BIOMECHANICAL ANALYSIS OF VARIANTS OF SPINOPELVIC FIXATION OF LONGITUDINAL SACRAL FRACTURES BY THE FINITE ELEMENT METHOD

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Objective. To analyze the strength of three types of spinopelvic fixation system configurations in longitudinal fracture of the sacrum by the finite element method.
Material and Methods. Biomechanical analysis was carried out by the finite element method. A three-dimensional model of a segment of the spinopelvic complex (SPC), including the pelvic bones, sacrum and L4 and L5 vertebrae, was created on the basis of the CT scan results of a healthy patient. Then, a longitudinal fracture of the sacrum was simulated on the developed model of the sacrum on the left side in zone 1 according to the Denis classification. Further, a comparative assessment of three variants of spinopelvic fixation systems with the help of biomechanical computer modeling was carried out: bilateral spinopelvic system L4—S2Alar, bilateral spinopelvic system L4—S2Alar with transverse connector installation, and bilateral spinopelvic system L4—S2Alar with L-shaped rod installation. The stability of fixation, as well as the amount of loads acting on the fixation elements and bone tissues were determined.
Results. As the rigidity of the structure increases by means of a transverse connector or an L-shaped rod, the load is redistributed between the screws located to the left and right of the fracture. The rigidity of the L4—S2Alar system with parallel, unconnected rods is much lower, which leads to a critical increase in loads on instrumentation and vertebrae.
Conclusion. Analysis of three variants of spinopelvic fixation of longitudinal fractures of the sacrum by finite element method revealed that bilateral spinopelvic system with pedicle screws installed in the L4 and L5 vertebrae and pelvic screws installed in the iliac bones through the lateral masses of S2, two on each side (L4—S2 Alar) and connected by two parallel rods (variant 1) is the least strong in comparison with the other variants. The strength of the fixation increases when the structure is supplemented with a transverse connector between the rods (variant 2). The L4—S2 Alar design with an L-shaped rod on the side of the longitudinal fracture of the sacrum (variant 3) proved to be the most strong.
Key Words: spinopelvic fixation, sacral fracture, pelvic fracture, spinopelvic dissociation, transpedicular fixation, biomechanical modeling.
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Longitudinal fractures account for 90 % of all sacral injuries caused by a loss of pelvic ring integrity [1]. Such injuries usually occur due to high-energy shock loads (falls from height, road accidents, etc.) and often result in vertical displacement of half of the pelvis [2].

The fundamental issue in sacral fracture surgery is to relieve instability and restore pelvic ring integrity. To accomplish this task, different types of surgical hardware are used [3], including various configurations of pedicle screws and rods. There is no single approach to choosing a spinopelvic fixation variant currently, which provokes discussions in the literature [4, 5]. The related question is about the mechanical reliability of the installed hardware and its configurations.

The objective is to analyze the strength of three types of spinopelvic fixation system configurations in longitudinal fractures of the sacrum using the finite element technique.

Material and Methods

Three variants of fixation system being used in real surgical treatment of a longitudinal fracture of the sacrum have been studied:

- bilateral spinopelvic system with pedicle screws installed into the L4 and L5 vertebrae and two pelvic screws installed into the iliac bones through the lateral masses of S2 on both sides (L4–S2Alar) connected by two parallel rods;
- bilateral spinopelvic system L4–S2Alar with additional installation of a transverse connector;
- bilateral spinopelvic system L4–S2Alar with installation of an L-shaped rod.

The analysis of the strength of each fixation variant was performed under biomechanical criteria of success assessment [6].

The staff of the Department of Computer Modeling in Biomedicine and Materials Science of the Saratov National Research State University named after N.G. Chernyshevsky performed biomechanical analysis by the finite element technique. A three-dimensional model of a segment of the spinopelvic complex (SPC), including the pelvic bones, sacrum, and L4 and L5 vertebrae, was created on the basis of the CT scan results of a patient without pathology of the musculoskeletal system. A longitudinal fracture of the sacrum was simulated on the developed model of the sacrum on the left side in zone 1 according to the Denis classification.

