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Biomechanical aspects of transpedicular fixation in the thoracolumbar junction area: the influence of lateroflexion

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The paradigm shift in surgery of the injured spine during the last few decades is characterized by the active implementation of the principle of stabilization without fusion. This approach significantly expands the possibilities of surgical interventions in terms of the completeness of decompression and spinal axis restoration, but also it determines higher requirements for the reliability of the fixation systems and the uniformity of load distribution on both metal systems and bone structures. Objective. To determine the features of load distribution in the area of the thoracolumbar junction after resection of one vertebra, as well as the effect of the transpedicular screw length and cross-links of the stabilization system. Methods. Mathematical finite-element model of the thoracolumbar human spine was developed. The model simulated the state after surgical treatment of a traumatic injury to the thoracolumbar junction with significant damage to the body of the Th_{XII} *vertebra. We studied 4 variants of transpedicular fixation (using monocortical screws and long bicortical screws, as well as two cross-links and without them). Results. When analyzing the stress-stain state of the model, we found that the most loaded bone structures during lateroflexion are the vertebral bodies. For the* L_{II} *vertebral body, the load values were 17.2, 16.2, 16.3, and 15.5 MPa, respectively, for models with monocortical screws without cross-links, bicortical screws without cross-links, monocortical screws and cross-links, and bicortical screws and cross-links. The peak loads on the transpedicular screws were recorded on those implanted in the body of the* Th_{XI} *vertebra (24.8, 25.7, 22.8 and 24.3 MPa, respectively, for the considered models) and in the body of the* L_{II} *vertebra (20.2, 24.6, 19, 7 and 23.7 MPa). Conclusions. The use of long transpedicular screws causes less stress on the bony elements than the short screws. At that time stresses on the screws themselves and the bone tissue around them increase. Cross-links help to reduce stress at all control points on models with both short and long transpedicular screws.*

Зміна поглядів на хірургію травмованого хребта протягом останніх декількох десятиліть характеризується активним упровадженням принципу стабілізації без консолідації. Це значно розширює можливості втручань щодо повноти декомпресії та повноцінності відновлення осі хребта, але висуває підвищені вимоги до надійності фіксувальних систем і рівномірності розподілу навантаження на металоконструкцію і кісткові структури. Мета. Вивчити особливості розподілу навантаження на моделі грудопоперекового переходу в разі резекції одного хребця, а також залежно від довжини транспедикулярного гвинта і поперечних стяжок системи стабілізації. Методи. Розроблено математичну скінченно-елементну модель грудопоперекового відділу хребта людини, яка імітує стан після хірургічного лікування його травматичного ушкодження зі значним ураженням тіла хребця Th_{XII}*. Дослідили 4 варіанти транспедикулярної фіксації (із використанням монокіркових фіксувальних і довгих біокіркових гвинтів, а також двох поперечних стяжок і без них). Результати. Аналіз напружено-деформованого стану моделі виявив, що найнавантаженішими кістковими структурами за латерофлексії є тіло хребця* L_{II}*, де величина навантаження становила 17,2; 16,2; 16,3 та 15,5 МПа, відповідно для моделей із монокірковими гвинтами без поперечних стяжок, бікірковими гвинтами без стяжок, монокірковими гвинтами та стяжками, бікірковими гвинтами й стяжками. Пікові навантаження на транспедикулярних гвинтах зафіксовано на імплантованих у тіло хребця* Th_{XI} *(24,8; 25,7; 22,8 і 24,3 МПа, відповідно для розглянутих моделей) та в тіло хребця* L_{II} *(20,2; 24,6; 19,7 і 23,7 МПа). Висновки. Використання довгих транспедикулярних гвинтів за нахилу вбік спричиняє менше напруження в кісткових елементах, ніж у моделі з короткими гвинтами, але на самих гвинтах і кістковій тканині навколо них напруження зростають. Поперечні стяжки сприяють зниженню напруження в усіх контрольних точках моделей як із короткими, так і з довгими фіксувальними гвинтами.*

Ключові слова. Скінченно-елементна модель, грудопоперековий перехід, корпоректомія, бікіркова транспедикулярна стабілізація, поперечна стяжка, латерофлексія.

