The substantiation of the elastic–viscoplastic model of the human spine for modeling the correction process of kyphoscoliotic deformation

ABSTRACT

Purpose: The relevance of the problem is caused by an increase in the number of spine-related diseases among children, including scoliosis. Currently, there are no methodologies for the treatment of scoliosis, which ensure an unambiguous positive result. The purpose of the article is to justify the spinal model as an elastic viscoplastic body for further mathematical modeling of the process of spine correction and search for its optimal conditions.

Methodology: The leading approach to the study of this problem is the development of techniques for the surgical treatment of deformities of the vertebral column with the aid of an external fixation device for the spine, providing for a rigid connection of the elements of the apparatus with each other and with the spine. The rigid connection between the elements of the external fixation device increases the degree of static indeterminacy of the design, which leads to the occurrence of additional dangerous stresses in the details of the apparatus and in the vertebrae. The control actions in such devices do not provide an adequate result for the process of correction of the vertebral column.

Results: The main result is the substantiation of the spine model as an elastic viscoplastic body. This will allow more detailed consideration of the medical and biological features of the spine and the physical and mechanical properties of human bone and soft tissues. The proposed model will allow developing an adaptive design of the device, taking into account specific features of the organism and more effectively managing the correction process.

Value: The materials of the article can be useful for scientists, doctors and specialists in conducting scientific research on the problem of spine deformation correction and the development of appropriate technical means.

Keywords: Apparatus for external fixation of the spine, deformation correction, kyphoscoliotic deformation of human spine, model of an elastic–viscoplastic body

INTRODUCTION

Scoliosis is a disease of the musculoskeletal system, which is characterized by a three-plane deformation of the human spine. In the pathology of the musculoskeletal system, idiopathic scoliosis occupies one of the first places, and the number of children with spine disease is up to 17%.[1] With the progression of spine deformity and the curvature of the spine >40°, a surgical method of treatment is used.

The modern stage in the development of surgical methods for the treatment of scoliosis begins in 1947 when Harrington developed an endocorrector and later the basic principles of surgical correction.[1,2] Harrington's method and devices have been used for about 40 years,[3,4] although the problem has not been finally solved.[1] The most important condition

Konstantin S Sergeev, Valery V Piven[1]

Department of Traumatology and Orthopedics, Tyumen State Medical University, [1]Department of Machinery and Equipment of the Oil and Gas Industry, Tyumen Industrial University, Tyumen, Russia

Address for correspondence: Dr. Konstantin S Sergeev, Tyumen State Medical University, 54, Odesskaya Street, 625023, Tyumen, Russian Federation, Russia.
E-mail: sergeev.trauma@inbox.ru

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for achieving a positive result of treatment of patients with various vertebral pathologies is the correction of the axis of the spinal column and the physiological curvature of its departments.[5]

MATERIALS AND METHODS

At present, numerous methods of conservative and operative correction of spinal deformations have been proposed.[6-19] In most cases, the solution of the problem of eradicating deformation and preventing a relapse consists in performing surgical treatment through the use of various instruments including transosseous osteosynthesis.[20,21]

The main method of treating the kyphoscoliotic deformation of the human spine is the effect of mechanical devices on the vertebrae.[22,23] All mechanical devices are divided into internal fixation devices and external fixation devices, the latter being those providing a hypodermic, one-time fixation of the vertebrae.[22,23] After this, the fasteners are usually not removed [Figures 1 and 2].

Advantages of internal fixation devices are one-operation session and short and accelerated rehabilitation period. These devices also have disadvantages: incomplete instantaneous correction in severe and rigid deformations, the need for traumatic mobilization operations, a high probability of early loosening of the fixators and endocorrectors, and a significant loss of the achieved correction due to high-contact stresses at the "implant-bone" border.[24]