All three considered fixation variants imply the use of pedicle screws installed into the L4 and L5 vertebrae on both sides and pelvic screws installed through the lateral masses of the sacrum into the iliac bone (S2Alar), two on each side, and differ in the way the screws are connected to each other. In the first system variant (Fig. 1a), two parallel rods (not connected to each other) are installed into the screw heads. In the second system variant (Fig. 1b), two parallel rods are installed into the screw heads and connected to each other with a transverse connector. In the third system variant (Fig. 1c), an L-shaped rod is installed, which, with its vertical part, connects the L4 and L5 screws and the pelvic screws on the side of the fracture. As for its horizontal part, it passes along the posterior surface of the sacrum to the opposite side from the fracture and is installed into the lower pelvic screw on the opposite side from the fracture. The L4 and L5 screws and the upper pelvic screw on the opposite side from the fracture are connected with a second rod.

Then, a comparative assessment of the considered fixation variants was performed using biomechanical computer modeling with the finite element technique. The fixation stability, as well as the amount of loads acting on the fixation elements and bone tissues were determined. The problem of the statics of a deformable solid body had been solved with the aim of determination of the stress-strain state of the "SPC segment – implants" system under the action of external surface loads (forces and moments). The surfaces of the acetabulum were rigidly fixed to prevent their displacement.

During modeling, the effect of six types of external loads was studied [1, 6, 7], the descriptions of which are given in Table 1 and Fig 2. The studied loads simulate the effects of human body weight as well as muscle forces during turns and rotations of the body. It should be noted that this biomechanical model simulates the state of bone tissues and their interaction with implants immediately after surgery. It does not presuppose the study of their long-term interaction, including the remodeling of bone tissue and its adaptation to external loads and implantable systems.

In biomechanical modeling, all materials were considered to be linearly elastic and isotropic [5, 6]. The data concerning the mechanical characteristics of bone tissues, intervertebral discs, and implants, as well as their junction coupling, were adopted from the literature [5].

When evaluating the stability and strength of each of the considered fixation variants, the strength parameters of cortical (tensile strength up to 161 MPa) and trabecular (tensile strength up to 15 MPa) bone tissues and implants (Ti6Al4V ELI Titanium Alloy with tensile strength up to 1,300 MPa) were considered [8–12].

The fixation stability was evaluated by the displacements of the fixed SPC segment under external loads. As for strength, it was estimated by means of internal forces (equivalent stresses) arising in the vertebrae, bone fragments of the sacrum and implants under the studied loads.

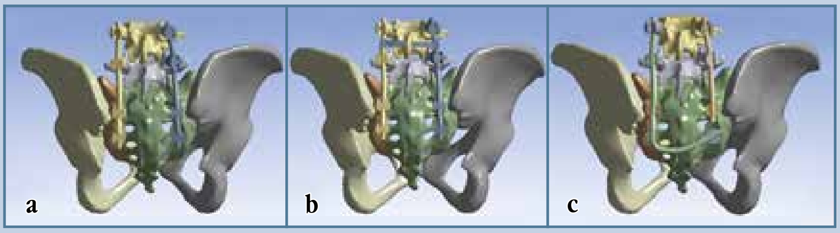

Fig. 1
Three-dimensional models of variants of the arrangement of the spinopelvic fixator in case of a longitudinal fracture of the sacrum: **a** – bilateral spinopelvic system L4–S2Alar; **b** – bilateral spinopelvic system L4–S2Alar with the installation of a transverse connector; **c** – bilateral spinopelvic system L4–S2Alar with installation of an L-shaped rod