Keywords. Finite element model, thoracolumbar junction, corpectomy, bicortical transpedicular stabilization, cross-links, lateroflexion

Introduction

Traumatic spine injuries are a medical and social problem. They rank third among injuries of the musculoskeletal system and are characterized by high rates of disability and permanent loss of working capacity. The increase in the number of traffic and industrial injuries, as well as falls from a height, leads to an increase in the number of patients with spinal column injuries of various degrees and nature. At the beginning of the 20th century the share of spinal injuries accounted for about 0.33 % of the total number of all traumatic injuries, with 5.0 % in the 1930s and more than 6.0 % in the 1940s and 1950s [1, 2]. According to the Global Burden of Disease, in 2019, about 90,000 primary traumatic spine injuries were registered in Ukraine (more than 200 cases per 100,000 population or 4.12 % of the total number of fractures) [3].

More than 90 % of spine injuries are known to be indirect in nature, causing damage to the most biomechanically vulnerable parts of the spine, mostly the cervical region and the thoracolumbar junction (TLJ) [4]. Injury to the osteoligamentous apparatus of one or more vertebral motor segments results in a partial or complete loss of their stability, support function, axis disturbance, in a number of cases — in compression of nerve formations of the spinal canal by bone fragments or displaced bone structures, which can cause neurological deficit. Accordingly, the main tasks of surgical intervention are stabilization, decompression and correction of the spinal axis, while the scope and necessity of each of these stages is determined individually depending on the specifics of the injury. For a long time, the achievement of a secondary stable spondylodesis was actually a mandatory criterion for the successful surgical correction of most traumatic injuries of the spinal column.

The introduction of new effective methods of intraoperative visualization into practical health care, as well as the improvement of implantable stabilization systems, contributed to the change of strategic approaches and certain technical aspects of performing surgical interventions in patients with traumatic spinal injuries. Analysis of the amount of medical care provided to patients with spinal cord injuries, in particular the areas of the thoracolumbar transition, in a historical aspect revealed the expansion of indications for surgical correction and an increase in the number of these interventions for significant destruction. Minimally invasive and hybrid (in combination with cementoplasty) interventions have been developed, which make it possible to achieve the maximum clinical effect with minimal trauma for the treatment of a large number of types of injuries [5, 6]. Under these circumstances, a situation may arise when it is not possible to achieve a true (secondary) spondylodesis due to bone regeneration.

The change in the paradigm of surgery of the injured spine during the last few decades has been characterized by the active implementation of the principle of stabilization without fusion. This significantly expands the possibilities of operative interventions regarding the completeness of decompression and the completeness of the restoration of the spine axis, but it puts forward greater requirements for the reliability of the fixation systems and the uniformity of the distribution of the load both on the metal structure and on the bone structures [7]. The TLJ area is one of the most damaged areas of the spine, so this approach can be used in the case of injuries of type A3 and A4 (large fragmentation of the vertebral body requires the removal of most of the bone fragments for decompression) or type C (restoration of the axis is impossible without partial or complete resection of the injured body vertebra). The use of telescopic body replacement systems greatly facilitates the restoration of support function.

Currently, these surgical interventions are increasingly used in clinical practice, as they are associated with better indicators of the quality of life of patients in the distant period after the injury. However, the biomechanical component that determines the specifics of the load on the fixed spine and, accordingly, the reliability of long-term fixation, has been little studied. In previous publications, the biomechanical characteristics of the stabilized fragment of the TLJ in the case of resection of the body of the Th_{XII} vertebra under the influence of flexion and extension loads were considered [8, 9]. We have studied the features of the loading of bone structures and metal construction elements in the case of asymmetric loading — lateroflexion.

