Original article

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The biomechanical state of the thoracolumbar junction with various options of transpedicular fixation under flexion load

Oleksii S. Nekhlopochyn[1], Vadim V. Verbov[2], Ievgen V. Cheshuk[2], Milan V. Vorodi[2], Michael Yu. Karpinsky[3], Oleksandr V. Yaresko[3]

[1] Spine Surgery Department, Romodanov Neurosurgery Institute, Kyiv, Ukraine
[2] Restorative Neurosurgery Department, Romodanov Neurosurgery Institute, Kyiv, Ukraine
[3] Biomechanics Laboratory, Sytenko Institute of Spine and Joint Pathology, Kharkiv, Ukraine

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Address for correspondence:
Oleksii S. Nekhlopochyn, PhD, Spine Surgery Department, Romodanov Neurosurgery Institute, 32 Platon Maiborody st., Kyiv, 04050, Ukraine, e-mail: AlexeyNS@gmail.com

Introduction. Morphological and biomechanical features of the thoracolumbar junction determine the large number of cases of traumatic bone injuries. Reconstructive and stabilizing surgeries performed in this area, due to the significant load on both the elements of hardware and bony structures, require high reliability of fixation.

Objective. To study the stress-strain state of the model of the thoracolumbar section of the spine after the Th12-L1 vertebrae resection with various options of transpedicular fixation under the influence of flexion load.

Materials and methods. The stress-strain state of the mathematical finite-element model of the thoracolumbar section of the human spine under the influence of flexion load was studied. The model simulated the condition after surgery for a significant traumatic lesion of the thoracolumbar junction with laminectomy, facetectomy, and corpectomy of the Th12 and L1 vertebrae. Four variants of transpedicular fixation were studied (using short or long bicortical fixation screws, two crosslinks and without them). Control points of the model characterizing the load distribution both in bony structures and on metal elements of fusion and body replacement systems were studied.

Results. Crosslinks have the greatest effect on reducing the level of stress both in the bony elements of the models and in the metal elements. When comparing the length of the screws, the use of monocortical screws was determined to have minor biomechanical advantages. The stress analysis of the area of the screw entry into the pedicle of the arch of the fixed vertebrae (clinically significant zone) revealed that in the model with short screws and without crosslinks, the stress for the vertebrae Th10, Th11, L2 and L3 is 5.0, 1.9, 7.8 and 13.6 MPa, respectively, while the presence of crosslinks reduces the corresponding values to 4.6, 1.9, 7.3 and 12.7 MPa. In models with bicortical screws, the corresponding values are 5.1, 2.3, 10.2, and 12.7 MPa in the absence of crosslinks and 4.7, 1.8, 9.9, and 12.2 MPa with the presence. A similar trend is observed in other control points. When comparing the results with the compression load in the models studied earlier, it was established that flexion causes an increase in the stress of the models with monocortical screws by an average of 33.7%, with bicortical screws by 39.6%.

Conclusions. In case of flexion load, the use of crosslinks makes it possible to reduce the level of stress in all control points of the models, regardless of the length of the used transpedicular screws, while the length of the screws does not have a fundamental effect on the stress distribution.

Keywords: *finite element model; thoracolumbar junction; two-level corpectomy; bicortical transpedicular stabilization; crosslink; flexion load*

Introduction

Restoring the support function of the spine during surgical treatment of traumatic injuries is one of the main conditions for effective implementation of the reconstructive and stabilizing stages of intervention [1]. A wide variety of variants of osteoligamentous changes of the spine resulting from the action of a traumatic agent on the human body, leads to a wide range of methods of their surgical correction [2, 3]. Due to the need to achieve the maximum efficiency of surgical intervention while minimizing its volume and risks of both intraoperative and postoperative complications, in some cases the most pathogenetically justified treatment methods are not biomechanically and clinically optimal. This dissonance is most evident in determining treatment tactics for traumatic injuries of the thoracolumbar junction (TLJ). Due to its morphological and biomechanical features, this area is highly prone to fractures, and therefore requires high fixation reliability [4, 5]. As an example, there is a current discussion regarding the tactics for surgical correction of burst fractures of the TLJ area [6, 7]. Thus, in the presence of multi-fragmentary injury of the vertebral body with a traumatic defect of its posterior wall, probable prolapse of fragments into the spinal canal, and intact or practically intact posterior osleoligamentous apparatus, "decompression from the side of compression", i.e., ventral or ventrolateral corpectomy, is pathogenetically justified [8]. This surgical procedure after the removal of bony elements involves the installation of a body replacement support in combination with a ventral plate or a rod [9]. However, as practice shows that this amount of fixation is often insufficient to achieve effective fusion due to the specificity of the injury area, so additional posterior stabilization is necessary. Introducing 4 screws into the body of one vertebra (2 anteriorly to fix the plate and 2 posteriorly transpedicularly) is technically difficult and risks damaging the intact body, so in most cases, when choosing this method of intervention, transpedicular fixation is applied to vertebrae adjacent to ventrally stabilized ones [10]. Obviously, the final result has disadvantages compared to classic 8-screw transpedicular fixation performed after posterior corpectomy and vertebral body replacement.