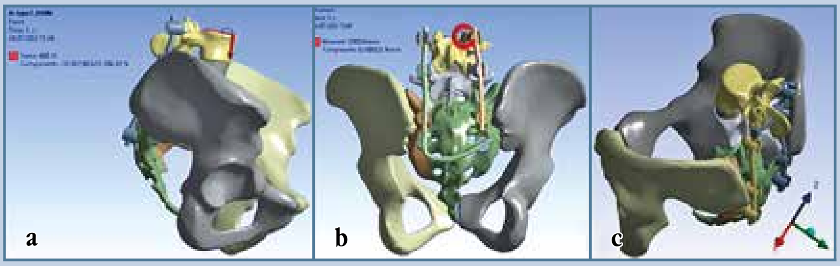

Fig. 2
The effect of external loads on the "SPC segment - implants": **a** – load in the standing position (vertically to the upper endplate of the L4 vertebra in the direction of the L5 vertebra); **b** – load moment of 10 N*m (tilt to the left); **c** – the location of the model relative to the coordinate system

Table 1

Types and magnitudes of loads under study

Standing position	Tilt forward	Tilt backward	Tilt to the right	Tilt to the left	Rotation around an axis
Force of 600 N	Force of 600 N and moment of 10 N*m around the x-axis	Force of 600 N and moment of -10 N*m around the x-axis	Force of 600 N and moment of -10 N*m around the y-axis	Force of 600 N and moment of 10 N*m around the y-axis	Force of 600 N and moment of 10 N*m around the z-axis

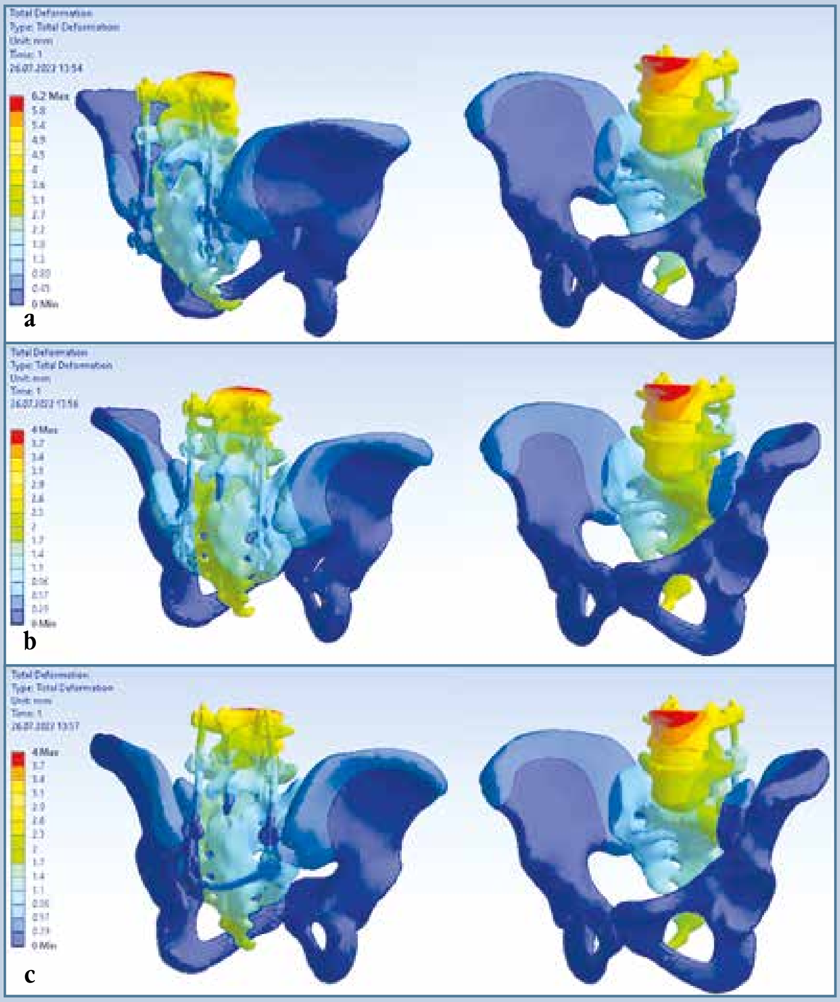

Fig. 3
The field of complete displacements in the standing position: a – variant 1; b – variant 2; c – variant 3

Results and Discussion

Fig. 3 and 4 illustrate typical fields of calculated complete displacements in modules and equivalent stresses. Complete displacements were calculated for each point as the distance passed from the initial location to the final position reached during the deformation.