Purpose. To study the features of load distribution in the thoracolumbar transition zone during surgical resection of one vertebra, as well as the effect on the load distribution of the length of the transpedicular screw and transverse ties of the stabilization system.

Material and methods

Since the biomechanical study of the effectiveness of various fixation options requires comprehensive information on the stress distribution and deformation of a large number of both bone and metal structures, the use of the finite element method for analysis was considered the most appropriate.

In the biomechanics laboratory of the State Institution Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Sciences of Ukraine a mathematical finite-element model of a human thoracolumbar spine was developed, which contained the vertebrae Th_{IX}–Th_{XI} and L_I–L_V, as well as elements of metal structures, namely an interbody support and a traspedicular 8-screw stabilization system. Vertebra Th_{XII} was removed. The model simulated the state after surgical treatment of a traumatic injury to the TLJ area with a significant lesion of the body of the Th_{XII} vertebra, which requires not only posterior decompression and stabilization, but also replacement of the support function of the vertebral body — installation of a body replacement implant.

Different variants of transpedicular fixation were modeled: with the use of standard-length transpedicular screws immersed in the vertebral body by 2/3, or long bicortical screws that pass through the inner cortical layer of the anterior surface of the vertebral body, as well as two transverse ties and without them. So, the studied model had 4 modifications: 1) monocortical screws without transverse ties; 2) bicortical screws without transverse ties; 3) monocortical screws and two transverse ties; 4) bicortical screws and two transverse ties. A detailed description and characteristics of the model are given in previous publications [8, 9].

Table 1

Mechanical characteristics of materials used during modeling

Material	Young's modulus, MPa	Poisson's ratio, ν
Cortical bone	10 000	0.30
Spongy bone	450	0.20
Articular cartilage	105.5	0.49
Intervertebral discs	4.2	0.45
Titan BT-16	110 000	0.30

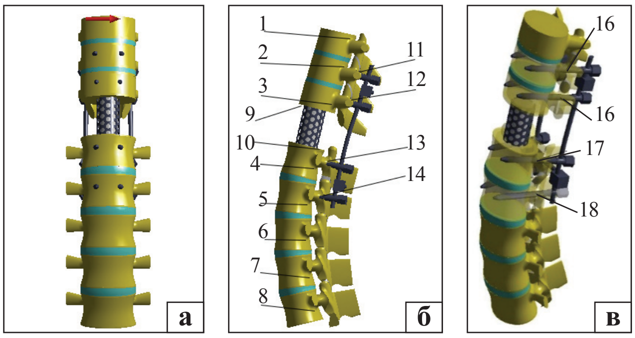

Fig. 1. Scheme of model loading (a) and location of control points (b, c). Explanation in the text

During modeling, the material was considered homogeneous and isotropic. A 10-node tetrahedron with a quadratic approximation was chosen as a finite element. The mechanical properties of biological tissues (cortical and spongy bones, intervertebral discs) for mathematical modeling were selected according to data [10, 11]. The material of metal construction elements was titanium. The mechanical characteristics of artificial materials were chosen from the technical literature [12]. For the analysis, we used such characteristics as E — modulus of elasticity (Young's modulus), ν — Poisson's ratio. Information on the mechanical characteristics of materials is given in Table 1.

We studied the stress-strain state of the models under the influence of a bending load acting from right to left and simulating the inclination of the body to the left, along the distal surface of the L_V disc, the model had a rigid fixation. The load was applied to the body of the Th_{IX} vertebra and the right facet joint. The magnitude of the load wa 350 N. The load diagram of the models is shown in Fig. 1, a.

