Original article

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Biomechanical evaluation of the pedicle screw insertion depth and role of cross-link in thoracolumbar junction fracture surgery: a finite element study under compressive loads

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Introduction. The thoracolumbar junction is one of the most frequently damaged parts of the human spine when exposed to a traumatic factor. Corpectomy in combination with posterior decompression and restoration of the spinal support function is often performed using an interbody implant and posterior transpedicular stabilization to achieve adequate decompression and stabilization in severe traumatic injuries of this level.

The surgery of this type is characterized by significant instability of the operated segment and determines increased requirements for the rigidity and reliability of posterior fixation. We have modeled the situation of a two-level corpectomy with subsequent replacement of bodies with a mesh implant and posterior transpedicular stabilization with 8 screws.

Objective. To study the stress-strain state of the thoracolumbar spine model after resection of the Th12-L1 vertebrae with different variants of transpedicular fixation under the influence of a compressive load.

Materials and methods. A mathematical finite element model of the human thoracolumbar spine has been developed, the components of which are the Th9 – Th11 and L2-L5 vertebrae (vertebrae Th12-L1 are removed), as well as elements of hardware - interbody support and transpedicular system. Four variants of transpedicular fixation were modeled: using short screws and long screws passing through the cortical layer of anterior wall of vertebral body, as well as two cross links and without them. The stress-strain state of the models was studied under the influence of a vertical compressive distributed load, which was applied to the body of the Th9 vertebra and its articular surfaces. The load value was 350 N, corresponding to the weight of the upper body.

Results. d It was found that transpedicular fixation of the thoracolumbar vertebrae with the use of long screws reduces the level of tension in the bone elements of the models. In the area of screw entry into the pedicle of the T10, T11, L2 and L3 vertebral arch, the load when using short screws was 3.1, 1.7, 3.9 and 12.1 MPa, respectively, when using bicortically installed screws - 2.9, 1.8, 3.8 and 10.6 MPa. The addition of two cross-links also reduces the maximum load values in critical areas of the model to a certain extent. In case of short screws combination and two cross-links, the load in these areas was 2.8, 1.7, 3.6 and 11.5 MPa, when using bicortical screws and cross-links - 2.8, 1.6, 3.3 and 9.3 MPa. The study of the stress-strain state of other parts of the model revealed a similar trend.

Conclusions. The use of long screws with fixation in the cortical bone of anterior part of the vertebral bodies reduces the level of tension in the bone elements of the models. The use of cross links provides greater rigidity to the transpedicular system, that also reduces the tension in the bone tissue.

Key words: *finite element model; thoracolumbar junction; corpectomy; transpedicular bicortical screws fixation; cross-link*

Introduction

The area of thoracolumbar junction is one of the most frequently compressed parts of the human spine when exposed to a traumatic factor. According to epidemiological studies, more than half of cases of traumatic injuries of the thoracolumbar regions are in the thoracolumbar junction zone [1,2]. The specificity of the biomechanics of this zone, namely the transition of a rather rigid and sedentary thoracic region to a much more mobile lumbar region, results in a wide range of possible pathomorphological variants of traumatic changes and increased requirements for stabilizing systems during surgery[3,4].

Choosing a surgical correction method for thoracolumbar junction injury remains a challenge due to the large number of goals that the surgeon must achieve. The most important criteria: adequate decompression of the structures of the spinal canal; reliable stabilization, which ensures the preservation of the restored sagittal profile with the involvement of a minimum number of spinal motion segments; the least traumatic surgical approach.

In most clinical cases, when posterior decompression and stabilization are performed, the question only arises about the length of fixation and the possibility and expediency of introducing screws into the compressed vertebra [5]. In case of significant damage to the body or vertebral bodies that have lost their support function, an anteroposterior or posterior corpectomy is performed. Such intervention is characterized by a particularly pronounced instability of the injured and operated spinal motion segment and requires reliable posterior stabilization.

