BIOMECHANICAL MODELING IN SURGICAL TREATMENT OF A PATIENT WITH TRUE LUMBAR SPONDYLOLISTHESIS

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Objective. To assess the results of clinical approbation of individual finite-element biomechanical model of a patient's spino-pelvic complex with subsequent modeling of the best option of surgical treatment.

Material and Methods. A biomechanical modeling of changes in the sagittal profile of a patient with degenerative disease of the lumbosacral spine, bilateral spondylolysis, and unstable grade 2 spondylolisthesis of the L4 vertebra was performed. The developed biomechanical model made it possible to assess the characteristics of the stress-strain state of the spinal motion segments aroused due to development of the disease. Within the built biomechanical model of the patient's spino-pelvic complex, a corrective operation was further modeled that assumed a preservation of harmonious profile of sagittal spino-pelvic relationships. Post-correction characteristics of the stress-strain state of spinal motion segments were studied and compared with preoperative parameters of the biomechanical model.

Results. Using methods of biomechanics and computer modeling allowed to calculate the stress-strain state of the lumbosacral spine under static load for two options of fixation and intervertebral cage implantation at the L4–L5 level: four transpedicular screws (L4–L5 vertebrae) and six transpedicular screws (L3–L4–L5 vertebrae). The simulation results showed that neither metal implants, nor elements of the lumbosacral spine experienced critical stresses and deformations that could lead to the destruction and instability of the implant.

Conclusion. The developed individual biomechanical finite-element solid model of the spine and pelvis allowed for biomechanical justification of prerequisites for the formation and further progression of degenerative changes in spinal motion segments associated with violations of the sagittal profile due to grade 2 spondylolisthesis of the L4 vertebra. The model built on the results of radiological examination biomechanically substantiated the best option of corrective spine surgery allowing to minimize stresses and deformations by choosing reasonable magnitude of correction of sagittal spino-pelvic parameters and configuration of transpedicular system.

Key Words: spondylolisthesis, sagittal balance, biomechanical modeling.

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True spondylolisthesis is the displacement of one of the lumbar vertebrae in the sagittal plane over the inferior one due to a bilateral defect in the inter-articular part of its arch. The proportion of patients with true spondylolisthesis amounts to 7–10 % of all patients complaining of persistent pain in the lumbar region [1]. According to modern concepts, the effectiveness of surgical treatment of such patients is defined not only by elimination of the compression of neural structures, but also by the required correction with the achievement of harmonious spino-pelvic relationships [2–4].

At the same time, the existing tactical approaches of orthopedic traumatologists and neurosurgeons (vertebrologists) to treatment of this category of patients are still debated to date, which results in variability in the choice of surgical technologies depending on the degree of displacement of the vertebra, segmental stability, the estimated volume of bone structure resection, and the magnitude of the required correction [4–7]. However, there are almost no studies devoted to substantiating the choice of one or another variant of surgical treatment of the specialized patients, as well as to the analysis of the achieved results from the biomechanical point of view.

This paper presents an applied biomechanical study aimed at substantiating the prerequisites for the development and progression of degenerative changes in the spinal motion segments in a patient with grade 2 spondylolisthesis of L4 vertebra before and after surgical treatment, as well as the experience of using patient-specific biomechanical modeling of corrective spinal surgery.

The purpose of the study is to assess the results of clinical approbation of patient-specific finite-element biomechanical model of the patient's spino-pelvic complex with subsequent modeling of the best option of surgical treatment.

Material and Methods

At the first stage of the study, we conducted biomechanical modeling of changes in the sagittal profile of a patient with degenerative disease of the lumbosacral spine, bilateral spondylolysis, unstable grade 2 spondylolisthesis of the L4 vertebra. The developed biomechanical model made it possible to assess the characteristics of the stress-strain state existing (due to the nature of the disease) in the spinal motion segments of the thoracic and lumbosacral spine. ANSYS, a finite element analysis system, was used to calculate and analyze the stresses arising in the vertebrae, intervertebral discs and implants upon application of a stationary load in different directions. Two variants of transpedicular fixation were considered: four transpedicular screws (L4–L5 vertebrae) and six transpedicular screws (L3–L4–L5 vertebrae).