For the convenience of studying changes in the stress-strain state of the models depending on the method of transpedicular fixation, the amount of stress was determined at the control points: 1 — the body of the Th_{IX} vertebra; 2 — the body of the Th_X vertebra; 3 — the body of the Th_{XI} vertebra; 4 — the body of the L_I vertebra; 5 — the body of the L_{II} vertebra; 6 — the body of the L_{III} vertebra; 7 — the body of the L_{IV} vertebra; 8 — the body of the L_V vertebra; 9 — the lower locking plate of the body of the Th_{XI} vertebra; 10 — the upper locking plate of the body of the L_I vertebra; 11 — entry of screws into the arch of the Th_X vertebra; 12 — entry of screws into the arch of the Th_{XI} vertebra; 13 — entry of screws into the arch of the L_I vertebra; 14 — entry of screws into the arch of the L_{II} vertebra; 15 — screws in the body of the Th_X vertebra; 16 — screws in the body of the Th_{XI} vertebra; 17 — screws in the body of the L_I vertebra; 18 — screws in the body of the L_{II} vertebra; 19 — ties between the screws in the bodies of the Th_X and Th_{XI} vertebrae; 20 — ties between the screws in the bodies of L_I–L_{II} vertebrae; 21 — interbody support.

Analysis of the stress-strain state of the models was carried out using the finite element method. The criterion for its evaluation was stress according to Mises [13]. Modeling was performed using the SolidWorks automated design system (Dassault Systemes, France). Calculations of the stress-strain state of the models were carried out using the CosmosM software complex [14].

Results

In the model with the use of transpedicular fixation with short screws without transverse ties (Fig. 2), the maximum stress values of 17.2 and 17.5 MPa were recorded in the bodies of the L_{II} and L_{IV} vertebrae, respectively. In the contact zones of the interbody support with the vertebral bodies, the maximum value (12.9 MPa) was registered on the upper end plate of the body of the L_{I} vertebra, while on the lower end plate of the body of the Th_{XI} vertebra, the stress value was much lower (6.2 MPa). Around the fixing screws, the maximum stress (7.3 MPa) occurred in the L_{II} vertebra. In other vertebrae, this indicator was from 3.5 to 3.9 MPa.

Regarding the metal structures, the screws in the bodies of the Th_{X} and Th_{XI} vertebrae were the most stressed (21.2 and 24.8 MPa, respectively), slightly less stress was registered on the fixing screw in the L_{III} vertebra (20.2 MPa). The amount of stress in the interbody resistance was 32.7 MPa.

The use of long screws of the stabilization system without transverse ties (Fig. 3) slightly reduced the amount of stress in all control points, except for the zone around the fixing screws, where a 10 % increase in stress was recorded, which is a consequence of its growth on the fixing screws. So, the indicators for the roots of the arches of the vertebrae Th_{X}, Th_{XI}, L_{I} and L_{II} were 8.0; 5.4; 7.5 and 12.2 MPa, respectively. In addition, this modification of the model was characterized by the highest, compared to other options, stress indicators in transpedicular screws, which is of fundamental importance for predicting the ability of fixation in the remote period.

The use of transverse ties together with short fixing screws (Fig. 4) had a positive effect on the stress-strain state of the model, in particular, it contributed to a decrease in the value of the maximum stress at all control points. The biggest difference was registered in the screw entry zones at the root of the arches. The stress reduction in these areas, compared to the use of short screws without transverse ties, averaged 11.8 %. In addition, the use of transverse fixators made it possible to reduce the load on transpedicular screws by an average of 7.0 %. The stress on the ties was 21.7 and 17.2 MPa on the top and bottom, respectively.

Transverse ties in combination with long fixing screws (Fig. 5) for the inclination of the trunk to the left also contributed to the reduction of stress in all control points of the model compared to the model without ties. The biggest difference (170 %) was registered in the roots of the vertebral arches. Compared with the short screw fixation model with transverse ties, the use of bicortical screws demonstrated a slight biomechanical advantage.

Information on the amount of tension in all control points of transpedicular fixation models is given in Table 2.

A comparison of the stress indicators under the influence of the load, which simulates the inclination of the trunk to the left, at the control points on the bone elements of the transpedicular fixation models (Fig. 6) revealed certain differences between the transpedicular fixation options and a tendency to decrease the indicators when using long screws and transverse ties. It is worth noting the fact that in the case of using long fixing screws without transverse ties, the tension in the vertebral bodies around the screws increased significantly.