According to the literature, the rigidity of transpedicular fixation, other things being equal, is determined by the number of fixed vertebrae, the projection of the installation of transpedicular screws, the depth of immersion of the screws into the vertebral body, and the presence of cross links [6-9]. Since an increase in the fixation length is neither biomechanically nor economically feasible, and the projection optimal from a biomechanical point of view insertion of a screw is not always achievable through anatomical features of the patients, the possibility of bicortical screw placement and additional strengthening of the system with cross links can be considered as the most universal methods of increasing the rigidity and reliability of spinal fusion. Despite the sufficient number of publications devoted to the correction of traumatic injuries of the thoracolumbar junction, we have not found works that demonstrate the effectiveness and practicability of using these methods in spinal fusion, which accompanies corporectomy as a result of traumatic exposure, that is, when both the anterior and posterior support complex are completely absent.

When developing the study design, we were guided by the fact that the absolute condition for establishing interbody support during resection of the body of an injured vertebra is complete intactness of endplates of vertebrae adjacent to the damaged one. Taking into account the above biomechanical features, the thoracolumbar junction is often characterized by a situation when, with significant damage to the body of one vertebra, which requires resection, traumatic changes of varying severity are observed in the adjacent vertebra. This necessitates a larger intervention. This situation was the object of our biomechanical research.

Objective: to study the stress-strain state of the model of the lumbar spine after resection of the Th12-L1 vertebrae under different variants of transpedicular fixation under the influence of compressive load.

Materials and methods

Study design: computer modeling.

In the laboratory of biomechanics of the Institute of Spine and Joints Pathology named after prof. M. I. Sytenko, Ukraine a mathematical finite-element model of the thoracolumbar human spine has been developed, the components of which are the Th9 – Th11, L2 – L5 vertebrae (vertebrae Th12-L1 are removed), as well as elements of hardware - interbody support and transpedicular system ***(Fig. 1 A)***.

4 variants of transpedicular fixation were modeled: using short fixing screws ***(Fig. 1B, 1D)*** and long screws that pass through the cortical layer of the anterior surface of the vertebral body ***(Fig. 1C, 1E)***, as well as two cross links ***(Fig. 1D, 1E)***.) and without them ***(Fig. 1B, 1C).***

In modeling, the material was considered homogeneous and isotropic. A 10-node tetrahedron with a quadratic approximation is chosen as a finite element. Data on the mechanical properties of biological tissues (cortical and cancellous bone, intervertebral discs) for mathematical modeling are taken from the literature [10–12]. The material of elements of endoprosthesis is titanium. The mechanical characteristics of artificial materials used in the modeling are taken from the publication Mitsuo Niinomi [13]. Indicators such as E - modulus of elasticity (Young's modulus), v - Poisson ratio were used for analysis ***(Table 1)***.

The stress-strain state of the models was investigated under the influence of a vertical compressive distributed load, which was applied to the body of the Th9 vertebra and its articular surfaces. The load value was 350 N, corresponding to the weight of the upper body [14]. The model was rigidly fixed along the distal surface of the L5 disc. The load diagram of models (indicated by arrows) is shown in ***Fig. 2***. In order to effectively study changes in the stress-strain state of the models depending on the method of transpedicular fixation the following control points were selected for recording the stress value (see ***Fig.2***): vertebral body Th9 (1), vertebral body Th10 (2), vertebral body Th11 (3), vertebral body L2 (4), vertebral body L3 (5), vertebral body L4 (6), vertebral body L5 (7), inferior endplate of the vertebral body Th11 (8), superior endplate of the vertebral body L2 (9), the entry point of the transpedicular screw into the vertebral arch Th10 (10), the entry point into the vertebral arch Th11 (11), the entry point into the vertebral arch L2 (12), the entry point into the vertebral arch L3 (13), the screw in the vertebral body Th10 (14), the screw in the vertebral body Th11 (15), the screw in the vertebral body L2 (16), the screw in the vertebral body L3 (17), cross links between the Th10 and Th11 vertebrae (18), cross links between the L2 and L3 vertebrae (19), body replacement support (20).

The study of the stress-strain state of the models was carried out using the finite element method. Von

Table 1. Mechanical characteristics of materials used in modeling [10–13]

Material	E, MPa	v
Cortical bone	10 000	0,3
Cancellous bone	450	0,2
Articular cartilage	10,5	0,49
Intervertebral discs	4,2	0,45
Titanium VT-16	110 000	0,3

Mises stress was used as a criterion for assessing the stress state of the models [15]. Modeling was performed using the SolidWorks computer-aided design system. Calculations of the stress-strain state of the models were performed using the CosmosM software package [16].