A wide range of surgical options and the lack of recommendations that stictly and unambiguously regulate the scope and technique of surgery depending on the nature of the injury result in a variety of both tactical and strategic approaches in the therapy of traumatic injuries of the TLJ area. However, analysis of the literature suggests that transpedicular fixation is the method that provides full fixation of the injured area of the thoracolumbar spine in most cases [11, 12]. Vertebral body resection in case of traumatic injury, unlike in case of oncological one, in which options are possible, is always performed according to the "disk-to-disk" principle. A compulsory condition for ensuring the supportability of a body replacement implant is the integrity of the endplates adjacent to the resected vertebral body. Type A3 and A4 injuries according to the AOSpine Thoracolumbar Spine Injury Classification System often involve the removal of the vertebral body due to its significant damage and displacement of bone fragments into the spinal canal [13]. Adjacent vertebral bodies in these types of injuries are usually intact, since an intense compression or flexion-compression action resulting in injury to the two adjacent vertebral bodies, almost always causes damage to the posterior capsular-ligamentous apparatus (type B2 or C in the presence of an axis displacement in any plane) [14]. Therefore, most resections of two vertebral bodies in case of traumatic damage to the TLJ area are performed with the most severe clinical and difficult for surgical correction type C injuries. In view of significant loss of spine supportability due to such large injuries, the issue of increasing the reliability of stabilization in case of resection of two vertebral bodies is relevant [15].

Previously, the model of the TLJ area modeling the outcome of surgical correction of a severe traumatic injury was considered and its features under the influence of compression load were studied. We also focused on the other most characteristic load pattern of the TLJ - flexion loads.

Objective: To study the stress-strain state of the model of the thoracolumbar section of the spine after the Th12-L1 vertebrae resection with various options of transpedicular fixation under the influence of flexion load.

Materials and methods

Study design - computer modeling.

A mathematical finite-element model of the thoracolumbar section of the human spine, which included vertebrae Th9–Th11 and L2–L5 was developed in the biomechanics laboratory of the Sytenko Institute of Spine and Joint Pathology of National Academy of Medical Sciences of Ukraine. Th12 and L1 vertebrae have been completely removed. The model also included elements of hardware - a body replacing implant between the bodies of the Th11 and L2 vertebrae and a traspedicular system of 8 screws installed in the bodies of the Th10, Th11, L2 and L3 vertebrae. The condition was simulated after surgical intervention for a significant traumatic lesion of the TLJ area with laminectomy, facetectomy, and Th12 and L1 corpectomy. A detailed description of the model is given in the previous publication [16].

The stress-strain state was studied under the influence of a flexion load acting posteriorly forward. The load was applied to the body of the Th9 vertebra and the articular surfaces of the facets. The load was 350 N. The model was rigidly fixed along the distal surface of the L5 disk.

The features of load distribution was studied using 4 variants of transpedicular fixation (using short fixation screws, which are standardly immersed in 2/3 of the vertebral body, and long screws that pass through the external cortical layer of the anterior surface of the vertebral body (bicortically)). The impact of using two crosslinks "rod-to-rod" type was also studied.

The control points of the model characterizing the load distribution both in the bony structures and on the metal elements of the stabilizing and body replacement systems were studied:

- Th9 (1), Th10 (2), Th11 (3), L2 (4), L3 (5), L4 (6) and L5 (7) vertebral bodies;
- endplates of the vertebrae in contact with the body replacement implant, namely the inferior endplate of the Th11 vertebra (8) and the superior endplate of the body of the L1 vertebra (9);
- screw entry points in the arch pedicles of Th10 (10), Th11 (11), L2 (12) and L3 (13) vertebrae;
- transpedicular screws in the vertebral bodies of Th10 (14), Th11 (15), L2 (16) and L3 (17);
- crosslinks fixed on beams between screws Th10–Th11 (18) and L2–L3 (19);
- body replacement implant (20).