At the second stage, the constructed patient-specific biomechanical model of the spine was used to simulate corrective surgery. The sagittal spino-pelvic parameters were corrected until a harmonious profile was achieved. We have subsequently re-examined the characteristics of the stress-strain state of the spinal motion segments of the thoracic and lumbar spine and calculated the magnitude and localization of stresses arising in the vertebrae, intervertebral discs and facet joint in case of standard load. We compared the obtained results to similar parameters at the first stage of the study.

Initial data. The results of CT scans of all parts of the spine and pelvis (from the level of C7 vertebra to the proximal parts of the femurs), as well as full body X-ray performed with the patient standing in two projections.

Creating a 3D-model of the spino-pelvic complex. At the initial stage, a three-dimensional computer model of the spine was built on the basis of CT data. Then, three-dimensional models of fixation systems (cage at the level of L4–L5) and transpedicular screws (4 screws for fixing L4–L5 vertebrae and 6 screws for fixing L3–L4–L5 vertebrae) were created. Then the models of the fixation systems and the spine were combined to produce the models shown in Fig. 1.

Finite-element modeling. The ANSYS 18 finite-element analysis system was used for numerical simulation, in which the stresses in the vertebrae, intervertebral discs and fixation systems were calculated and analyzed. The spinal loading was simulated by bending and twisting moments in three anatomical planes, which were applied to the upper endplate of the L1 vertebra (Fig. 2, red arrows) [8, 9]. The magnitude of the moments was 7.5 N • m [10].

Thus, we calculated two types of operations with four loading options. Mechanical characteristics of the elements of the spine and the implants were taken from literary sources [8, 9, 11]. The sacrum was firmly secured in three directions.

Results and Discussion

The results of finite-element modeling are presented for two variants of spinal fixation at the levels L4–L5 and L3–L4–L5 with the installation of a PEEK-ceramic cage at the L4–L5 level.

Fig. 3 shows the biomechanical fields of movement for the lumbosacral spinal segments in the case of loading with a twisting moment. The displacement field is typical for other investigated loading options.

The largest values of displacements for both types of fixation and four applied loading moments are shown in Table 1.

With all the load cases considered, the four-screw design turned out to be more rigid and stable than the six-screw design. This conclusion is confirmed by the third column in Table 1; the fourth column shows the differences in fixation with four and six screws. Since the 4-screw fixation does not immobilize L3 vertebra, its range of movements is wider in case of 4-screw fixation.

The analysis of the deformations in the discs (Table 2) shows that the fixation option with four screws is preferable from the biomechanical point of view. In fact, the deformations of the L5–S1, L2–L3 and L1–L2 discs with 4-screw fixation are not larger than those of the same discs when the metal structure is installed using six pedicle screws. And only the L3–L4 disc turns out to be more deformed in the case of 4-screw fixation, since the 6-screw system provides better fixation to it.

Table 3 shows the highest values of effective stresses arising in the lumbar vertebrae for both models under review.

In the case of the 6-screw configuration of the transpedicular fixators, the stress in L1 and L2 vertebrae turned out to be the same as for the 4-screw configuration. The 6-screw configuration resulted in higher stress in the L3 vertebra than the 4-screw configuration of the fixation system. For L4 and L5 vertebrae, the stress in case of the 4-screw configuration is higher than with the 6-screw configuration, but the orders of magnitude were the same.

Therefore, it can be concluded that from the biomechanical point of view the transpedicular fixation at a single level (with the 4-screw system) is preferable to fixation at two levels, since it provides higher stability and does not load intervertebral discs above and below the fixed segment.

Patient N., 19 years old, who suffered from the degenerative disease of the lumbosacral spine, bilateral spondylolysis, unstable grade 2 L4 spondylolisthesis and pain vertebrogenic and muscular tonic syndrome underwent L4 laminectomy, L4–L5 discectomy, posterior internal correction (reduction) and fixation of the spine with transpedicular system at the level of L4–L5, posterior interbody spinal fusion with a cage, the L4–L5 posterolateral fusion with autografts (Fig. 4) in accordance with the preoperative planning and the performed biomechanical modeling.

Conducting the surgery based on the data of the performed biomechanical modeling and planning made it possible to achieve the calculated harmonious values of the sagittal spino-pelvic relationships (Table 4).