Statistical processing was not performed due to the specifics of the data.

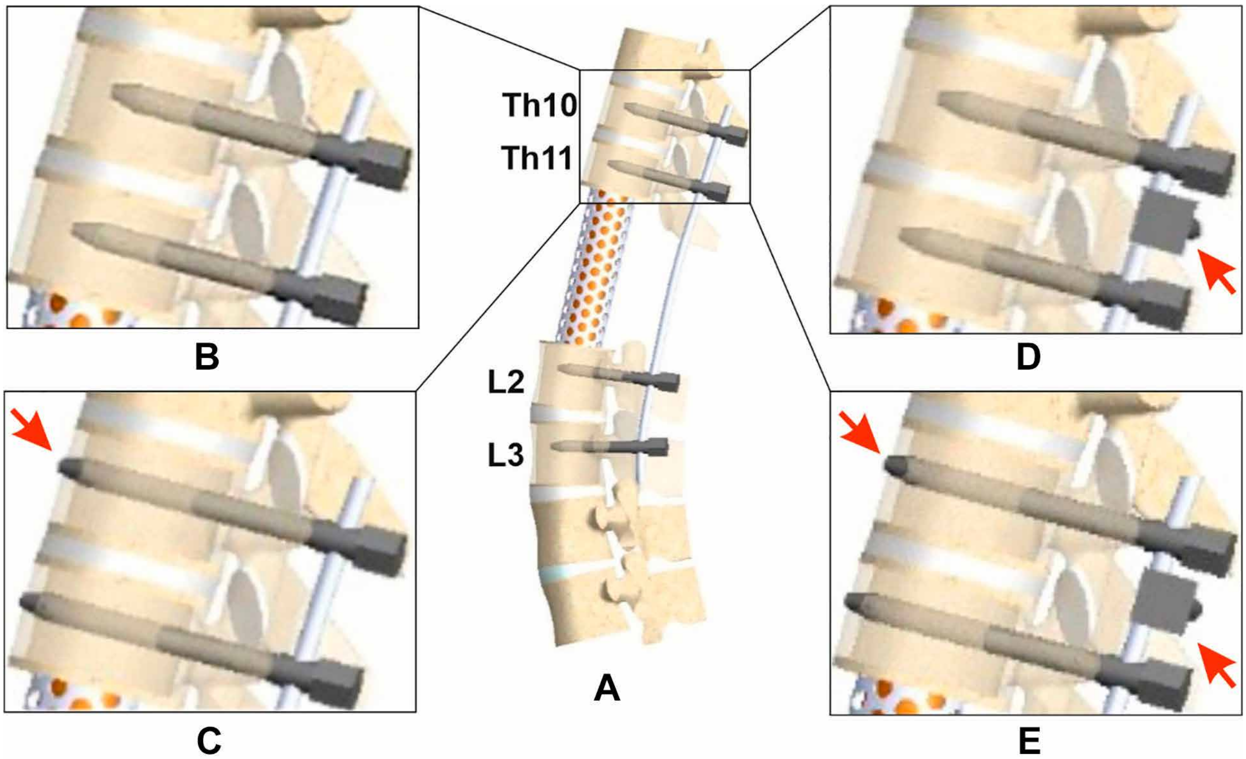

Fig. 1. Mathematical finite-element model of the thoracolumbar spine: A - general view. Various variants of transpedicular fixation: B - short screws without cross links; C - long screws without cross links; D - short screws with cross links; E - long screws with cross links. The arrows on C, D, and E indicate differences from B. The method of fixation the L2 and L3 vertebrae is identical to that for the Th10 and Th11 vertebrae for each model (not shown)