The layout diagram of control points is shown in ***Fig. 1***.

The study of the stress-strain state of the models was carried out using the finite element method. The criterion for assessing the stress state of the models was stress according to von Mises [17]. Modeling was performed using the SolidWorks computer-aided design system (Dassault Systemes, France). The COSMOSWorks finite element analysis package integrated into the design environment was used to calculate the stress-strain state [18].

This article contains some figures that are displayed in color online but in black and white in the print edition

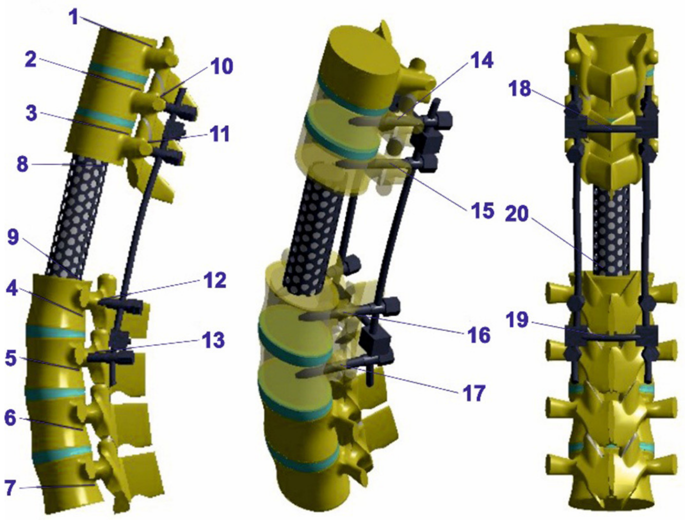

Fig. 1. The layout diagram of control points (explanation in the text)

Results and discussion

When using transpedicular fixation with short screws without crosslinks and modeling the forward tilt of the body *(Fig. 2)*, the maximum stress of 16.8 MPa occurred in the body of the vertebra located more caudal to the fixed area of the spine (L4). The values were also high in the adjacent vertebral bodies (L3 – 14.8 MPa, L5 – 13.7 MPa) and the contact points of the vertebrae with interbody support: the superior endplate of the L2 vertebra – 13.6 MPa, the inferior endplate of the Th11 vertebra – 13.4 MPa. Around the fixation screws, the maximum stress occurred in the caudal group of the fixed vertebrae (L2 vertebral arch pedicle – 7.8 MPa, L3 vertebral arch pedicle – 13.6 MPa). Regarding the screws themselves, a different pattern was observed: the screws located most distally from the resection zone were subjected to the greatest load. Thus, the load on the transpedicular screw in the body of the Th10 vertebra was 34.3 MPa, on the screw in the body of the L3 vertebra - 45.5 MPa. The stress in the interbody support was 42.0 MPa.

Replacement of transpedicular screws with long bicortical screws without using crosslinks did not result in a significant change in stress in the bony elements of the model *(Fig. 3)* except for the endplate of the L2 vertebral body, which was in contact with the interbody support (16.7 MPa, which exceeds the corresponding value of the previous model at 22.7%). Surgical hardware were more stressed than in the model with short screws. Thus, the maximum indicator in the interbody support was 46.7 MPa, while on the screws in the bodies of the Th10 and L3 vertebrae – it was 38.8 and 48.4 MPa, respectively.

