Research Article

Determination of Stresses in the Apparatus of External Fixation of the Human Spine

Piven Valeriy Vasilievich[1]

[1] *Department of Machinery and Equipment of the Oil and Gas Industry, Industrial University of Tyumen, Tyumen, Russia.*

Email: *pivenvv @ yandex.ru*

ABSTRACT

This present work aims to increase the effectiveness of the spine external fixation device by optimizing its stress-strain state. Insufficient studies of the problems of the stress-strain state of the pedicle screw closure vertebra column, as well as the occurrence of dangerous stresses in the pedicle screw with various combinations of control efforts, are made to correct spinal deformity with a large factor of safety. In many cases, it is not possible to create the required correction action on the spine. A high degree of statistical determination of the structure, the ambiguity of the impact of the device on the vertebrae, and the change in the internal control efforts in adjusting the distraction rods limit the use of external fixation for complex spine deformities. Determination of stresses in dangerous sections of rods-screws depending on the control actions is the basis for mathematical modeling of the process of correction. An algorithm for mathematical modeling of the stress-strain state of the external fixation apparatus of the spine is proposed. By calculationand experimentation, we were able to determine the mechanical stresses in the dangerous section of the structural elements of the device. To prevent dangerous stresses when turning the vertebrae, it is necessary to apply asymmetrical multidirectional load. With complex deformities of the spine, an additional impact of a couple of forces is necessary to turn the vertebrae.

Key words: *Distraction force, External fixation, Spine, Scoliosis*

INTRODUCTION

Overload of vertebral column segments caused by various factors and in some cases, it leads to kyphoscoliosis - a deformity of the spine [1-6]. When choosing the optimal tactics of surgical treatment [7-16] it is possible to install various implants and frame structures mounting directly on the vertebrae, with a strong degree of scoliosis with the use of anexternal fixation device of the spine [17-19]. In some cases, it is advisable combining the use of these two ways: in the first stage of correction of the deformation of the spine for external fixation, then the subcutaneous installation of implants or other structures.

Applied as the optimization process of correcting the scoliotic deformity of a person, the external fixation device is a spatial core structure fixed with the help of rodscrews in the vertebral bodies [20]. Similar constructive schemes and details can also be used in the treatment of various spinal injuries.

The present work aims to increase the effectiveness of the external fixation device by optimizing its stress-strain state. Determination of stresses in dangerous cross-sections of rods-screws depending on the control actions acts as the basis of the mathematical modeling correction process.

Mathematical design and optimal loading conditions of the device to ensure the necessary corrective actions on the vertebrae can be realized using a developed schemewith the original rheological properties of an elastic-

viscous-plastic base (vertebral bodies), and ways of embedding the supporting elements, the stress-strain state of spatial rod system and its geometric and mechanical characteristics [21].

There are technological and technical methods of reducing stress in a dangerous section of parts of the external fixation device, but in all cases, it is necessary to take into account the stress in the dangerous sections of the parts of the device and the vertebral bodies [22].

