., 2015]. However, we haven’t found any studies dedicated to investigation of stress-strain state of main sacrum and pelvic elements in iliolumbar ligament syndrome.

Objective of the study was to substantiate pathogenic role of iliolumbar ligament stiffness increase in formation of lower back pain by examining the stress-strain state of ‘lumbosacral region of the spine-pelvis’ kinematic chain in iliolumbar ligament syndrome.

MATERIAL AND METHODS

To analyze the stress-strain state of ‘lumbar spine – sacrum – iliosacral joint – pelvis’ biomechanical system, including iliolumbar ligament and other ligaments of pelvic girdles, the problem of elastic body straining under the external forces should be solved. The solution to the problem can be received from the variational formulation, based on the application of virtual work principle:

$$\delta \int_V 0.5(\sigma_{ij}\epsilon_{ij})dV - \sigma \int_V fudV - \sigma \int_V pudS = 0 \quad (1)$$

must be supplemented by kinematic equations and state equations

$$\begin{aligned} \sigma_{ij} &= D_{ijkl} \epsilon_{kl}, \\ \epsilon_{ij} &= 0.5(u_{i,j} + u_{j,i}), \end{aligned} \quad (2)$$

and also, conditions on the border Su

$$U_i = U_i^0, \quad (3)$$

- where; u – displacement field;
- s – stress field;
- e – deformation field;
- p – surface forces field;
- Dijkl – elastic constant;
- V – body volume;
- Sp – body surface with known forces.

For biomechanical systems the solution of equations given above can be received with the help of various numerical methods. The finite elements method (FEM) became the most common in biomechanical problems. In finite elements method the approximate solution is built in the form of superposition of approximation functions. On the first stage of problem solution, the body is divided into fields of simpler shape (FE), geometrical dimensions of which are much less that the sizes of the whole biomechanical system. Modern program complex generates simpler shape mesh, by using automatically in most cases, elements with triangular faces. At the junction of elements (nodal points) the real stress field interchanges by the action of forces and displacements.

The simpler shape type is characterized by the number of nods and the degree of approximation of unknowns inside the domain and largely determines the accuracy of the finite elements method solution. The selection of finite elements method type for biomechanical models in modern program complexes occurs automatically and requires intervention only in special cases. Polynomial approximation of unknowns in element volume is usually either linear or quadratic, but can also have higher order. Linear, quadratic of simpler shape of higher order depends on what polynomial is selected as an approximation of determinative displacement inside the element (between the nods). The elements used in the construction of design model are presented in the figure 1.

Substitution of approximate solution into a functional leads to matrix equation

$$[K]\{u\} = \{F\},$$

- where; [K] – stiffness matrix of a model;
- {u} – vector of nodal displacement;
- {F} – vector of nodal forces.

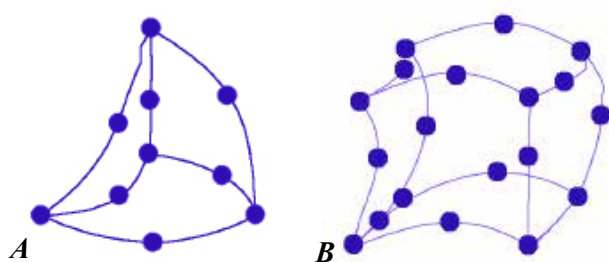


FIGURE 1. Finite elements types for biomechanical systems; 10-nodal tetrahedron (A) and 20-nodal prism (B) with quadratic approximation

The solution of simultaneous equations (4) will be nodal displacements to define strain and stress components and for every body part [Zienkiewicz O, Taylor R, 2005].

Huber-Mises-Hencky criterion, by which the stress intensity is selected as an equivalent stress is often used for strength assessment in biomechanical problems.

In foreign literature the stress intensity, computed using a formula

$$\sigma_1 = 2^{-1/2} [(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]^{1/2}$$

is called von Mises stress.

In performed researches different types of biological material were considered: compact and cancellous bone, cartilaginous tissue, intervertebral disc, ligaments. In this research the material is considered to be homogeneous and isotropic. In the work is used the data, most frequently encountered in literature [Cowin S.C, 2001; Kwacz M et al., 2015; Ibarz E, 2013]. As the subject of our research was the influence of iliolumbal ligament stiffness increase on stress-stain state changes of ‘lumbosacral region of the spine–pelvis’ kinematic chain the elasticity modulus of ligaments varied.

In literary sources that light pelvis biomechanics, the ligament stiffness is denoted [García J, 2000; Phillips A, 2007].