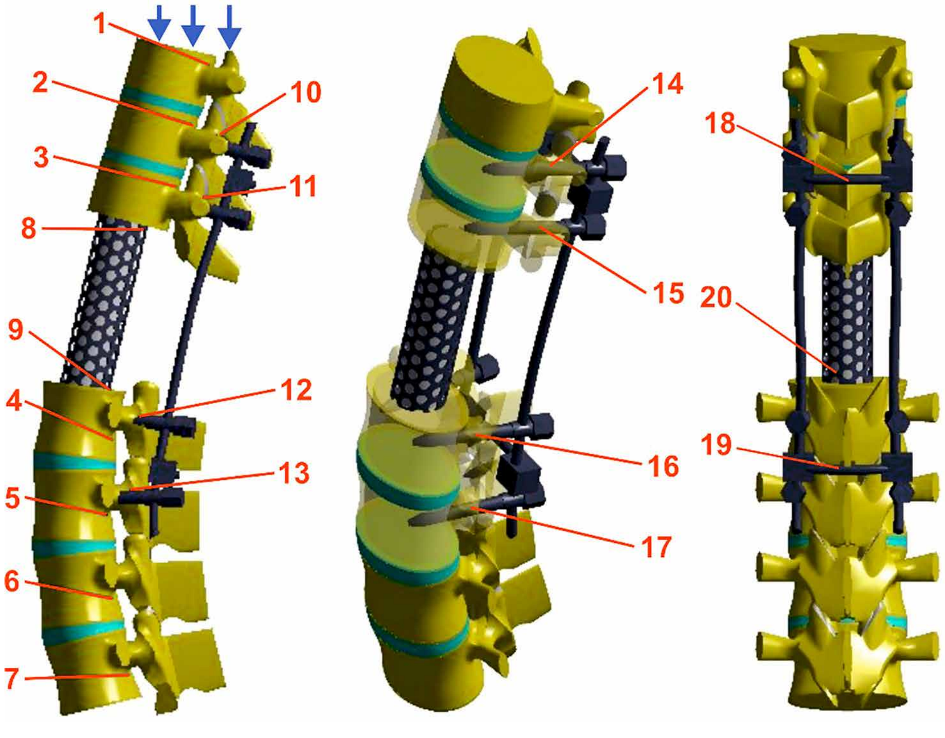

Fig. 2. The diagram of the load of models and the arrangement of control points. Explanation in the text

Results and discussion

The stress distribution in the study of stress-strain state of thoracolumbar spine model after resection of the Th12 – L1 vertebrae under the influence of compressive load and modeling of transpedicular fixation with short screws without cross links are shown in ***Fig. 3***.

When using short screws for transpedicular fixation and in the absence of cross links, the maximum stresses in the bone elements of the model are observed in the L3 and L4 vertebrae - 12.5 and 11.6 MPa, respectively. Also, a high level of tension was observed around the pedicle screws in the L3 vertebra - 12.1 MPa. In other vertebrae, the stress around the screws is much less, minimal - in the Th11 vertebra (1.7 MPa). In the Th10 and L2 vertebrae, the stress was 3.1 and 3.9 MPa, respectively.

Among the metal elements of the model, the most loaded were pedicle screws in the L3 vertebra, where the stress was maximum (34.1 MPa). Minimal stresses were observed on the screws in the L2 vertebra - 7.1 MPa. On pedicle screws in the Th10 and Th11 vertebrae, the maximum stress was 20.7 and 17.9 MPa, respectively. The stress in the interbody support was 29.0 MPa, in places of its contact with the bone tissue of the Th11 vertebra - 5.9 MPa, on the L2 vertebra - 6.9 MPa.

The stress distribution in the model with transpedicular fixation with long screws without cross links is shown in ***Fig. 4***.