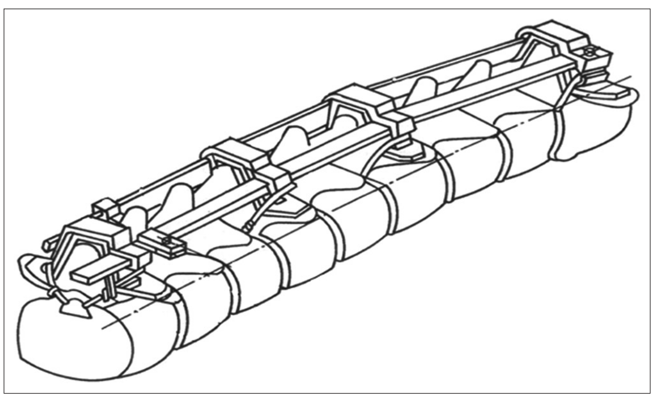

Figure 1: Spine corrector with internal fixation

Apparatus of external fixation is spatially rod metal structures in which the rod screws are screwed directly into the body of the vertebra.[22,23] The main parts of such devices are located outside the skin [Figures 3 and 4].

Advantages of external fixation devices are the possibility of controlled action on the vertebral bodies during correction, the inclusion of any necessary vertebrae of the entire vertebral column, the correction process dependent on the condition and the actual curvature of the spine during treatment, and removal of the apparatus from the patient after treatment.

Apparatuses of external fixation of the spine are spatial core structures with a high degree of static uncertainty. The reason for this is the presence of unnecessary mechanical connections between the individual elements of the structure. The high static uncertainty of the apparatus design can lead to additional stresses in its details, which hinders the correction process. In this regard, the most effective devices are external fixation ones, having a simplified design, a minimum number of internal mechanical connections, and providing a controlled impact on the spine.

RESULTS

Designing any mechanical device exerting influence on the spine, medical and biological features of the spine and physical and mechanical properties of human bone and soft tissues should be taken into account.

From the point of view of mechanics, the human spine can be represented as a model of an elastic–viscoplastic body. Taking into account the mechanical properties of the spine and soft tissues, the model of the viscoelastic body of Kelvin-Voigt,[25,26]

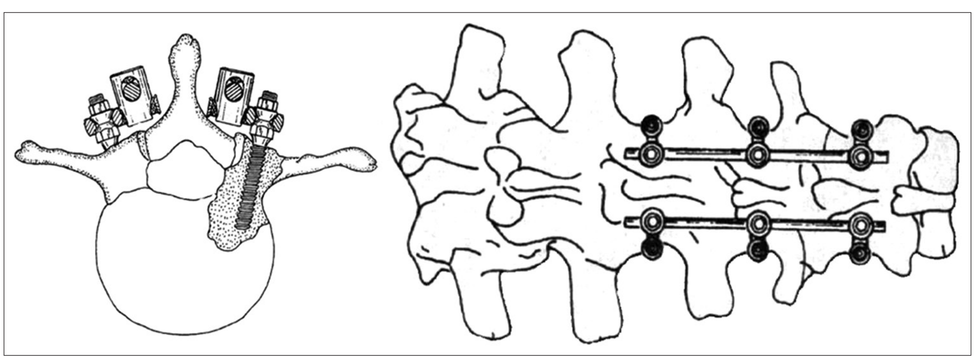

Figure 2: Universal connection for fixing the spine

consisting of a finite number of vertebral links, should serve as the basis here. A multilink model is called the generalized Kelvin model.[27,28] The total deformation of the spine will be composed of deformations occurring around the individual vertebrae.

To take into account the plastic properties that appear in the correction process, the Saint-Venant plastic body model should be added to the above model.[29,30] The joint action of these two models [Figure 5] will most adequately describe the processes occurring in spine deformation correction.

Elastic properties of the spine are suggested to be taken into account [Figure 5] with the help of (1) Hooke's modules (springs 1, 2, 3, and 4) with different elasticity coefficients; (2) Newton modules (pistons with calibrated holes 5, 6, and 7, through which liquid can pass) with different viscosity coefficients; (3) Saint-Venant modules 8, 9, and 10, characterizing the plastic properties, with the corresponding yield limits.