The use of a transverse connector between the rods (variant 2) and an L-shaped rod (variant 3), significantly stabilizes fixation (the first biomechanical criterion of success [6]), and reduces displacement in the fixed segment (Table 2). Similar displacement values under similar loads were found in the study of A.V. Dol et al. [5]. According to this paper, the greatest displacements were achieved when tilting forward.

It should be noted that in variants 2 and 3, in comparison with the first one, the equivalent stresses on the lower right screw grow considerably and the stresses on the upper left pedicle screw reduce, as shown in Figs. 5–7. So we can conclude that with an increase in the rigidity of the system by means of a transverse connector or/and an L-shaped rod, the load is redistributed between the screws placed to the left and right of the fracture. In other words, the left bone fragment of the sacrum is also maintained by the right part of the fixing system in the second and third fixation variants. Meanwhile, the rigidity of the system of the first fixation variant is not enough to hold the fragments, which results in a critical enhanced load on the surgical hardware (Table 3).

In this case, the most loaded element of the fixation system is the left rod, which is also illustrated in Figs. 5–7. These conclusions are applicable to all the loads under consideration.

The analysis of equivalent stresses in implants was performed to identify their highest values and compare them with the tensile strength (safety factor is equal to 3) [13]. The implants are made of titanium alloy, whose tensile strength is 1,300 MPa. Therefore, the permissible stress is no more than 433 MPa. The analysis of the equivalent stress values from Table 3 indicates that variants 2 and 3 meet the strength criterion (the second biomechanical criterion of success [6]).

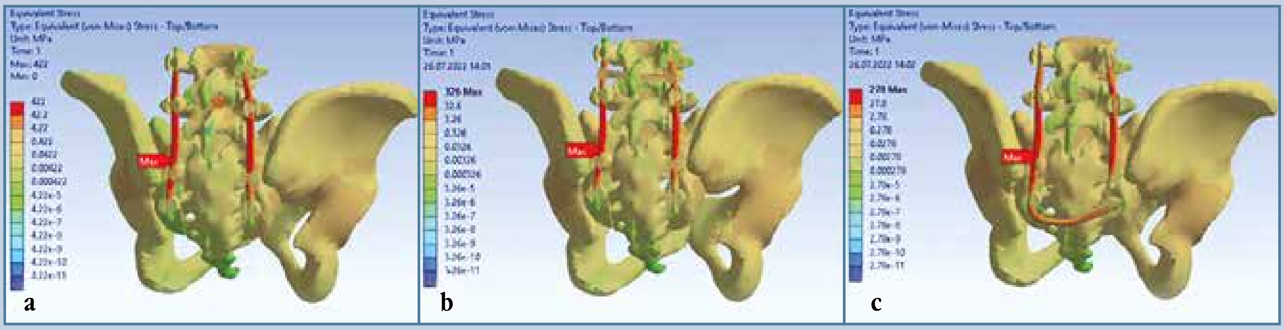

Fig. 4
The field of equivalent stresses in the standing position: **a** – variant 1; **b** – variant 2; **c** – variant 3

Table 2
Maximum complete displacements in the model for three fixation variants, mm

Variants	Standing position	Tilt forward	Tilt backward	Tilt to the right	Tilt to the left	Rotation around the vertical axis
1	6.2	8.1	4.2	6.8	6.1	6.2
2	4.0	5.2	2.7	4.4	3.8	4.0
3	4.0	5.4	2.5	4.3	3.9	4.4

Meanwhile, variant 1 does not meet this criterion for most of the loads studied (Table 3).

For all fixation variants, there are no stress in the bone tissues of the sacrum that can destroy them (Tables 4, 5). It should be noted that fixation variants 2 and 3 promoted the achievement of lower equivalent stresses in implants and bone tissues with all the studied loading variants.