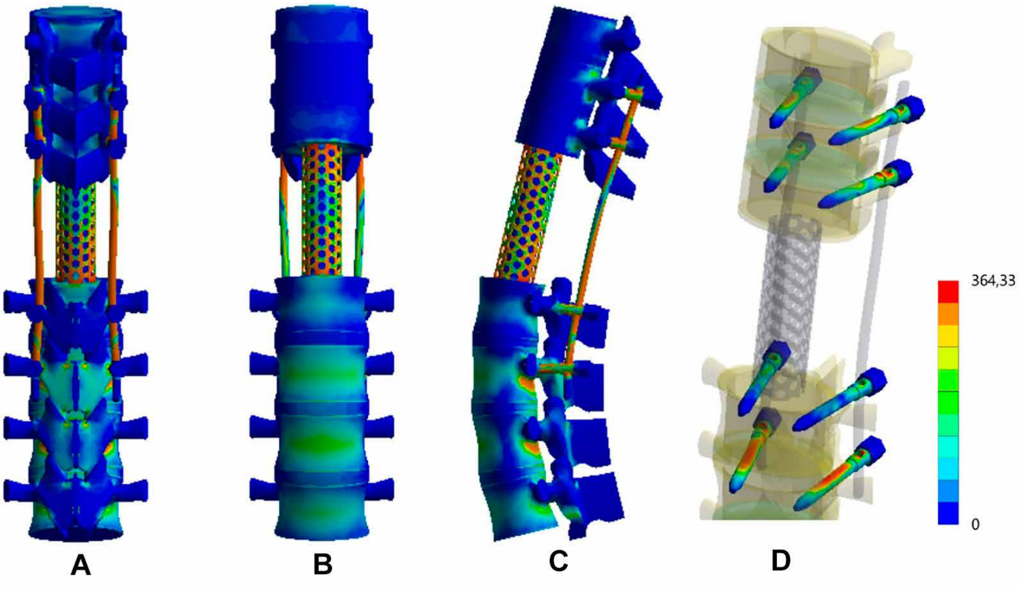

Fig. 3. The stress distribution under the influence of compressive load in the thoracolumbar spine model after resection of the Th12-L1 vertebrae. Transpedicular fixation with short screws without cross links: A - front view; B - rear view; B - side view; D - visualization of the load of screws

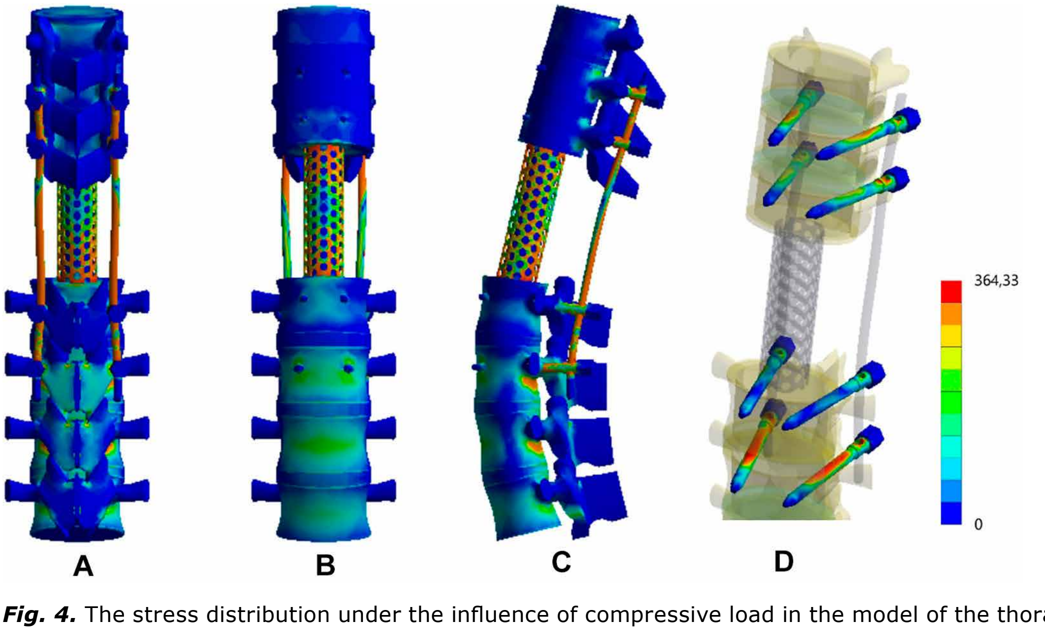

Fig. 4. The stress distribution under the influence of compressive load in the model of the thoracolumbar spine after resection of the Th12-L1 vertebrae. Transpedicular fixation with long screws without cross links: A - front view; B - rear view; C - side view; D - visualization of the load of the screws

It was found that the use of long pedicle screws helps reduce stress in the bone elements of the model at almost all control points, except for the vertebral body L5, where the stress increased to 8.1 MPa compared to fixation with short screws (7.8 MPa). An increase in stress on pedicle screws was observed. Thus, in the Th10 vertebra the stress was 23.2 MPa, in the Th11 vertebra - 19.1 MPa and reached a maximum in the L3 vertebra - 43.5 MPa. The exception were the screws that fixed the L2 vertebra. The stress on them was decreased to 4.5 MPa, in the interbody support - to 25.5 MPa.