It was established that in the case of a trunk tilt to the left, the amount of stress in the metal elements in different versions of transpedicular fixation differs slightly (Fig. 7). At most control points, the combination of monocortical screws and transverse ties showed the lowest stress values.

Discussion

Due to the small number of publications, it is impossible to compare the results obtained by us with the indicators of other researchers. Despite the widespread use of the finite element analysis method during the simulation of the correction of various pathological conditions of the human musculoskeletal system in general, and in particular spinal injuries, it was not possible to find studies comparable in design to ours. This is probably explained by the significant variability of approaches to surgical correction of traumatic injuries of the TLJ. Some authors adhere to the most conservative tactics, claiming that resection of the vertebral body in case of fractures is impractical, and posterior stabilization with appropriate postoperative rehabilitation makes it possible to achieve adequate consolidation of fragments [15].

On the other hand, the improvement of medical instruments and more modern methods of anesthetic support made it possible to actively use lateral and anterolateral accesses to the area of the TLJ with

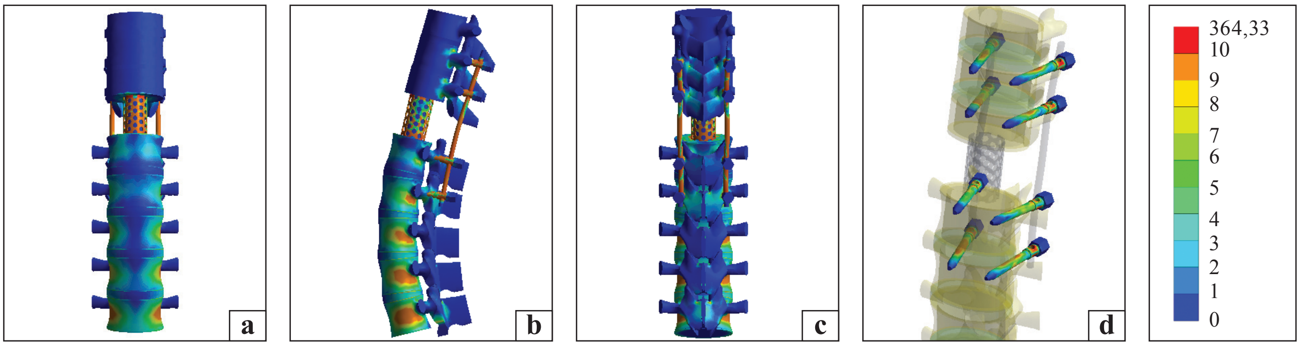

Fig. 2. Stress distribution in the model of the thoracolumbar spine after resection of the Th_{XII} vertebra under the influence of a load that simulates a trunk tilt to the left. Transpedicular fixation with short screws without transverse ties (modification of model No. 1): a — anterior view; b — lateral view; c — posterior view; d — screws