MATERIALS AND METHODS

To achieve a positive result for the correction of spinal deformity, the parts of the device must create a stress-deformed state to provide the necessary torque on the vertebrae in the sagittal plane. This should carry out strength limitations on the parts of the apparatus and the body of the individual as well. A dangerous section of the shaft of the screw is its point embedded in the vertebra. With the destruction of the rod-screws, the problem arises out of the threaded portion, in which case the surgery for the correction of spinal deformity will have to be postponed. Optimization of the above options can be achieved by a mathematical design of the process of correction. The decomposition of the optimization process **(Figure 1)** should include the formation of a block of input data, a mathematical design block with the search for optimal values of the adjustable parameters of internal forces in the details of the apparatus. With a phased implementation of the algorithm, it is necessary to provide feedback to the initial data generation unit to take into account the actual strength state of the vertebral body.
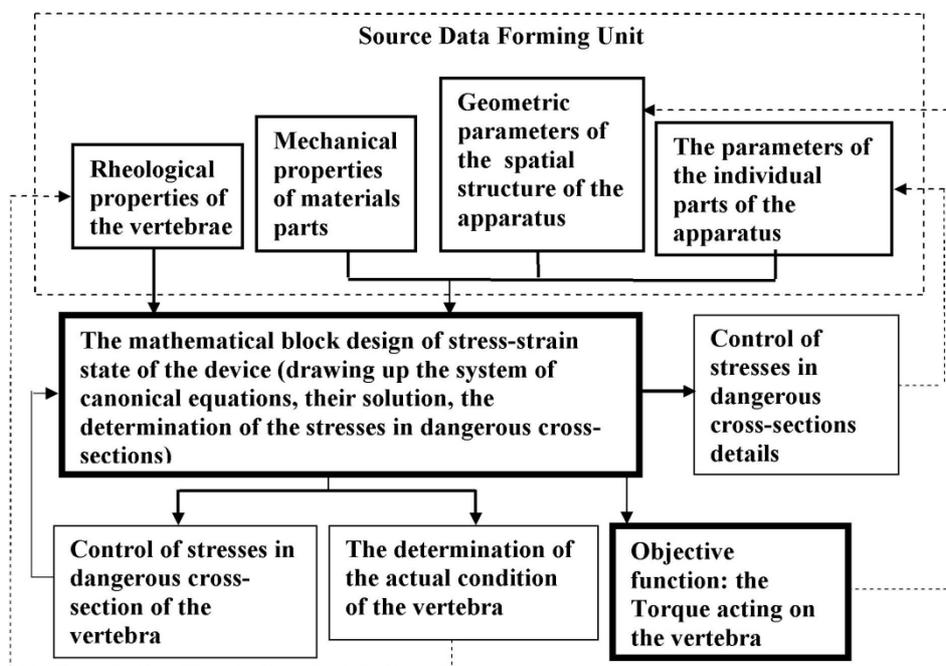
Figure 1. Decomposition scheme of correction of spinal deformity

During mathematical modeling for finding the unknown power factors, the force method was used [23, 24]. The external fixation device of the spine is a statistically indeterminate space-frame design. A high degree of static in determination leads to an additional internal effort in the details of the apparatus, to high stress, and reduces the efficiency of the apparatus.

To estimate the internal forces in the dangerous sections of the rod-screws of the external fixation device, we considered the scheme of the device with two lateral plates and the sealing of shafts of screws in the vertebral bodies **(Figures 2 and 3)**. The computational model adopted is perpendicular to the installation rod screws to the plate.

Considering the case when one of the adjusting rods creates alongitudinal tensile force (P) and the other longitudinal compressive stress (-P). The specified force system is a skew-symmetric load with a plane ofsymmetry passing through the ZZ, $Z'Z'$axes. To disclose static indeterminacy, as the main system [23], we take the force scheme shown in **Figure 4**.

To solve this problem by the method offorcesto find the four unknown values of internal forces, it is necessary to solve the following system of canonical equations [23]:

$$
\begin{aligned}
\delta_{11} \cdot X_1 + \delta_{12} \cdot X_2 + \delta_{13} \cdot X_3 + \delta_{14} \cdot X_4 &= -\Delta_{1p}; \\
\delta_{21} \cdot X_1 + \delta_{22} \cdot X_2 + \delta_{23} \cdot X_3 + \delta_{24} \cdot X_4 &= -\Delta_{2p}; \\
\delta_{31} \cdot X_1 + \delta_{32} \cdot X_2 + \delta_{33} \cdot X_3 + \delta_{34} \cdot X_4 &= -\Delta_{3p}; \\
\delta_{41} \cdot X_1 + \delta_{42} \cdot X_2 + \delta_{43} \cdot X_3 + \delta_{44} \cdot X_4 &= -\Delta_{4p},
\end{aligned}
\tag{1}
$$