When the model is under an instantaneous mechanical strain σ, the spring 1 will deform. After removal of the strain, all elements return to their original position. With continuous influence, the parallel elements 2, 3, 4 and 5, 6, 7 will have the same deformation and different strain. Pistons will move at a limited speed. If the strain in the elements 8, 9, and 10 does not reach the yield point after the removal of the external strain by the springs 2, 3, and 4, the elements of the structure will gradually return to their initial position.

If the strain in the elements 8, 9, and 10 has reached the yield point, then the overall deformation of the entire structure will occur. Pistons 5, 6, and 7 will limit the rate of plastic deformation. In this case, the total linear dimension will increase. When the external strain is removed, the springs 2, 3, and 4 return part of the entire system to its original position, but residual plastic deformation remains.

When designing an apparatus for the external fixation of the spine, it is necessary to mechanically limit the maximum value of the overall deformation of the structure and consequently the deformation of the spine to avoid undesirable consequences. In the working mode of correcting the deformation of the spine, the apparatus should function in the zone of yield point.

DISCUSSION

The model presented above allows taking into account the elastic, viscous, and plastic properties of the spine and soft tissues. Accounting for possible causes of scoliosis and for individual characteristics of the body requires a detailed study of the physical and mechanical properties of the spine and soft tissues in relation to the deformation correction process. A full accumulation of the necessary statistical data is possible

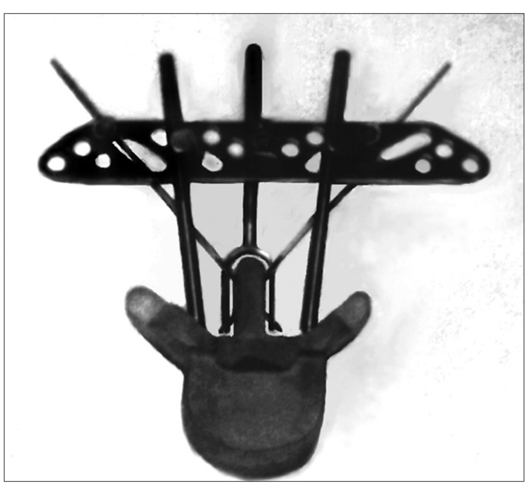

Figure 3: Fixation element of the spinous process

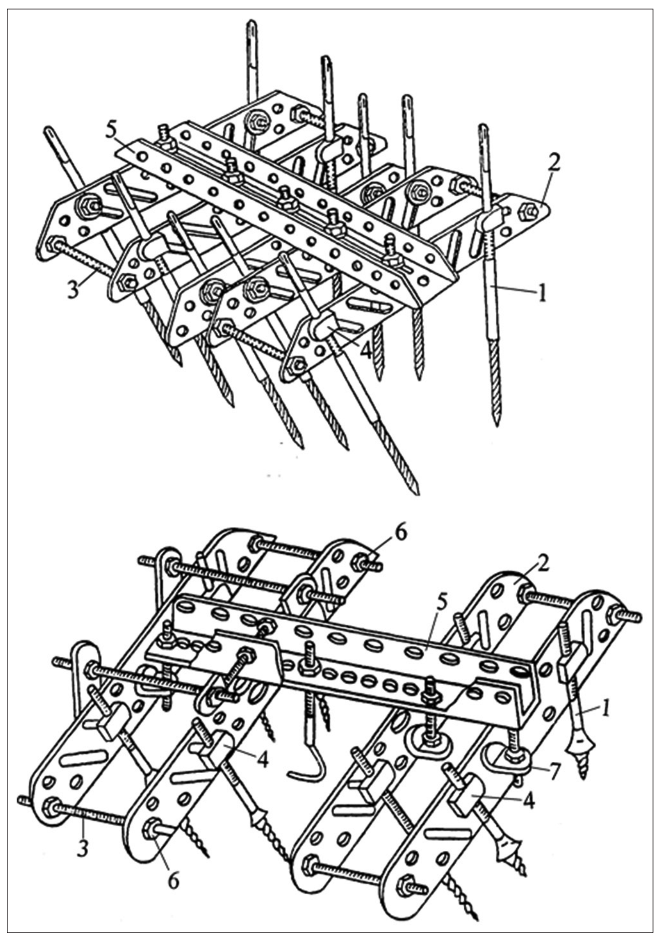

Figure 4: External fixation devices used in the treatment of injuries and diseases of the spine: 1 – rod-screw; 2 – plate; 3 – adjusting rod; 4 – bolt clamp; 5 –microchannel; 6 – nut; 7 – bracket