Conclusion

From the biomechanical point of view, fixation with four transpedicular screws is preferable to fixation with six screws, since it is more stable and is characterized by lower stresses and deformations in the vertebrae and intervertebral discs. Moreover, this variant of the surgery does not require the fixation

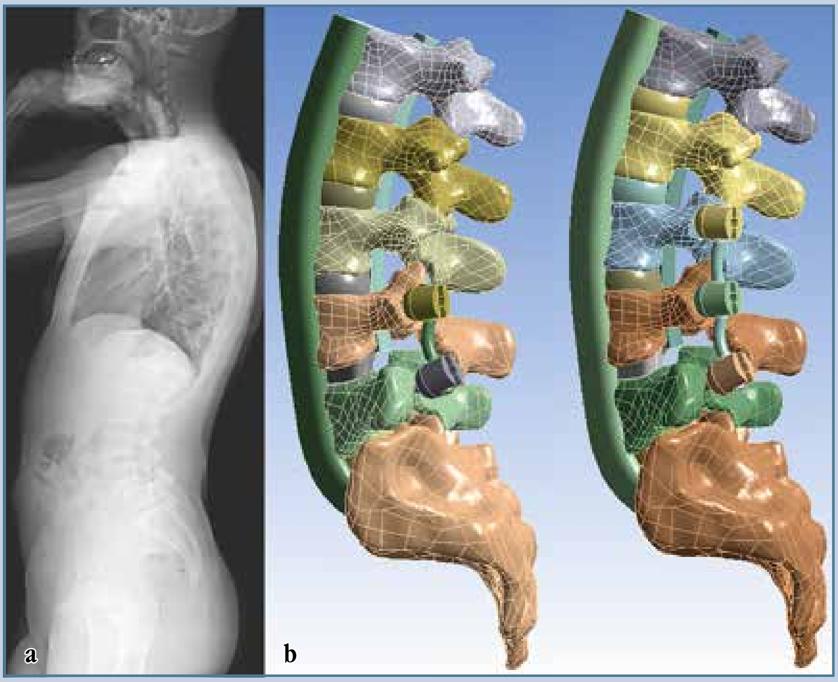


Fig. 1
X-ray of the spine (sagittal projection) of a patient with unstable grade 2 spondylolisthesis of L4 vertebra **(a)** and models of the lumbosacral spine with established pedicle fixation systems: 4 screws on the left, 6 screws on the right **(b)**

of the L3–L4 spinal motion segment that is not subject to degenerative changes, which would have entailed a cascade of degenerative changes in the corresponding intervertebral disc. The correction achieved with the use of this arrangement of the transpedicular system in combination with anterior fusion is sufficient not only for the reduction of L4 vertebra, but also for balanced spino-pelvic relationships.

Achievement of the harmonious sagittal profile (correction of the deformity) in combination with optimal fixation of the spine from the biological and biomechanical points of view ensured that the spino-pelvic complex is in a state in which stresses and deformations are minimized in the structures of the spinal motion segments, in the pedicle screws, rods and interbody cage.

Therefore, patient-specific biomechanical modeling of available options for correction and fixation of the spine has demonstrated its effectiveness in clinical practice for simulating the biomechanical parameters of the functioning of spinal segments in the postoperative period.

The study did not have sponsorship. The authors declare no conflict of interest.