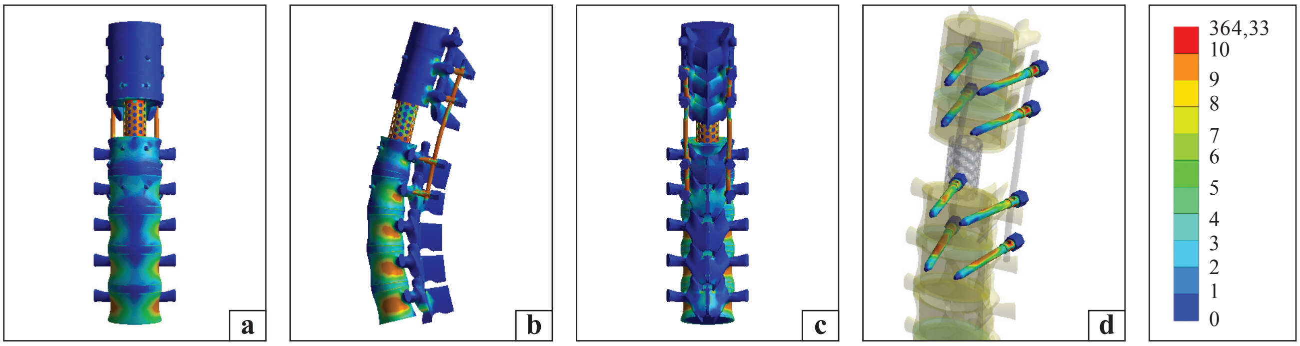

Fig. 3. Stress distribution in the model of the thoracolumbar spine after resection of the Th_{XII} vertebra under the influence of a load that simulates a trunk tilt to the left. Transpedicular fixation with bicortical screws without transverse ties (modification of model No. 2): a — anterior view; b — lateral view; c — posterior view; d — screws

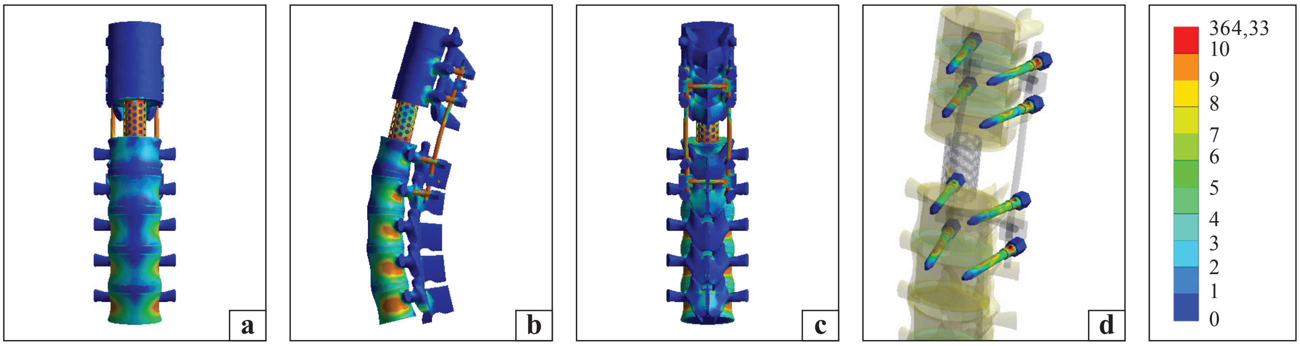

Fig. 4. Stress distribution in the model of the thoracolumbar spine after resection of the Th_{XII} vertebra under the influence of a load that simulates a trunk tilt to the left. Transpedicular fixation with monocortical screws in the presence of transverse ties in the system (modification of model No. 3): a — anterior view; b — lateral view; c — posterior view; d — screws