where δ_{ij}– move in the direction of the i – th power factor under the action of j – th individual factor; X_i is the internal force factors; Δ_{ip} - move in the direction of the i – th power factor under the action of the force P.
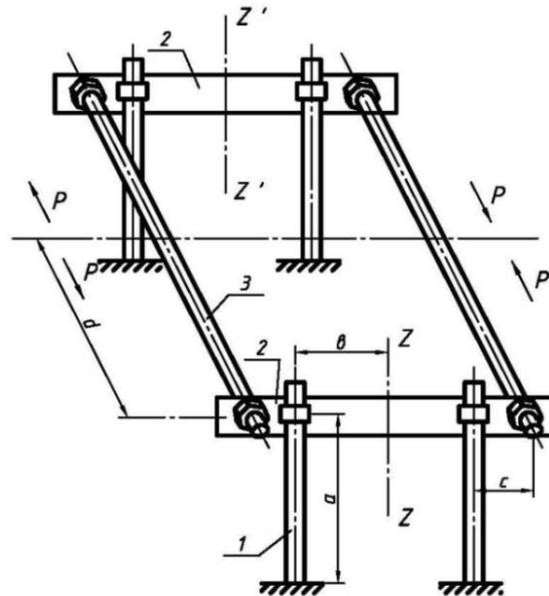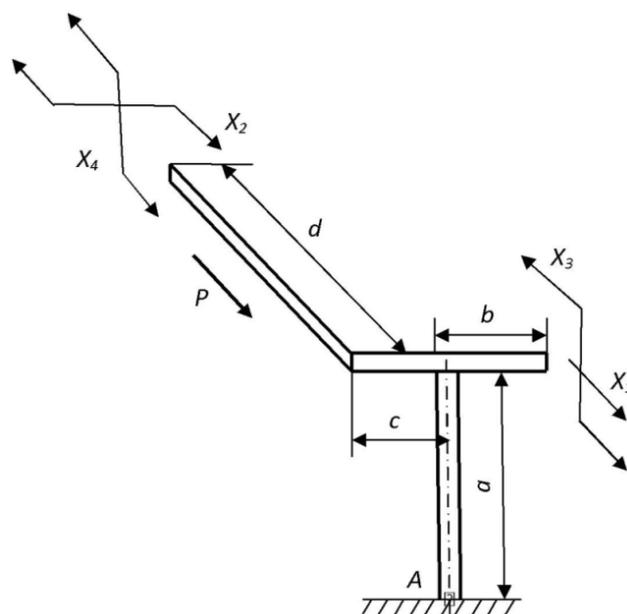In the experiment, the internal forces and moments were measured using force sensors.

Figure 2. Diagram of apparatus: 1 - rodscrew; 2 - plate; 3 - adjusting rod
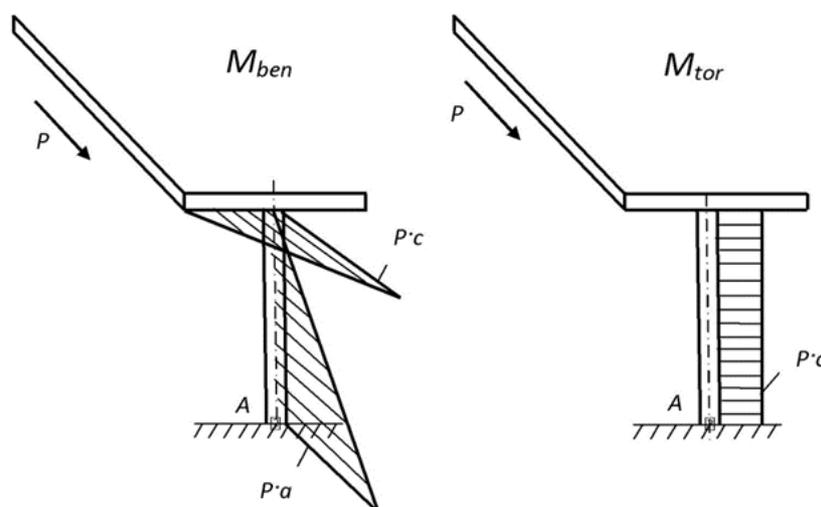

Figure 3. Scheme fixation rodscrews to the vertebra

Figure 4. Basic system in the calculation of forces

Plot bending and torsional moments from the action of load *P* are shown in **Figure 5**.