It can be concluded that variants 2 and 3 are optimal in terms of biomechanics and the application of biomechanical parameters for evaluating fixation success. Concurrently, the third variant is advantageous since its execution identified lower levels of equivalent stress than variants 1 and 2.

Conclusion

Analysis of three variants of spinopelvic fixation of longitudinal fractures of the sacrum by finite element technique showed that the bilateral spinopelvic system with pedicle screws installed in the L4 and L5 vertebrae and pelvic screws installed in the iliac bones through the lateral masses of S2, two on each side (L4–S2 Alar), and connected by two parallel rods (variant 1) is the weakest in comparison with the other variants. The fixation strength is enhanced when the system is supplemented with a transverse connector between the rods (variant 2). The L4–S2 Alar system with an L-shaped rod on the side of the longitudinal fracture of the sacrum (variant 3) proved to be the strongest.

The study had no sponsors.
The authors declare that they have no conflict of interest.
The study was approved by the local ethical committees of the institutions.
All authors contributed significantly to the research and preparation of the article, read and approved the final version before publication.

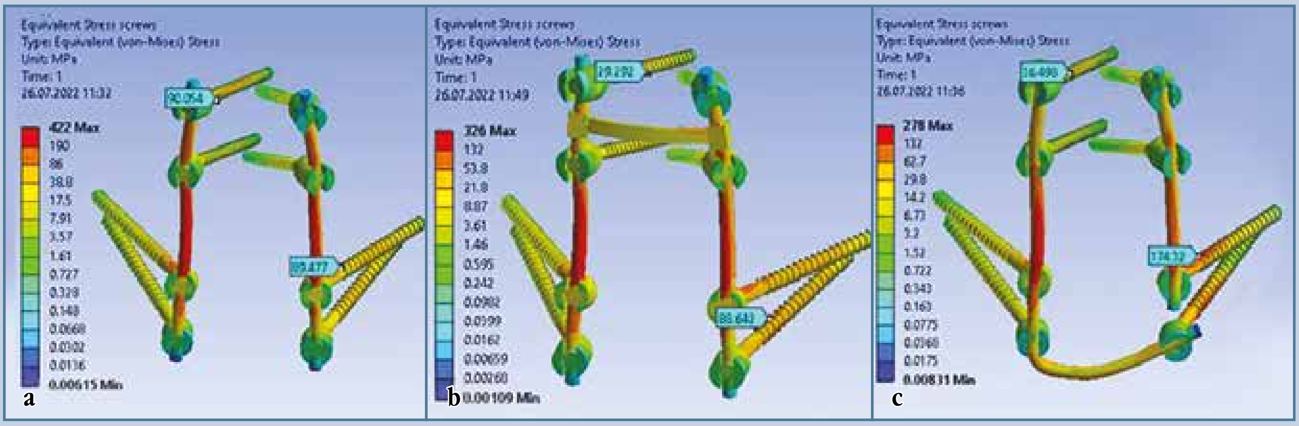

Fig. 5
The field of equivalent stresses on implants in standing position: **a** – variant 1; **b** – variant 2; **c** – variant 3