In considering ligaments broadly as homogeneous beam of uniform cross section, elastically deformed along an axis, we can write the ligament stiffness coefficient as

$$k = E \frac{S}{L_0}$$

where; E — Young’s modulus (modulus of elasticity) of ligament tissue;

S — cross section area of ligament transaction;

L₀ — the ligament length.

That is to say, knowing the average of cross section area and length of ligaments by the stiffness we can always determine the modulus of elasticity, and the stiffer the ligament, the higher its elasticity modulus.

In our research the data on ligament mechanical characteristics, described in the works of [Eichens-er P et al., 2011] and [Zaharie D et al., 2018] were used.

The modulus of elasticity (Young’s modulus E) and the Poisson ratio ν for different materials are summarized in the table 2.

TABLE 2.

Mechanical characteristics of biological tissues

Tissue	E (MPa)	ν
Compact bone	18350	0.3
Cancellous bone	330	0.3
Cartilage	10.5	0.49
Intervertebral disc	4.2	0.45
Ligaments	1-100	0.45

Resulting muscle forces in different body positions in pelvic region are rather well addressed in literature [Heller M et al., 2001; Williams R et al., 2014; Erdemir A et al., 2007]. The prime load is body weight. In the calculation the body weight was taken equal to 700 H. The intensity of equivalent forces for pelvis are taken according to data reduced in the work of [Miller R et al., 2009].

The geometrical model was developed on the basis of tomographic 0,5 – 1 slices of pelvis for irregular regions [Istomin A, 2002]. The ligamentous apparatus was also modeled on the basis of tomographic data considering the density of intact or pathologically changed fibers.

The design model is illustrated in figure 2. In the

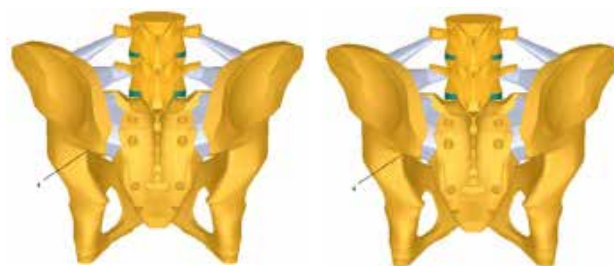


FIGURE 2. The model of ‘lumbosacral region of the spine–pelvis’ kinematic chain and control points.

figure control points of stress measurement are also shown. simpler shape model consists of 41592 simpler shape (10-nodal isoparametric tetrahedrons) and has 65982 nodes. The model development and calculations were made in the SolidWorks program. Von Mises stress (stress intensity in domestic literature) was used for the assessment of stress state.

For stress-strain state investigation in ‘lumbar spine – sacrum – iliosacral joint – pelvis’ biomechanical system in intact iliolumbar ligament a calculation was made on a model at modulus of elasticity of iliolumbar ligament value 1 Mpa and in iliolumbar ligament syndrome modeling a calculation was made on a similar model, but in modulus of elasticity value of its fibers was of 100 Mpa.

RESULTS AND DISCUSSION

The analysis of the calculation of stress-strain state intact model showed that the most stressed area in kinematic chain ‘lumbosacral region of the spine–pelvis’ is the iliac bone-acetabular area junction (Fig. 3). The stress degree in this area is equal to 5-6 MPa. The increase stress state is also recorded in the area of sacroiliac joint, either on the side of iliac bone or on the side of sacral bone (3 Mpa).

The stress-strain state distribution in intervertebral discs is shown more detailed in the figures 4.4, 4.5. In intervertebral disc of L4-L5 vertebrae the front side is more stressed – 0.4 MPa, moreover, on the bottom side of intervertebral disc the irregularity in the distribution between front and back side is more expressed.

In intervertebral disc of L5-S1 vertebrae (Fig .5) in contrast to the disc of L4-L5 vertebrae front and back sides are approximately equally stressed. The stressed state level is higher. The bottom side of intervertebral L5-S1 disc is more stressed. The stress state level isn’t in excess of the limit of strength for intervertebral disc of 4 MPa.

On the cranial side (Fig. 5a) of intervertebral disc the stress state level in the front side 0.8 MPa is twice as high as in the back 0.4 MPa. On the bottom side (Fig. 5b) the stress state level in the front part is 0.6 MPa, and in the back part – 0.4 MPa.

Based on calculation the following conclusions can be made:

In intervertebral disc of L4-L5 vertebrae more stressed is the front part of discs.