Figure 5. Plot bending (M_{ben}) and torsional (M_{tor}) moments of force *P*

Calculations of canonical coefficients carried out in a known mannerwhen the value of the force $P = 200$ *N*, the parameters $a = 0.06$ *m*; $b = 0.04$ *m*; $s = 0.03$ *m*; $d = 0.02$ *m*. as a result we get the following system of equations [23]:

$$0.0001 \cdot X_1 + 0.0017 \cdot X_2 + 0.0010 \cdot X_3 + 0.0010 \cdot X_4 = 0.0020;$$
$$0.0017 \cdot X_1 + 0.0572 \cdot X_2 = 0.2240;$$
$$0.0010 \cdot X_1 + 0.0341 \cdot X_3 + 0.0333 \cdot X_4 = 0.2; \tag{2}$$
$$0.0010 \cdot X_1 + 0.0333 \cdot X_3 + 0.0394 \cdot X_4 = 0.2.$$

RESULTS AND DISCUSSION

When solving the system of equations (2) in the program "MATCAD" we obtained the following values of unknowns: $X_1 = 61.0$; $X_2 = 2.1$; $X_3 = 6.8$; $X_4 = 0.9$.
Bending moment in a dangerous section of rodscrews (*A*)

$$M_{benA} = X_1 \cdot a - X_3 + P \cdot d - X_4 = 7.96 \, H \cdot m. \tag{3}$$

Torque *T*.

$$M_{torA} = -X_1 \cdot b - X_2 + P \cdot c = 1.46 \, H \cdot m. \tag{4}$$

Stress in p. *A*

$$\sigma = \frac{\sqrt{M_{benA}^2 + M_{torA}^2}}{W_x} = 3.8 \cdot 10^8 H/m^2. \tag{5}$$

To turn the vertebra, the sum of the effects of power factors should be aimed at creating maximum torque M_{torZ}.

$$M_{torz} = P\,(c + b) - X_2 = 11.9 \, H \cdot m. \tag{6}$$

The discrepancy between the theoretical and experimental data was not more than 12%.

The obtained results may be used in the optimization of the stress-strain state of the apparatus for external fixation of the spine in various layout solutions, including a large number of elements. The choice of specific vertebrae, which should influence the maximum torque should be produced taking into account the initial deformation of the spine.

The determination of the maximum diameter of the rodscrew is limited by the mechanical properties of the bone tissue. This diameter is chosen depending on the type of vertebra, its anatomical structure. For example, for the lumbar vertebra L1, the length of the threaded part of the screw rod should be 40-42 mm, and its diameter-4 mm. Optimal values of control forces in the distraction rods must be performed using mathematical modeling, the decomposition diagram of which is shown in **Figure 1**. The limiting parameters in the simulation are stresses in dangerous sections, determined from the dependences obtained in the work.

Further studies on the correction of spinal deformities should be continued in the direction of developing guidelines for physician staff on controlling the device for external fixation of the spine, developed based on mathematical modeling, taking into account the results obtained in this study.

A series of experiments were carried out to experimentally determine the stresses arising in the rodscrew. Mechanical stresses were evaluated using strain gauge equipment. Strain gauges were mounted at the base of the rodscrew, which was screwed into a wooden bar **(Figure 6)**. The rodscrewwas rigidly connected by a plate, to which they were attached with L-shaped clamps.

The distance from the sealing point of the rodscrew to the *L*-shaped clamp was 73 mm. The force *P* was created using weights of 10 *H* and 15 *H*. The points of application of the load *P* are indicated by the numbers 1-9 **(Figure 7)**. Securing loads through holes 1, 2, 3, 5, 7, 8, 9 **(Figure 7)** corresponds to the possible options for the mounting location of the adjustment rods 3 **(Figure 2)**.

According to the obtained calculated and experimental data, a graph of the dependence of the bending stresses in the rodscrew, depending on the point of application of the force *P*, is constructed **(Figure 7)**. The presented results show the percentage of stress in the dangerous cross-section of the rodscrewin comparison with the case when the entire load falls on one screw rod without fixing it to the plate.