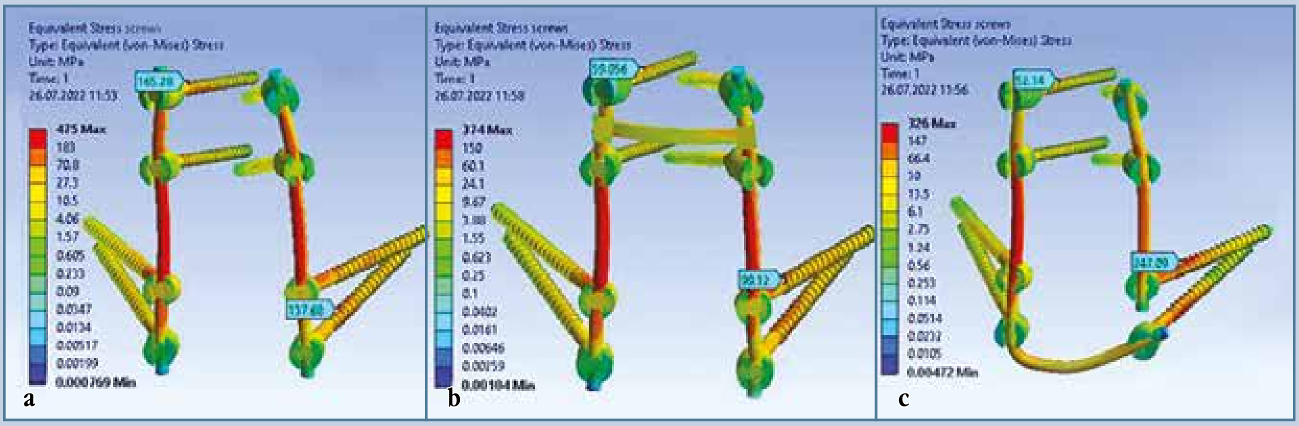

Fig. 6
The field of equivalent stresses on implants when tilted forward: **a** – variant 1; **b** – variant 2; **c** – variant 3

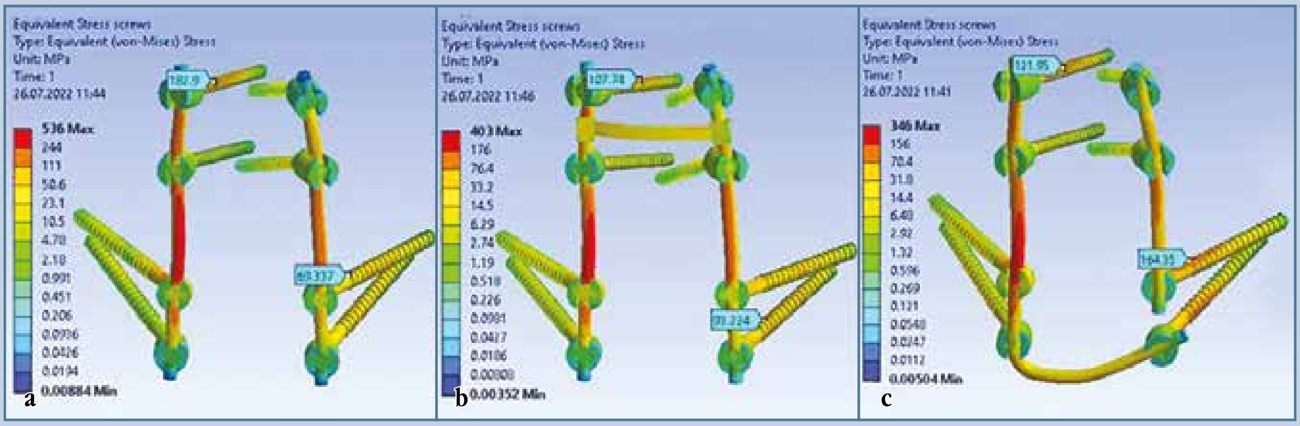

Fig. 7
The field of equivalent stresses on implants when tilted to the left: **a** – variant 1; **b** – variant 2; **c** – variant 3

Table 3

Maximum equivalent stresses in implants for three fixation variants, MPa

Variants	Standing position	Tilt forward	Tilt backward	Tilt to the right	Tilt to the left	Rotation around the vertical axis
1	422	475	367	483	537	443
2	326	374	275	343	404	290
3	326	293	160	235	346	281

Table 4

Maximum equivalent stresses in trabecular bone of sacral fragments for three fixation variants, MPa

Variants	Standing position	Tilt forward	Tilt backward	Tilt to the right	Tilt to the left	Rotation around the vertical axis
1	11	12	11	11	12	8
2	11	11	10	12	9	7
3	10	10	7	11	14	8

Table 5

Maximum equivalent stresses in the cortical bone of sacral fragments for three fixation variants, MPa

Variants	Standing position	Tilt forward	Tilt backward	Tilt to the right	Tilt to the left	Rotation around the vertical axis
1	82	104	58	81	82	77
2	82	105	58	81	83	79
3	71	96	45	70	72	70

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