The influence on the stress-strain state of the use of cross links on the posterior support of the transpedicular structure with short screws was investigated ***(Fig. 5).***

The use of cross links in combination with short pedicle screws in comparison with the model without links causes a slight increase in the level of stress in the Th11 vertebral body from 5.6 to 5.8 MPa. The magnitude of stress in the areas of contact of the interbody support with bone tissue, as well as in the vertebral body Th9 and around the points of entry of the screws into the vertebral body Th11 was not changed. At other control points on the bone elements of the model, a slight decrease in the level of stress was recorded.

On the elements of the transpedicular structure, a decrease in mechanical stress was revealed with the exception of pedicle screws in the L2 vertebral body, where the stress increased slightly from 7.1 to 7.4 MPa.

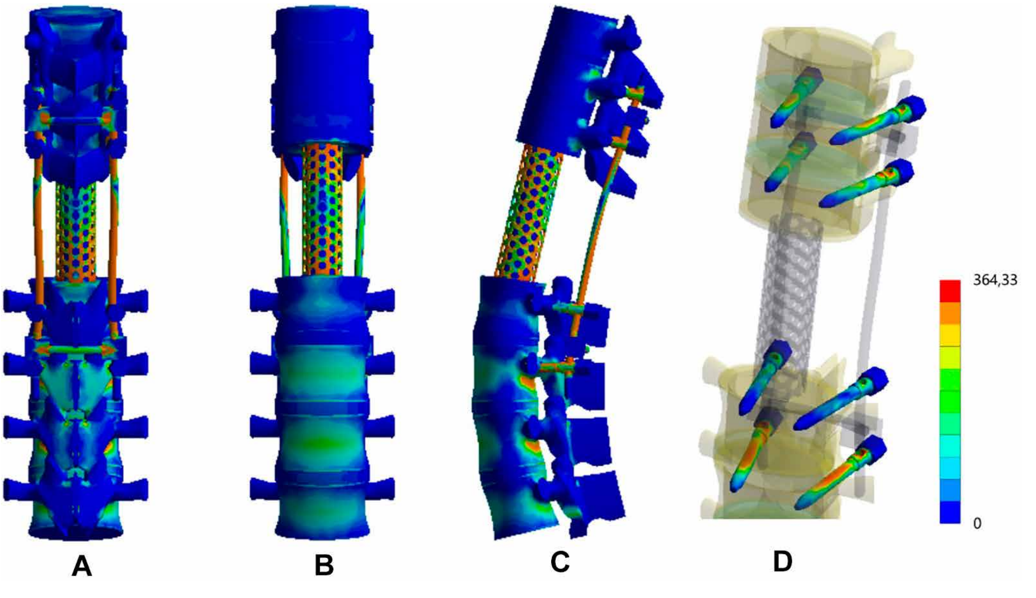

Fig. 5. The stress distribution under the influence of compressive load in the thoracolumbar spine model after resection of Th12-L1 vertebrae. Transpedicular fixation with short screws with cross links: A - front view; B - rear view; C - side view; D - visualization of the load of the screws