The analysis of the results showed the following. With an asymmetric load of the rodscrew **(Figure 6)**, one of the rodscrew carries a significant load. This can lead to dangerous stress in the sealing of the rodscrew or the body of the vertebra. For example, when a load is applied at point 1 **(Figure 7)**, the first screw rod accounts for up to 70% of the total stress, while the second one accounts for up to 30 %. The symmetrical and equal stress of the rodscrewis achieved when a load is applied at point 5. When moving away from this point, the stress difference in the rodscrew may differ by 2.5 times. The discrepancy between the experimental and theoretical data was 9-11%.
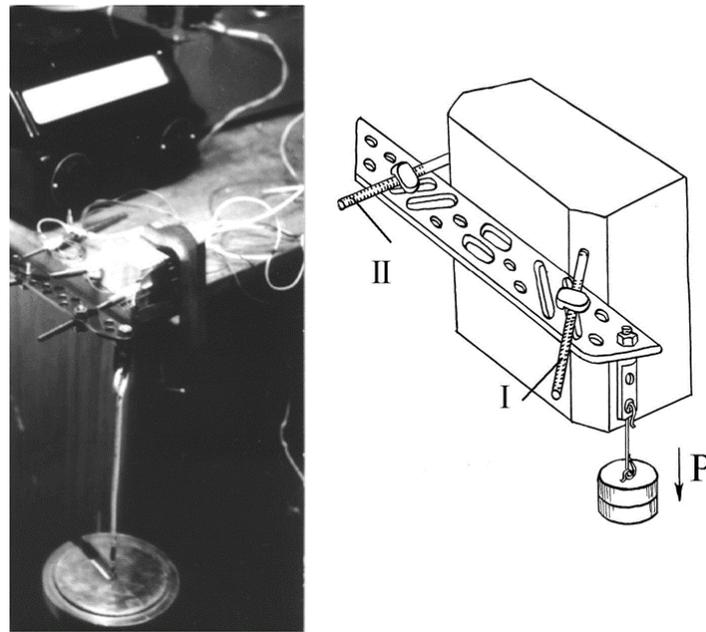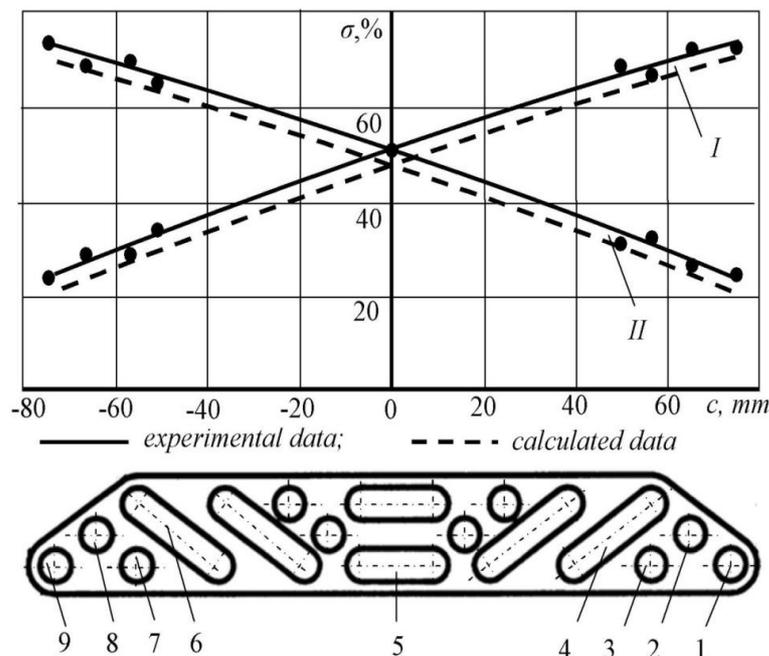
Figure 6. Diagram of the load application (P) on the rodscrew I and II connected by a plate

For the stresses in any rod-screw not to reach the limit value, it is necessary to apply asymmetrical load to plate 2 **(Figure 2)**. At the same time, the maximum torque of the M_{torZ} will also be provided (Formula 6). Forces P must be applied at both ends of the plate in opposite directions.