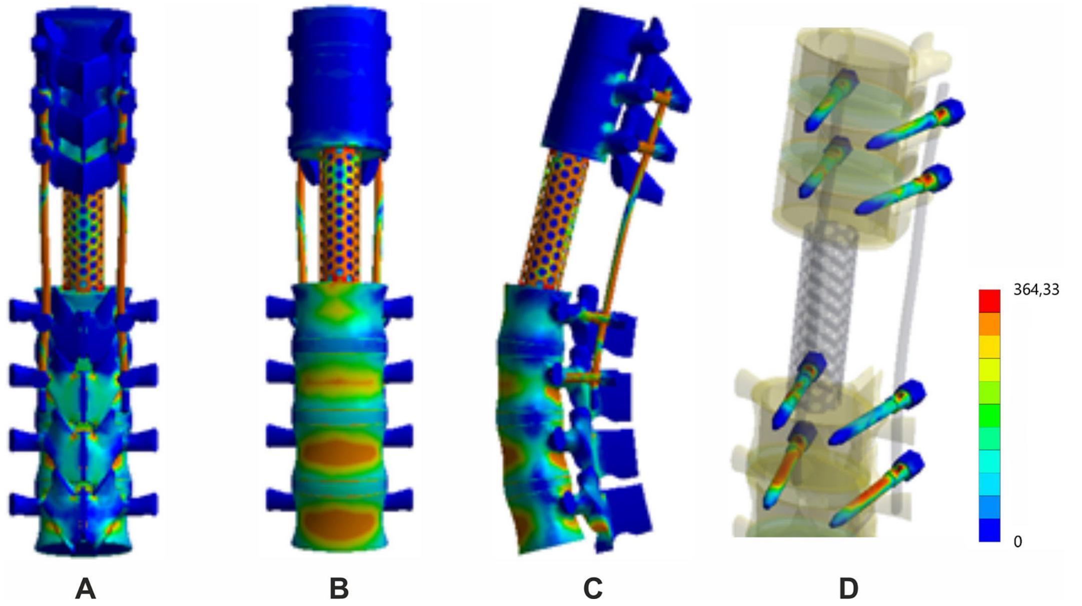

Fig. 2. Stress distribution in the thoracolumbar spine model after resection of Th12 and L1 vertebrae under the influence of flexion load. Transpedicular fixation with short screws without crosslinks: a – posterior view; b – anterior view; c – lateral view; d - screws

The use of crosslinks reduces stress levels when the body is tilted forward in all control points of the model of transpedicular fixation using short screws with the use of crosslinks ***(Fig. 4)***. The biggest difference was registered in the body of the L3 vertebra (10.0% decrease). The load decrease was also recorded on the endplates of the Th11 and L1 vertebrae (by 7.5 and 8.1%, respectively). Stress on the crosslinks was 3.3 MPa on the superior endplate and 10.9 MPa on the inferior one.

As the conducted studies showed, the use of long screws in combination with crosslinks when the body was tilted forward did not result in significant changes in the stress-strain state of the model compared to the model with short screws, except for an increase in the stress level on the interbody support to 43.0 MPa and on the extreme fixation screws - up to 47.8 MPa on the lower one and up to 36.5 MPa on the upper one ***(Fig. 5).*** However, compared to the model using long

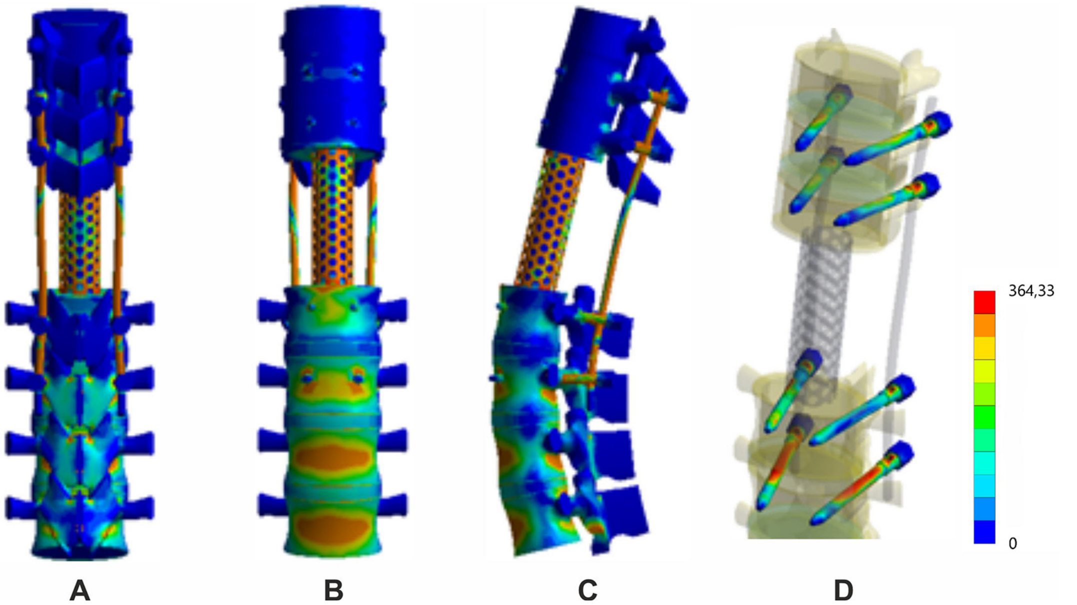

Fig. 3. Stress distribution in the thoracolumbar spine model after resection of Th12 and L1 vertebrae under the influence of flexion load. Transpedicular fixation without crosslinks using long bicortical screws: a – posterior view; b – anterior view; c – lateral view; d - screws