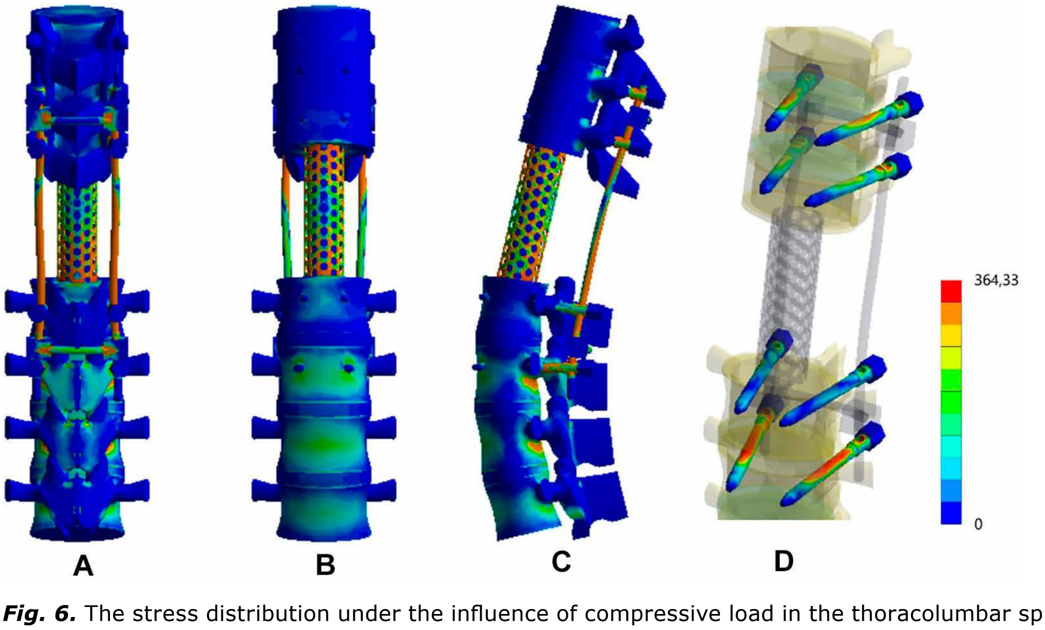

Fig. 6. The stress distribution under the influence of compressive load in the thoracolumbar spine model after resection of the Th12-L1 vertebrae. Transpedicular fixation with long screws with cross links: A - front view; B - rear view; C - side view; D - visualization of the load of the screws

The maximum stress was recorded on the cross links between the Th10 and Th11 vertebrae (3.1 MPa) and between the L2 and L3 vertebrae (7.1 MPa).

The effect of compressive load during transpedicular fixation with long screws and cross links was studied ***(Fig. 6).***

It was found that transpedicular fixation of thoracolumbar vertebrae using cross links in combination with long screws allows obtaining a minimum level of tension in the bone elements at all control points of the studied models. An increase in the stress on the fixing screws in the vertebral bodies of Th10, Th11, L3 up to 23.1, 18.6 and 40.0 MPa, respectively was revealed. However, these indicators are slightly lower than in the version with short screws.

Data on the magnitude of stress under the influence of compressive load at all control points of the thoracolumbar spine models after resection of the Th12-L1 vertebrae are given in ***Table. 2.***

The use of long screws with fixation in the cortical layer of the bone of the anterior part of the vertebral bodies allows reducing the level of tension in the bone elements of the models. This can be explained by the fact that the transpedicular structure receives a greater load than when using short screws. This is evidenced by an increase in stress level in the elements of the hardware. The use of cross links provides greater rigidity to the transpedicular structure, and further reduces stress in the bone tissue.

When analyzing the literature no studies were found similar in design to those carried out by us, which to a certain extent limits the comparison of indicators. However, the data obtained are generally consistent with published results of other authors. Thus, Mina A. et al. when modeling the surgical stabilization of the thoracolumbar spine with a resected body of one vertebra, it was demonstrated that when 8 pedicle screws are used, the maximum load falls on the lower

Table 2. The magnitude of stress under the influence of compressive load in the thoracolumbar spine models after resection of the Th12 – L5 vertebrae in different variants of transpedicular fixation