In intervertebral disc of L5-S1 vertebrae on cranial

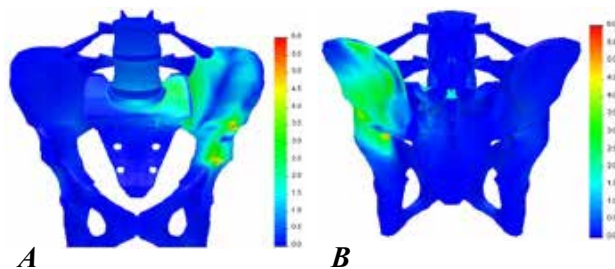


FIGURE 3. Stress intensity (von Mises stress) in ‘lumbosacral region of the spine–pelvis’ kinematic chain: A) front view; B) back view.

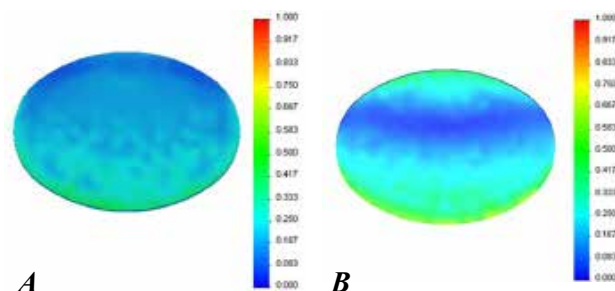


FIGURE 4. Stress intensity (von Mises stress) in L4-L5 disc: A) top view; B) view from below.

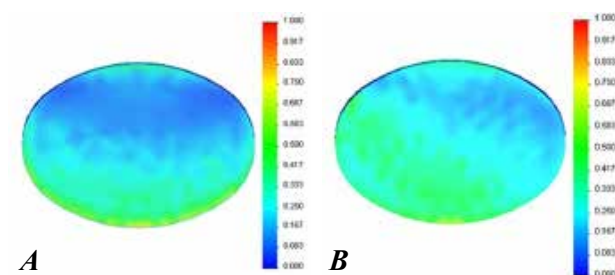
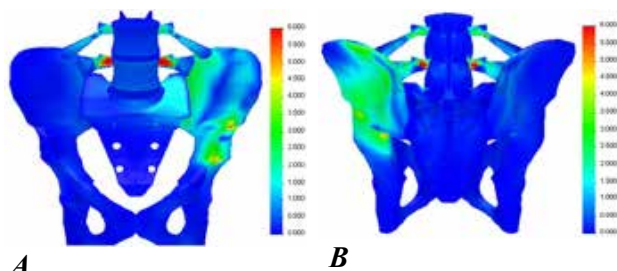


FIGURE 5. Stress intensity (von Mises stress) in L4-L5 disc: A) top view; B) view from below.

surface more stressed is the front part and for caudal surface the front part from the side of support leg.

The stress state level in intervertebral disks of L5-S1 vertebrae and L4-L5 vertebrae is approximately the same. The stress state level in disks in single-support standing is significantly lower than the limit of strength. The stress-strain state calculation analysis in ‘lumbar spine – sacrum – iliosacral joint – pelvis’ biomechanical system in modulus of elasticity value 100 Mpa showed (Fig. 6) that the general nature of stress-strain state distribution hasn’t changed.

But the stress state level in different pelvis parts changed. In iliac bone there were almost no changes in the stress state level. The difference stress state in control points didn’t exceed 0.5 MPa. In sacrum, in sacroiliac joint region the value of stress von Mises



A **B**
FIGURE 6. Stress intensity (von Mises stress) in 'lumbo-sacral region of the spine-pelvis' kinematic chain: **A)** front view; **B)** back view.

decreased and was equal to 1.8 MPa (2.7 MPa in the previous calculation). In articular process of vertebrae, the stress state level increased sharply and was equal to 2.8 MPa for L4 vertebra (0.1 MPa in previous calculation) and 12.3 MPa for L5 vertebra (0.3 MPa in previous calculation).

In the fig. 7, 8 the distribution of stress-strain state in intervertebral discs for the variant with soft ligament (Fig. 7a, b, 8a, b) and for the variant with tough ligament (Fig. 7c, d, 8c, d) is shown more detailed. In intervertebral disc of L4-L5 vertebrae the distribution of stress-strain state didn't change, the stress state level almost didn't change either, the highest value of von Mises stress was equal to 0.62 MPa (0.67 MPa for the variant with soft ligaments).