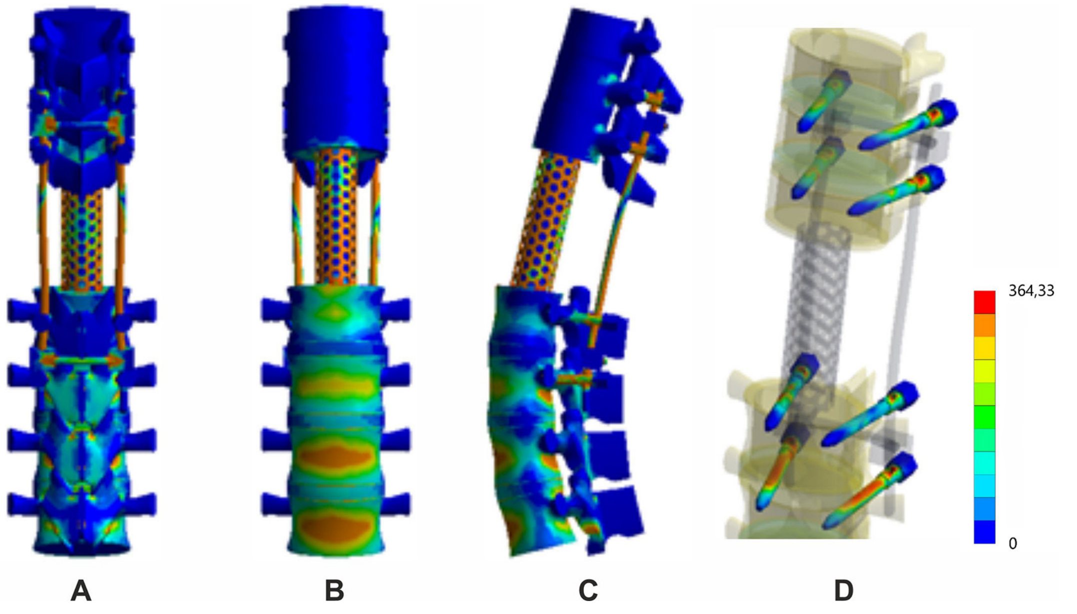

Fig. 4. Stress distribution in the thoracolumbar spine model after resection of Th12 and L1 vertebrae under the influence of flexion load. Transpedicular fixation using crosslinks and short screws: a – posterior view; b – anterior view; c – lateral view; d - screws

screws without crosslinks, the stress level decreased at all control points of the model.

Data on the maximum stress in all control points of the models for all variants of transpedicular fixation are shown in the **Table**.

Consequently, no fundamental differences between the options for transpedicular fixation of the spine were found when the trunk was tilted forward. An increased stress level was detected in the contact area of the interbody support with the L2 vertebra (point 9) when using long screws without crosslinks, but the addition of crosslinks eliminated this deficiency. Also noteworthy was the stress in the L2 vertebra around the fixation screw (control point 12), which increased when using long screws regardless of the presence or absence of crosslinks.

The results of biomechanical studies of the load on the spine indicate that in the absence of gross degenerative-dystrophic or any traumatic changes, the load acting on the body of the vertebra is mainly compressive in nature. Therefore, flexion load, rotation or lateral tilt, which form the traditional load patterns of the spine as a whole, in one vertebral-motor segment with the help of the intervertebral disc and the capsular-ligamentous apparatus of the posterior support complex, are transformed into compression [19]. This fact has been confirmed by both morphological and clinical observations. It is clear that the features of the trabecular architecture of the spongy substance of the vertebral body are determined by the nature of the load [20]. In fact, the heterogeneity of the microstructure and mechanical properties is the result of adaptation and a key factor determining the ability of the vertebral body to withstand a certain type of load. At the same time, it is natural that the arrangement of trabeculae in the vertebrae of the thoracolumbar region, which is mainly vertical in nature, is most adapted to resistance of compression. The maximum share of the load perceived by trabecular bone, according to research of S.K. Eswaran et al., is 76–89% of the total load applied to the vertebra [21]. In addition, it has been observed that the density of the trabecular structure of the anterior parts of the body is less than that of the posterior ones, which also favours the morphological focus on resistance to compression load rather than flexion [20].