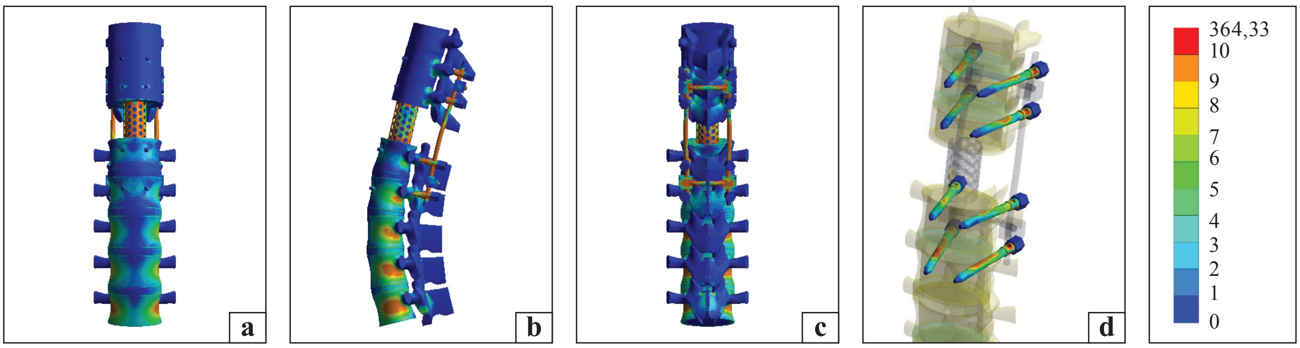

Fig. 5. Stress distribution in the model of the thoracolumbar spine after resection of the Th_{XII} vertebra under the influence of a load that simulates a trunk tilt to the left. Transpedicular fixation with bicortical screws in the presence of transverse ties in the system (modification of model No. 4): a — anterior view; b — lateral view; c — posterior view; d — screws

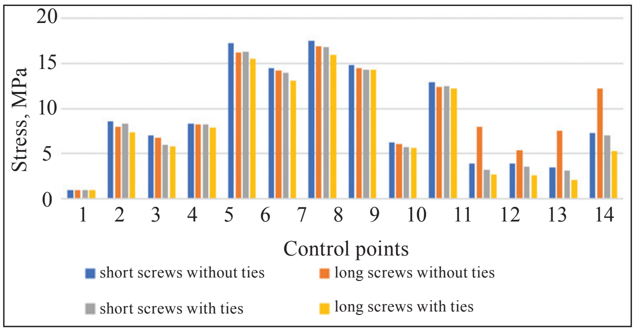

Fig. 6. The amount of stress at the control points on the bone elements of the models

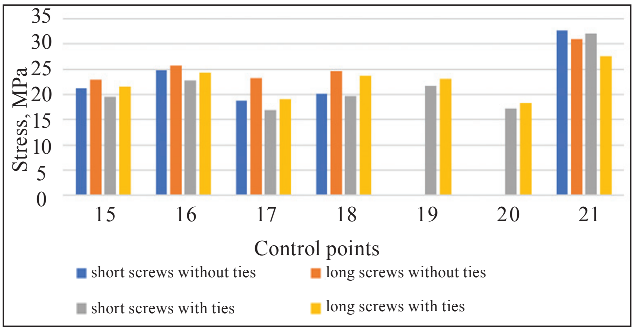

Fig. 7. The amount of stress at the control points on the elements of the metal structures of the models

Table 2

Stresses under the influence of a load that simulates a trunk tilt to the left in models of the thoracolumbar spine after resection of the Th_{XII} vertebra with different options for transpedicular fixation

Control point			Stress, MPa			
			screws without ties		screws with ties	
№	зона		short	long	short	long
1	Bony tissue	The body of the Th_{IX} vertebra	1.0	1.0	1.0	1.0
2		The body of the Th_{X} vertebra	8.6	8.0	8.3	7.4
3		The body of the Th_{XI} vertebra	7.0	6.8	6.0	5.8
4		The body of the L_{I} vertebra	8.3	8.2	8.2	7.9
5		The body of the L_{II} vertebra	17.2	16.2	16.3	15.5
6		The body of the L_{III} vertebra	14.5	14.2	13.9	13.1
7		The body of the L_{IV} vertebra	17.5	16.9	16.8	15.9
8		The body of the L_{V} vertebra	14.8	14.5	14.3	14.3
9		The lower locking plate of Th_{XI} vertebra	6.2	6.1	5.7	5.6
10		The upper locking plate of the L_{I} vertebra	12.9	12.4	12.5	12.2
11		Entry of screws into the arch of the Th_{X} vertebra	3.9	8.0	3.2	2.7
12		Entry of screws into the arch of the Th_{XI} vertebra	3.9	5.4	3.6	2.6
13		Entry of screws into the arch of the L_{II} vertebra	3.5	7.5	3.1	2.1
14		Entry of screws into the arch of the L_{III} vertebra	7.3	12.2	7.0	5.3
15	Metal constructions	Screws in the body of the Th_{X} vertebra	21.2	23.0	19.5	21.6
16		Screws in the body of the Th_{XI} vertebra	24.8	25.7	22.8	24.3
17		Screws in the body of the L_{I} vertebra	18.7	23.3	16.9	19.1
18		Screws in the body of the L_{II} vertebra	20.2	24.6	19.7	23.7
19		Ties between the screws in the bodies of the Th_{X} and Th_{XI} vertebra	—	—	21.7	23.1
20		Ties between the screws in the bodies of the L_{I} and L_{II} vertebra	—	—	17.2	18.3
21		Interbody support	32.7	30.9	32.0	27.5