Control points			Stress, MPa			
			Without links		**With links**	
№	**area**		**Short screws**	**Long screws**	**Short screws**	**Long screws**
1	Bony tissue	vertebral body Th9	2,8	2,6	2,8	2,6
2		vertebral body Th10	7,1	6,7	6,4	5,8
3		vertebral body Th11	5,6	4,2	5,8	3,6
4		vertebral body L2	4,5	4,2	4,2	4,1
5		vertebral body L3	12,5	12,3	12,3	11,1
6		vertebral body L4	11,6	11,2	11,2	11,1
7		vertebral body L5	7,8	8,1	7,0	7,0
8		inferior part of vertebral body Th11	5,9	6,0	5,9	5,9
9		superior part of vertebral body L2	6,9	6,8	6,9	6,7
10		entry of the screws into the vertebral arch Th10	3,1	2,9	2,8	2,8
11		entry of the screws into the vertebral arch Th11	1,7	1,8	1,7	1,6
12		entry of the screws into the vertebral arch L2	3,9	3,8	3,6	3,3
13		entry of the screws into the vertebral arch L3	12,1	10,6	11,5	9,3
14	Hardware	screws in the vertebral body Th10	20,7	23,2	20,1	23,1
15		screws in the vertebral body Th11	17,9	19,1	17,0	18,6
16		screws in the vertebral body L2	7,1	4,5	7,4	5,1
17		screws in the vertebral body L3	34,1	43,5	33,6	40,0
18		links between the vertebrae Th10 i Th11	–	–	3,1	2,6
19		links between the vertebrae L2 i L3	–	–	7,1	6,4
20		interbody support	29,0	25,5	27,0	22,0

pair [17]. Similar conclusions were drawn by Chen Chen-Sheng et al., analyzing cases of fragmentation of transpedicular fixators. According to them, the main reason for the failure of the stabilization system is metal fatigue [18]. A number of *ex vivo* experiments confirm the revealed trend [19,20].

Many researchers came to the conclusion about the biomechanical feasibility of using the bicortical transpedicular fixation. Thus, back in 1992, J.N. Weinstein et al. noted that the mechanical stability of the transpedicular screw installed in the thoracic or lumbar vertebra is 60% determined by the pedicle, 15–20% - by spongiosis of the vertebral body and 20–25% - by perforation of the anterior wall of the vertebral body [21]. Y. Shibasaki et al., using artificial vertebrae and various methods of screw installation have demonstrated that bicortical placement provides more distraction force compared to monocortical [22]. K.J. Karami et al. in *ex vivo* studies using 10 samples of the lumbar spine, subjected to cyclic bending load, also found that bicortical screw placement provides greater stability than the middle or precortical placement. However, in all these studies, the extraction force was used as the stability criterion, which to some extent minimizes the clinical significance of the obtained data. Thus, the analysis of complications of transpedicular fixation shows that the frequency of spontaneous screw extraction is much lower than its fragmentation, which directly depends on the degree of stress in the «metal-bone» system in the area of the screw entry into the pedicle [18,23,24].

The study of the effectiveness of the use of cross links when performing posterior transpedicular fixation of the thoracolumbar spine by different methods of installing screws was carried out mainly when modeling functional loads. Thus, G. Lynn et al. when modeling the complete destabilization of the L1 vertebra and fixation of the Th12 and L2 vertebrae by the transpedicular system, it was demonstrated that the use of two cross links can reduce the range of motion in stabilized segments under rotational loads by 38%, under lateral bending up to 89% [25]. G. Wahba et al. note that the use of cross links when stabilizing the burst fracture of the thoracolumbar junction significantly increases the rigidity of the system at lateral flexion and moderately - when bending forward. During extension, the presence or absence of transverse stabilization of the system does not cause statistically significant differences in the range of motions. A similar pattern is observed with maximum effort. Thus, the load that leads to the inability of stabilization is the same for the samples regardless of the use of cross links [26].

The fundamental difference between our study and previous ones is a comprehensive analysis of the maximum stress indicators in various elements of the model of the operated thoracolumbar spine and assessment of the system precisely under physiological axial loads. This is most critical for patients in the early rehabilitation period, since the obligatory external fixation with a rigid brace, provided in the extent of operation modeled in our study, significantly limits both flexion-extension and rotational loads, and the failure of stabilization in the early postoperative period develops at the axial compression effect due to its own weight.

Conclusions

The study demonstrates that when performing surgery with complete resection of two vertebrae at the thoracolumbar level and subsequent physiological axial load:

1. The use of long screws with fixation in the cortical layer of the anterior part of the vertebral bodies allows reducing the level of tension in the bone elements of the models.

2. The use of cross links gives greater rigidity to the transpedicular structure, which also allows to further reducing the level of tension in the bone tissue.

Disclosure

Conflict of interest

The authors declare that they have no conflicts of interest.

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