On the other hand, the nature of the load on the vertebral body is easy to find clinically when analysing the pathomorphology of osteoporotic non-traumatic fractures. It has been noted that vertebral body injuries occurring mainly at the moment of spinal flexion, has signs of compression action exerted by a uniform decrease in the height of both the anterior and posterior walls of the vertebral body [22].

All the above data refer only to the intact spine, whereas for the stabilized spine, the load vectors acting on the spine in general and the fixed area in particular coincide. This fact often leads to the misinterpretation of biomechanical findings, since the stabilized TLJ in a patient who is in a neutral vertical position is affected by flexion rather than compression load.

The TLJ site is the only area where the intensity of the flexion moment is independent of the depth of the spinal curvature and is about 8 N·m. Maintaining the vertical position of the body is achieved by balancing between flexion, determined by the body weight, located in front of the spine, and extension efforts of the muscles. As for the TLJ, it is mainly the erector muscle of the spine (*m. erector spinae*) and multifidus muscles (*m. multifidi*) [19]. The very fact of traumatic impact and to a large extent transferred surgical intervention affect the condition of deep muscles of the back, often partially or completely depriving them of their extensor function.

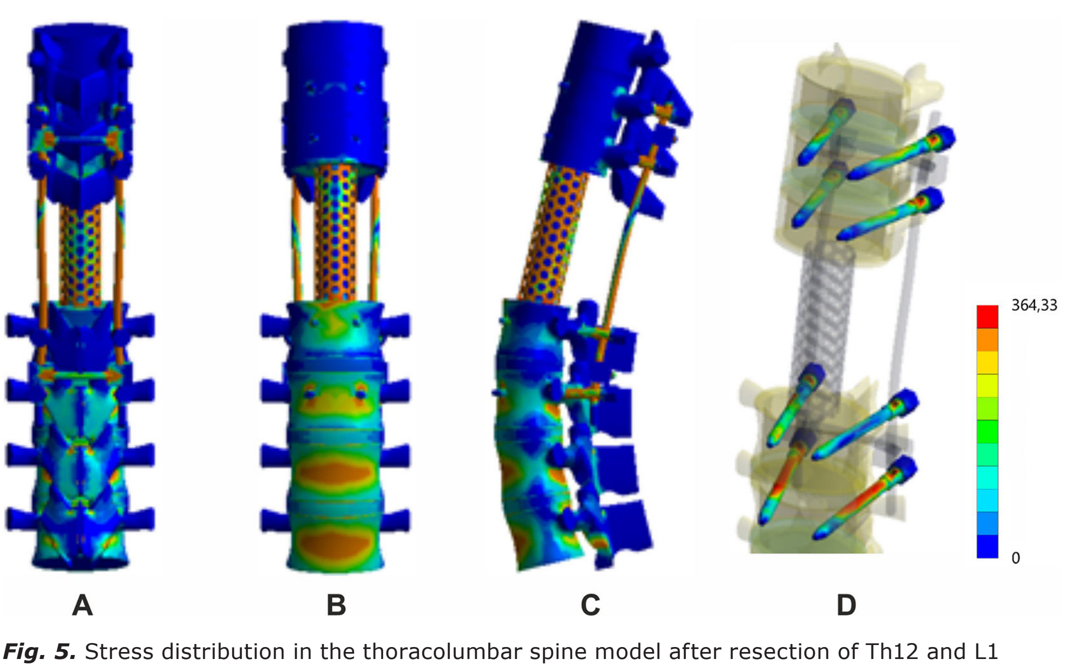

Fig. 5. Stress distribution in the thoracolumbar spine model after resection of Th12 and L1 vertebrae under the influence of flexion load. Transpedicular fixation using crosslinks and long screws: a – posterior view; b – anterior view; c – lateral view; d - screws

Table. Stress under the influence of flexion load in models of the thoracolumbar spine after resection of the Th12 and L1 vertebrae with various transpedicular fixation options