Analysis of formula 8 allows us to conclude: to create the maximum torque M_{torZ} on the vertebra, it is advisable to add the impact of a pair of forces. This pair of forces is denoted as X_2 **(Figure 4)**. The direction of action of the pair of forces should be opposite to the direction shown in the figure: - X_2.

The need for an additional impact of a pair of forces on the plates for turning the vertebrae arises in cases where, due to the peculiarities of the curvature of the spine, it is impossible to provide a symmetrical impact with the forces of P. The need for a pair of forces appears when installing the external fixation device of the spine, consisting of three or more plates with complex deformities of the spine. In this case, it is advisable to apply a couple of forces for additional rotation of individual vertebrae.

Figure 7. Graph of the dependence of stresses (σ) on bending in the rodscrew (I and II) depending on the point of application of the force P and the diagram of the plate with holes: 1, 2, 3, ... 9 – holes through which loads were attached

CONCLUSION

This study presents the results of the study in the simulation of mechanical stresses in the details of the external fixation apparatus of the spine. The simplest case of using an external fixation device is considered when only two vertebrae are used to correct spinal deformity. In more complex forms of scoliosis, at least three vertebrae are involved. The external fixation device must be equipped with a set of simple elements. This arrangement is considered in this paper. The calculation of more complex structures of devices should be carried out based on the results obtained.

REFERENCES

1. Pellise F, Vila-Casademunt A, Ferrer M, Domingo-Sabat M, Bago J, Perez-Grueso FJ, et al. Impact on health-related quality of life of adult spinal deformity (ASD) compared with other chronic conditions. Eur Spine Jl. 2015;24(1):3-11.
2. Jo DJ, Kim YS, Kim SM, Kim KT, Seo EM. Clinical and radiological outcomes of modified posterior closing wedge osteotomy for the treatment of posttraumatic thoracolumbar kyphosis. J Neurosurg Spine. 2015;23(4):510–7.
3. Czaprowski D, Stoliński Ł, Tyrakowsk M, Kozinoda M, Kotwicki T. Non-structural misalignments of body posture in the sagittal plane. Scoliosis Spinal Disord. 2018;13(6). Available from: https://doi.org/10.1186/s13013-018-0151-5
4. McAviney J, Roberts K, Sullivan B, Alevras AJ, Graham PL, Brown BT. The prevalence of adult de novo scoliosis: A systematic review and meta-analysis. Eur Spine J. 2020;29(12):2960-9. Available from: https://link.springer.com/content/pdf/10.1007/s00586-020-06453-0.pdf
5. Mostafavi Z, Houshyar J, Aliasgarzadeh A, Aghamohammadzadeh N, Sadra V, Khani M, et al. Comparison of the Bone Mineral Density between Acromegaly Patients and Healthy Individuals. Arch Pharm Pract. 2019;10(4):15-21.
6. Ibrahim S, Ahmed SA, Ahmed SM, Ahmed SK. Osteoarthritis: The Effect of Specific Watsu Therapy on Peak Torque and Functional Parameters-An Analytical Study. Pharmacophore. 2020;11(5):46-50.
7. Afonin DN. Web system support to decision making in surgery. Biomed Eng. 2011;45(2):64-7.
8. Mikhaylovskiy MV, Alshevskaya AA. Magnetically controlled growing rods in early-onset scoliosis surgery: a review of English-language literature. Spine Surg. 2020;17(1):25-41.
9. Figueiredo N, Kananeh SF, Sigueira HH, Figueiredo RC, Al Sebai MW. The use of magnetically controlled growth rod device for pediatric scoliosis. Neurosciences (Riyadh). 2016;21(1):17-25. Available from: https//doi.org/10.17712/nsj.2016.1.20150266
10. Akbarbnia BA, Keskinen H, Helenius I, Panteliadis P, Nnadi C, Cheung KMC, et al. Comparison of primary and conversion surgerywith magnetically controlled growing rods in children with early-onset scoliosis (EOS). Spine J. 2016;16(4):54. Available from: https//doi.org/10.1016/j.spinee.2016.01.051
11. Hosseini P, Pawelek J, Mundis GM, Yaszay B, Ferguson J, Helenius I, et al. Magnetically controlled growing rods for early-onset scoliosis: a multicenter study of 23 cases with minimum 2 years follow-up. Spine. 2016;41(18):1456-62. Available from: https//doi.org/10.1097/BRS.0000000000001561
12. Chernyadjeva MA, Vasyura AS. Urgical treatment of progressive idiopathic scoliosis in adolescents aged 10-14 years: literature review. Spine Surg. 2019;16(3):33-40.
13. Cheng MF, Ma HL, Lin HH, Chou PH, Wang ST, Liu CL, et al. Anterior release may not be necessary for idiopathic scoliosis with a large curve of more than 75° and a flexibility of less than 25. Spine J. 2018;18(5):769-75. Available from: https//doi.org/10.1016/j.spinee.2017.09.001