In intervertebral disc of L5-S1 vertebrae (Fig.8c, d) in contrast to the disc of L4-L5 vertebrae (Fig.7c, d) front and back parts are approximately equally

stressed, but the stress state level is almost twice as high. So, on the front edge of cranial surface of intervertebral disc the stress level equals to 1.1 MPa (0.7 MPa for the variant with soft ligaments). Caudal side of intervertebral L5-S1 disc is more stressed 1.3 MPa (0.6 MPa for the variant with soft ligaments) and in contrast to the variant with soft ligaments its back part is more stressed. The stress state level isn't in excess of the limit of strength for intervertebral disc 4 MPa.

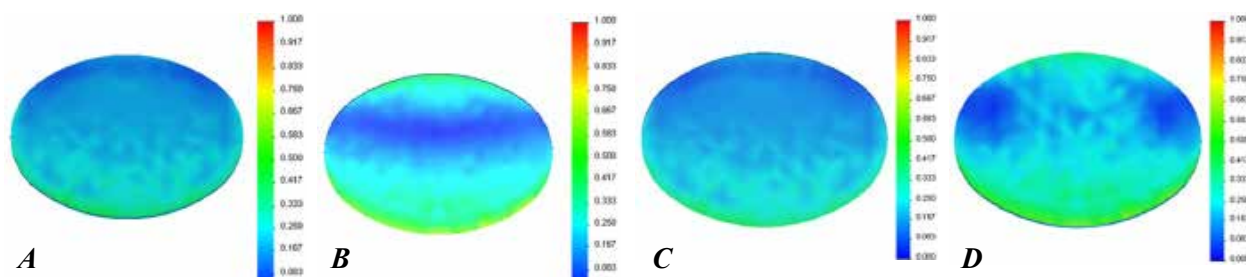
Based on calculation the following conclusions can be made:

The generic character of stress-strain state distribution in pelvis didn't change. In articular process of vertebrae, the stress state level increased sharply. In intervertebral disc of L4-L5 vertebrae the character of stress-strain state distribution and stress state level almost didn't changed.

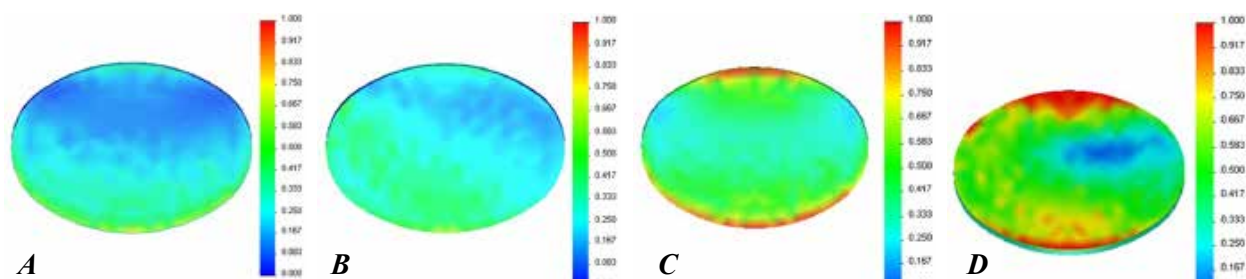
In intervertebral disc of L5-S1 vertebrae the character of stress-strain state distribution, for caudal surface more stressed is its back part. The stress state level increased approximately in two times.

In the fig. 9 are presented the diagrams of comparison of stress state level in control points of pelvis and intervertebral disks for different values of modulus of elasticity of iliolumbar ligament value.

Based on calculation the following conclusion can be made: the increase of modulus of elasticity leads to the increase of stress state level of iliolum-



A **B** **C** **D**
FIGURE 7. Stress intensity (von Mises stress) in L4-L5 disc: **A)** top view, **B)** view from below for the variant of soft ligament and **C)** top view, **D)** view from below for the variant of tough ligament.



A **B** **C** **D**
FIGURE 8. Stress intensity (von Mises stress) in L5-S1 disc: **A)** top view, **B)** view from below for the variant of soft ligament and **C)** top view; **D)** view from below for the variant of tough ligament.

bar ligament and to the stress-strain state redistribution in intervertebral L5-S1 disc. Thus, a pathological circle of degenerative changes development in kinematic chain 'lumbosacral region of the spine-pelvis' in iliolumbar ligament syndrome is modeled.

One of the most discussible aspects of iliolumbar ligament treatment is the application of prolotherapy (sclerogenic injections). Staude V.A (2005) run a mathematic modeling using the finite elements method of artificial fibrosis of back supportive complex ligaments of spinal motion segment to justify the increase of its load-carrying capacity in

its degenerative instability.