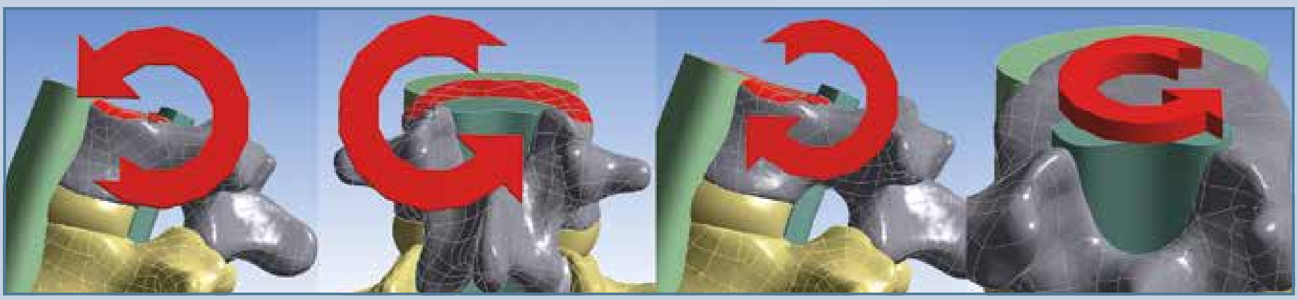


Fig. 2
Applied twisting and bending moments

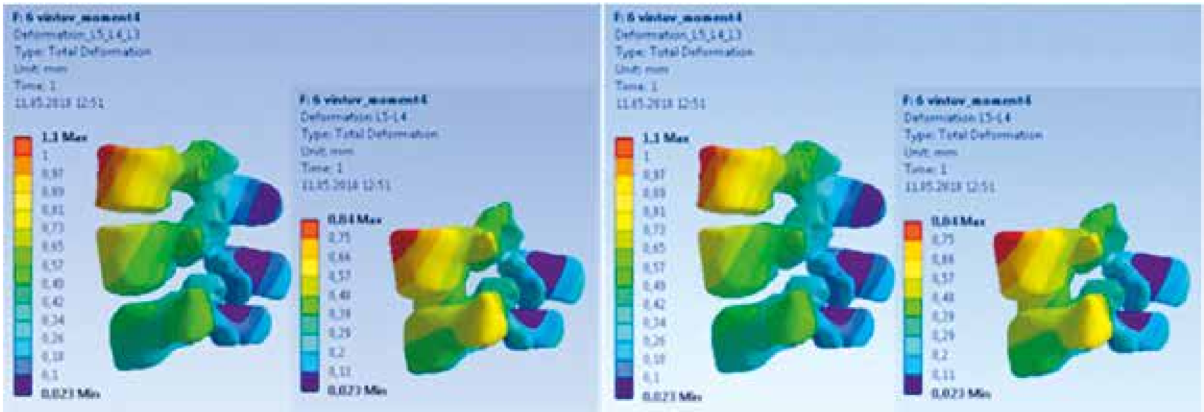


Fig. 3
Biomechanical movements for two models (twisting moment): fixing with four (left) and six (right) screws

Table 1
Movement in the elements of the lumbosacral spine, mm

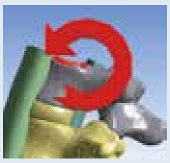
Loading moment	Type of fixation	L4–L5	L3–L4–L5
	4 screws	1.00	2.00
	6 screws	1.30	2.00
	4 screws	0.75	2.30
	6 screws	0.87	1.20
	4 screws	1.00	2.00
	6 screws	1.30	1.80
	4 screws	0.70	1.90
	6 screws	0.80	1.10

Table 2

Deformations in the intervertebral discs, mm

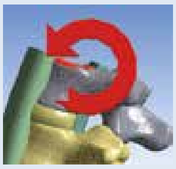
Loading moment	Type of fixation	L5–S1	L3–L4	L2–L3	L1–L2
	4 screws	0.08	0.09	0.08	0.10
	6 screws	0.12	0.05	0.09	0.10
	4 screws	0.23	0.20	0.16	0.22
	6 screws	0.30	0.01	0.19	0.39
	4 screws	0.08	0.09	0.08	0.10
	6 screws	0.12	0.05	0.09	0.10
	4 screws	0.18	0.13	0.08	0.09
	6 screws	0.25	0.01	0.08	0.11

Table 3

Tension in the vertebrae, MPa

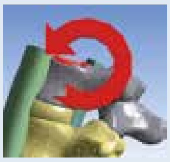
Loading moment	Type of fixation	L1	L2	L3	L4	L5
	4 screws	4	4	4	46	49
	6 screws	4	4	57	43	58
	4 screws	6	7	5	38	76
	6 screws	6	7	45	24	35
	4 screws	4	4	4	46	49
	6 screws	4	4	57	43	59
	4 screws	4	4	5	45	44
	6 screws	4	4	50	33	27

Table 4

Characteristics of the patient's sagittal spino-pelvic parameters, deg.

Parameters	Prior to the surgery	After the surgery	Calculated
Pelvic Incidence	47	47	47
Sacral Slope	27	36	39 ± 6
Pelvic Tilt	20	15	9 ± 6
L1—S1	51	61	63 ± 11
L4—S1	18	35	42 ± 7

Fig. 4
X-ray of the spine of patient N., 19 years old, with unstable grade 2 spondylolisthesis of L4 vertebra after corrective surgery (sagittal projection)

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