14. Serarslan U, Alici E, Akcali O, Kosay C, Unal M, Gultekin A. There is no remarkable difference between pedicle screw and hybrid construct in the correction of Lenke type-1 curves. Turk Neurosurg. 2018;28(5):799-804. Available from: https//doi.org/10.5137/1019-5149.JTN.20522-17.1

15. Tsirikos AI, Loughenbury PR. Single rod instrumentation in patients with scoliosis and co-morbidities: Indications and outcomes. World J Orthop. 2018;9(9):138-48. Available from: https//doi.org/10.5312/wjo.v9.i9.138

16. O'Donnell C, Michael N, Pan X, Emans J, Garg S, Erickson M. Anterior spinal fusion and posterior spinal fusion both effectively treat Lenke type 5 curves in adolescent idiopathic scoliosis: a multicenter study. Spine Deform. 2018;6(3):231-40. Available from: https//doi.org/10.1016/j.jspd.2017.09.054

17. Kovalenko RA, Ptashnikov DA, Savello AV, Masevnin SV, Kashin VA. A rare case of treatment of giant paravertebral arteriovenous malformation combined with idiopathic scoliosis. Spine Surg. 2019;16(3):47-54.

18. Sergeev KS, Piven VV. The substantiation of the elastic-viscoplastic model of the human spine for modeling the correction process of kyphoscoliotic deformation. J Craniovertebr Junction Spine. 2018;9(1):32-6.

19. Piven VV, Lyulin SV, Kovalenko PI, Mushtaeva YA. Mechanics of external fixation device of spine: reducing the mounting stress. In: Materials Science and Engineering. Processing Equipment, Mechanical Engineering Processes and Metals Treatment [conference proceedings on the Internet]; 2018;327(4):042078.

20. Shevtsov VI, Piven VV, Kovalenko PI, Khudjaev AT, Mushtaeva JuA, inventors. Federal State Budgetary Institution "National Ilizarov Medical Research Centre for Traumatology and Ortopaedics" Ministry Healthcare, Russian Federation, assignee. Method of external fixation of vertebral column and device for method embodiment. RUS Patent 2218118C2. 2003-12-10.

21. Piven VV, Bityukov GE. Validation of the mathematical model of frame construction stress-strain state. News of higher educational institutions. Oil and gas. 2010;3:107-11.

22. Makarevich SV. Historical aspects of transpedicular fixation of the spine: literature review. Hir. Pozvonoc. 2018;15(4):95-106. [In Russian]. Available from: http://dx.doi.org/10.14531/ss2018.4.95-106

23. Feodos'ev VI. Soprotivlenie materialov. Moscow: Izdatel'stvo MGTU; 2016. 544 p.

24. Patnaik S, Hopkins D. Strength of Materials: A New Unified Theory for the 21st Century. Oxford: Elsevier; 2003. 750p.