In shear loads in case of certain geometrical dimensions of fibrosing tissue the stress level in intervertebral disc and deformability of spinal motion segment decreased. But this data cannot be directly compared with the results of our research, because of modeling only the fibrosis of supraspinal and interspinous ligaments, moreover, in conditions of degenerative instability in lumbar spine.

Fibrosis is a primary component of pathogenesis in iliolumbar ligament syndrome, moreover, degenerative changes in other structures of spinal motion segment is of the secondary nature.

The opponents of such approach to iliolumbar ligament treatment note the negative influence of lumbar stiffness increase on the function of contiguous anatomical structures. [Dagenais S et al., 2005]. 'European recommendations for the treatment of chronic nonspecific lower back pain' recommend not to use prolotherapy [European Guidelines for the Management of Chronic Non-Specific Low Back Pain, 2006]. In our opinion, prolotherapy is applicable in cases of development of degenerative instability of lumbosacral spine. But in iliolumbar ligament syndrome artificial fibrosis can only aggravate pathological changes by unfavorable stress-strain state redistribution in intervertebral disc L5-S1, which will negatively affect the risk of development of degenerative changes in it and in contiguous links of 'lumbosacral region of the spine-pelvis' kinematic chain.

CONCLUSION

The increase of ligament modulus of elasticity, which is characteristic of iliolumbar ligament syndrome leads to not only the increase of stress state level itself, but also to stress-strain state redistribution in intervertebral L5-S1 disc. The use of prolotherapy and other methods of lower back pain treatment, which lead to ligament sclerosis is fraught with the development and progression of degenerative changes in intervertebral L5-S1 disc. These changes, in turn, will affect on load redistribution and involvement of all structures of 'lumbosacral region of the spine-pelvis' kinematic chain. Therefore, the concept of treatment of this ligamentopathy must establish incremental recovery of modulus of elasticity of iliolumbar ligament.

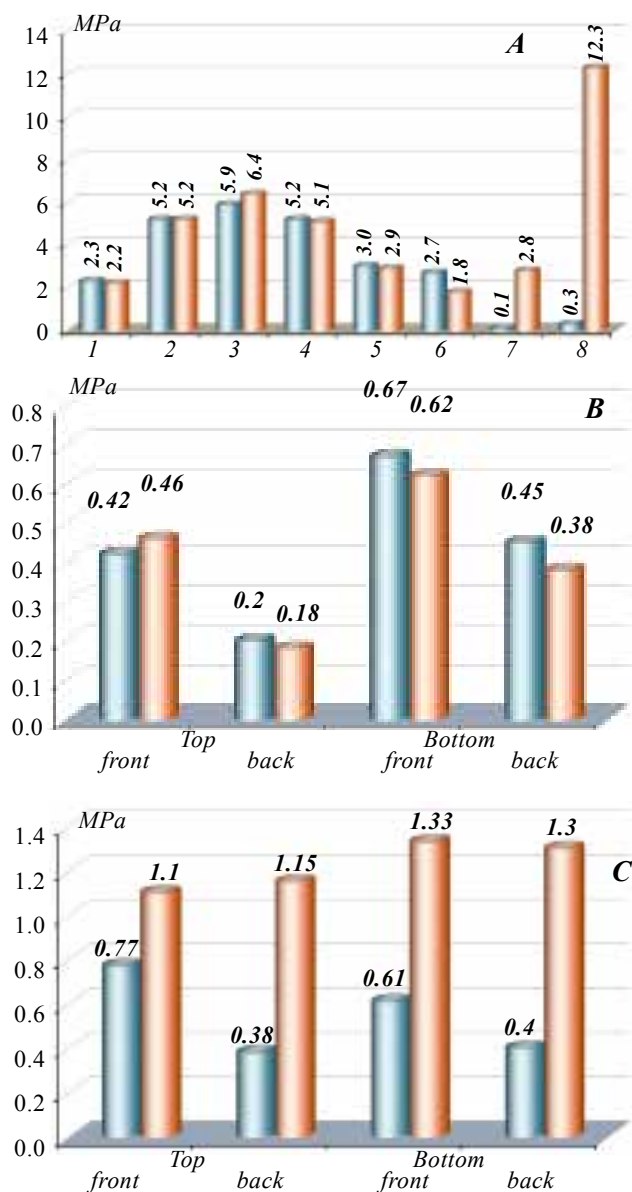


FIGURE 9. Stress von Mises in different values of modulus of elasticity: A) iliac bone; B) intervertebral disc of L4-L5 vertebrae; C) intervertebral disc of L5-S1 vertebrae. In each pair for left columns E = 1 MPa, for right columns E = 100 MPa.

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