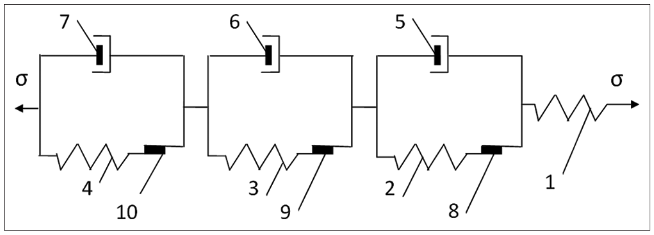

Figure 5: Elastic–viscoplastic body model

only regarding the results of the impact of mechanical devices in surgical treatment on the spine.

The next stage in the development of the above-mentioned direction should be designing an apparatus for external fixation of the spine, taking into account its physical and mechanical properties and providing adaptive effects on the vertebrae with regard to the current spine geometry and the actual state of soft tissues during correction.

Mathematical modeling and optimization of the process of spine deformation correction are possible for various designs of the correcting device, which will allow choosing the most suitable option. For specific situations in the treatment of scoliosis with the help of mechanical devices, the physical and mechanical properties of the spine and soft tissues should be taken into account at each stage of correction, and the design of the apparatus allows changing its control actions on the spine within sufficiently wide limits.

Mathematical modeling of the correction process will evaluate the effect of static indeterminacy of the construction, and to find the most appropriate options to reduce it, that is to remove its superfluous mechanical bonds with the spine. Considering the spine as a mechanical system with a high degree of mobility, it can be assumed that the device for its deformation correction should have the same mobility fixable at different details of the apparatus. In most cases, this fixation should be nominal due to the creating of an elastic effect in the given boundaries.

Mathematical description of the strain-deformed state of the apparatus and the spine, and the definition of empirical coefficients will later adequately describe and optimize the correction process. Mathematical modeling will also allow substantiating the optimal design solutions for the device. All this will ultimately lead to more effective application of external spine fixation devices.

CONCLUSIONS

Analysis of the methods of treatment of scoliotic deformation of the spine and the mechanical devices used for this allows drawing the following conclusions:

1. External deformations' correction is a promising and effective method of treatment of acquired and congenital kyphoscoliotic deformities of the spinal column. In the absence of bone intervertebral blocking, external mechanical impact on the vertebrae using an external fixation device allows completely eliminating all the components of deformation without resorting to mobilizing operations
2. Comparison of the effectiveness of devices with hypodermal fixation of vertebrae and external fixation apparatus shows the prospects for the development of scoliosis treatment techniques with the help of external fixation devices. Such devices allow carrying out a dosed controlled effect on the spine and have versatility. Their use in complex kyphoscoliotic deformations is also possible. The advantage of external fixation devices is also the removal of all parts of the device from the patient's body after treatment
3. The development of external fixation devices should be based on the modeling of the strain-deformed state of their parts and the spine. It is necessary to take into account the nature of the elastic–viscoplastic properties of the spine
4. To prevent possible injury during treatment, the control impact of the apparatus on the spine should be commensurate with the magnitude of the elastic, viscous, and plastic characteristics of the spine. The device must adaptively affect the spine, adjusting to its geometric parameters and physical and mechanical properties. To reduce the duration of treatment, it is necessary to exclude zero strain and strain close to zero
5. To exclude uncontrolled strains in the design of the external spine fixation apparatus and in vertebrae, the connection of the parts should develop in the direction of reducing the degree of static indeterminacy of the structure
6. The limiting factor in spine correction deformation should be the rate of plastic deformation.

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Conflicts of interest

There are no conflicts of interest.

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