Control point			Stress, MPa			
			Model without crosslinks		Model with crosslinks	
№	Area		short screws	long screws	short screws	long screws
1	Bony tissue	Vertebral body Th9	1,4	1,4	1,3	1,4
2		Vertebral body Th10	6,2	5,7	5,8	5,6
3		Vertebral body Th11	6,6	7,0	6,2	6,7
4		Vertebral body L2	8,3	7,8	8,2	7,6
5		Vertebral body L3	14,8	14,9	13,2	13,1
6		Vertebral body L4	16,8	16,8	16,6	16,3
7		Vertebral body L5	13,7	13,5	13,6	13,1
8		Inferior vertebral body Th11	13,4	13,3	12,4	12,7
9		Superior vertebral body L2	13,6	16,7	12,5	12,6
10		Screw entry in vertebral arch pedicles Th10	5,0	5,1	4,6	4,7
11		Screw entry in vertebral arch pedicles Th11	1,9	2,3	1,9	1,8
12		Screw entry in vertebral arch pedicles L2	7,8	10,2	7,3	9,9
13		Screw entry in vertebral arch pedicles L3	13,6	12,7	12,7	12,2
14	Hardware	Screws in the vertebral body Th10	34,3	38,8	31,5	36,5
15		Screws in the vertebral body Th11	34,0	34,1	32,3	32,1
16		Screws in the vertebral body L2	29,6	27,5	28,9	26,7
17		Screws in the vertebral body L3	45,5	48,4	43,6	47,8
18		Crosslinks between screws in the vertebral bodies Th10 and Th11			3,3	3,2
19		Crosslinks between screws in the vertebral bodies L2 and L3			10,9	10,8
20		Interbody support	42,0	46,7	41,2	43,0

The implanted stabilization system therefore has an even greater load in terms of countering the flexion moment.

Adapting the above data to the clinical situation, it can be argued that simulated compression load on a stabilized TLJ that has been perfomed earlier corresponds to the neutral vertical position of a patient wearing a rigid unloading thoracolumbar brace, while this study corresponds to a similar position without a brace [16]. Given that the analyzed volume of surgical intervention involves permanent internal fixation, and verticalization of the patient is a priority task in the complex of rehabilitation measures, because it has a significant psychological impact on the injured person, it is reasonable to compare the data of the studies performed. In the analysis, only models using crosslinks were considered due to their indisputable biomechanical advantage.

It was found that the action of flexion on the fixed part of the TLJ leads to a significant increase in stress in almost all elements of the models, with the exception of the body of the vertebra located more cranially than the fixation zone, and the most cranially of fixed vertebra (Th9 and Th10) ***(Fig. 6)***. Compared to compression, the stress during flexion on the body of the Th9 vertebra is almost twice as low (by 115.4% when using short screws and by 85.7% when using bicortical screws). Significantly smaller differences were recorded for the load on the body of the Th10 vertebra (by 10.3 and 3.6% when using short and long screws, respectively). In all other control points, the load increased on average by 33.7% for the model with monocortical screws and by 39.6% for the model with bicortical screws. The load increased by 46.3% in the body of the Th11 vertebra when using long screws and only by 6.5% when using monocortical screws. The L2 vertebral body showed a 50.0% increase in load regardless of transpedicle screw length, while the load on the L3 vertebral body was little changed. The load on all other bony elements of the model increased without significant differences between monocortical and bicortical screws.

When analyzing the nature of changes in the load on the elements of hardware during the simulation of flexion compared to compression exposure ***(Fig. 7)***, it was found that the load increased on average by 36.6% in the model with monocortical screws and by 40.6% in the model with bicortical screws. Compared to compression, the load increase was most critical for screws implanted in the L2 vertebral body, by 74.4 and 80.9%, respectively, for monocortical and bicortical fixation.

The results of the study showed that crosslinks have the greatest influence on the load reduction in both the bony elements of the models and in the surgical hardware. The use of short or long screws have no significant effect on load distribution in flexion simulations, but the use of monocortical screws has certain advantages. Comparison of the results with compression load simulation, revealed an average increase in stress of 33.7–40.6%, and in some elements of the studied structures, up to 80.9%. The obtained indicators are arguments in favour of using a brace in the postoperative period. However, given the fact that the period of external fixation is actually limited, when assessing the feasibility of using a particular transpedicular stabilization method, the indicators obtained during flexion simulation should be considered. The data should be interpreted in relation to their clinical significance, as well as by comparing them with the results of studies of other loading patterns, which require additional studies.