subsequent resection of the vertebral body. Such interventions are mostly combined with posterior stabilization. Discussion of the advantages of surgical approaches (anterior, posterior or combined) for spinal injuries is still relevant [16, 17]. Mostly, in biomechanical studies, these, “most modern” tactical approaches are considered [18–20].

Gradually accumulated clinical experience and analysis of the long-term results of treatment of patients with traumatic injuries of the thoracolumbar spine allowed a number of researchers to conclude that in most cases it is the isolated posterior access that is the most reasonable, as it allows solving all surgical tasks with minimal risks of iatrogenic injuries of critical importance anatomical structures [21–23]. Such a strategy, against the background of the almost complete absence of biomechanical studies that would correspond to the volume of interventions being carried out, determines the relevance of our study.

One of the few publications that make it possible to indirectly confirm the results of our research is the work of M. Alizadeh and M. R. A. Kadir [24]. The authors demonstrate the expediency of using 8-screw stabilization for resection of the body of one vertebra in the TLJ area. The high stress on the elements of the model was confirmed during the simulation of lateroflexion. However, the analysis of the load on the components of the metal structure was not carried out in this study, and the main attention was paid to the assessment of the condition of the intervertebral discs. A similar load distribution during lateral tilt simulation was demonstrated by M. J. Bolesta et al. by ex vivo loading of spinal column fragments [25].

Analysis of the nature of load distribution during lateroflexion revealed peculiarities compared to other load patterns. Thus, high stress indicators were registered in the body of the L_{II} vertebra, which indicates that the tilt to the side is the most unfavorable in terms of the extraction risks of the most caudally located elements of the stabilization system. The load on the screws is maximum both in the body of the L_{II} vertebra, which is natural, and in the body of the Th_{XI} vertebra. However, transpedicular screws are usually loaded relatively uniformly at different levels, and the difference in performance regardless of the design of the stabilization system does not exceed 10 %. This to some extent confirms the mechanical ability of 8-screw fixation for resection of one vertebra in the area of the TLJ, as no significant risks of fragmentation of transpedicularly installed elements were found.

The comparison of the results presented in this publication with the data of our earlier studies is quite indicative. Thus, with the resection of two vertebral bodies in the TLJ zone, similar types of stabilization during lateroflexion cause much less load on the corresponding vertebral bodies and much more on the transpedicular screws, which does not exceed the strength characteristics. This testifies to the adequacy of the given results, as it correlates with clinical observations of the course of the postoperative period in patients who underwent surgical interventions, comparable to the simulated ones.

The fragment of the study presented in the publication is the final in a series of experiments aimed at optimizing the reliability of transpedicular fixation of a traumatically damaged area of the thoracic spine. The comparison and analysis of the data obtained for different options for loading the stabilized area of the TLJ will make it possible to identify the most critical areas and provide practical recommendations for reducing the risks of fixation failure in the remote postoperative period.

Conclusions

The use of long fixation screws with a trunk tilt to the left causes stress in the bony elements somewhat less than in the model with short screws. At the same time, the stress on the screws themselves and the bone tissue around them increases. The difference in indicators at most monitored points of both models does not exceed 10%.

Transverse ties help to reduce stress at all control points on models with both short and long locking screws.

Conflict of interest. The authors declare no conflict of interest.

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BIOMECHANICAL ASPECTS OF TRANSPEDICULAR FIXATION IN THE THORACOLUMBAR JUNCTION AREA: THE INFLUENCE OF LATEROFLEXION

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