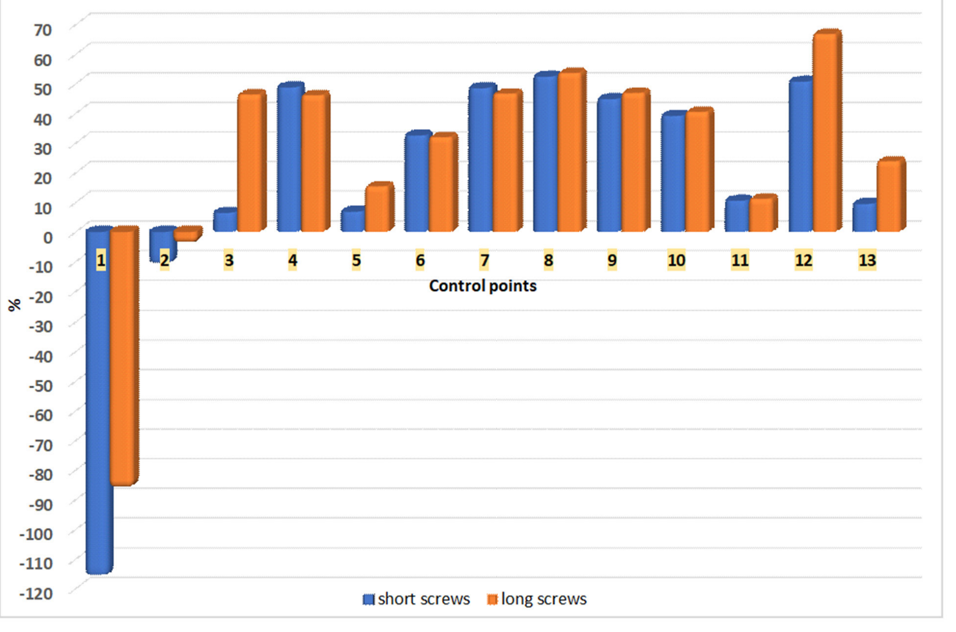

Fig. 6. Change in the amount of load in bony structures of models with crosslinks under the influence of flexion load compared to compression

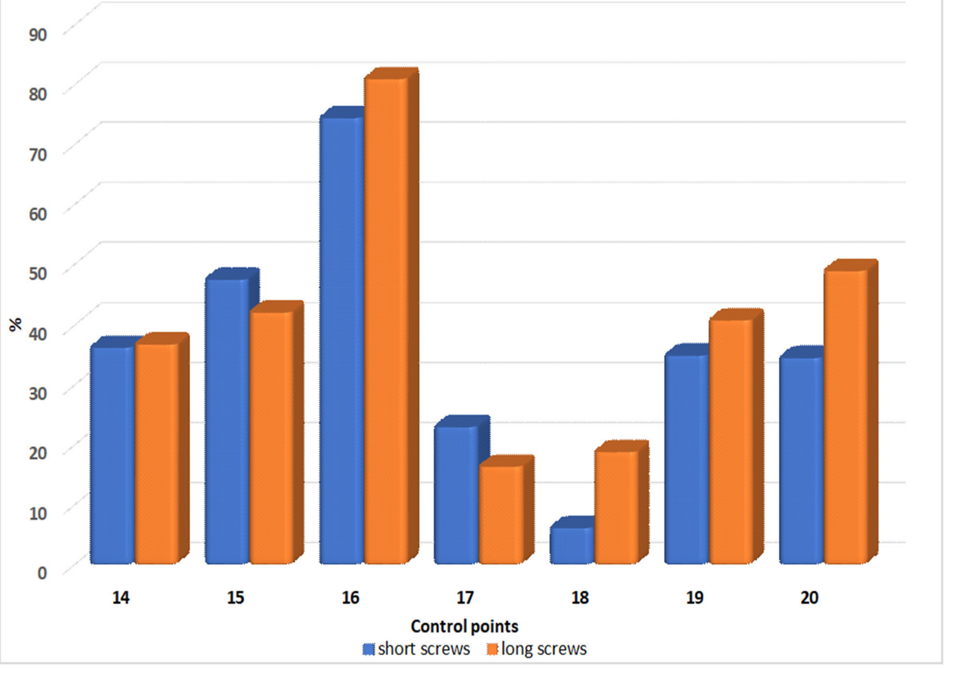

Fig. 7. Change in the amount of load on the surgical hardware elements of models with crosslinks under the influence of flexion load compared to compression

Conclusions

In flexion load, the use of crosslinks makes it possible to reduce the stress level at all control points of the models, irrespective of the length of the fixation screws.

The length of the fixation screws has no fundamental effect on the stress distribution in the models when the body is tilted forward.

When comparing the obtained results with compression load modeling, it was found that the stress increases by an average of 33.7–40.6%, and in some elements by up to 80.9%.

The findings are arguments in favour of using a brace in the postoperative period.

Information disclosure

Conflict of interest

The authors declare no conflict of interest.

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