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ASSESSMENT OF BIOMECHANICAL STABILITY OF THE THORACOLUMBAR JUNCTION WITH A BURST FRACTURE OF TH12 FOLLOWING SURGICAL STABILIZATION UNDER ROTATIONAL LOADING

Oleksii Nekhlopochyn, Vadim Verbov, Ievgen Cheshuk, Mykhailo Karpinsky, Olexander Yaresko

The thoracolumbar junction is the most vulnerable to traumatic injuries, with over 65 % of injuries to the thoracolumbar spine occurring in this region.
Objective: *To examine the stress-strain state of the thoracolumbar spine model with a burst fracture of the Th12 vertebra under various transpedicular fixation options influenced by rotational loading.*
Materials and Methods: *A mathematical finite-element model of the human thoracolumbar spine was developed, including a burst fracture of the Th12 vertebra and a transpedicular stabilization system containing eight screws implanted in the Th10, Th11, L1, and L2 vertebrae. Four variants of transpedicular fixation were modelled using short and long screws passing through the anterior surface of the vertebra, with and without two crosslinks.*
Results: *The analysis showed sufficiently high loading values for both the bone structures of the models and the elements of the metal construct. The maximum stress level in the body of the damaged vertebra was 33.2, 26.7, 30.1, and 24.2 MPa, respectively, for models with monocortical screws without crosslinks, bicortical screws without crosslinks, monocortical screws with crosslinks, and bicortical screws with crosslinks. High values were also recorded for the vertebrae adjacent to the damaged one: 13.0, 8.4, 10.9, and 7.1 MPa for the L1 vertebra and 10.2, 8.9, 7.1, and 6.2 MPa for the Th11 vertebra in the respective models. The stress on the supporting rods was registered at 582.0, 512.5, 512.6, and 452.7 MPa respectively.*
Conclusion: *The conducted analysis demonstrated that under rotational loading, the model with monocortical screws without crosslinks shows the highest peak loads at control points, whereas the model with bicortical screws and crosslinks shows the minimum. Meanwhile, models with short screws and crosslinks and long screws without crosslinks exhibit comparable results*
Keywords: *Thoracolumbar junction, traumatic injury, transpedicular fixation, burst fracture, rotational loading*

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1. Introduction

The thoracolumbar junction (TLJ) of the spine, spanning from Th10 to L2, is the most susceptible region to traumatic injuries [1]. This increased vulnerability is due to the unique biomechanical properties of this segment: the thoracic part of the spine, situated above this transition, features a rigid structure reinforced by the attachment of ribs and the presence of the sternum, which significantly restricts its mobility. Conversely, the lumbar section, beginning below, exhibits considerably greater flexibility. This sharp contrast in mobility between adjacent segments forces the TLJ to adapt to diverse mechanical loads, subjects it to increased mechanical stress and, consequently, to potential injuries [2]. According to epidemiological studies, over 65 % of all traumatic injuries to the thoracolumbar spine occur in the TLJ area [3].

Currently, practising spinal surgeons have a wide range of methods and techniques at their disposal that successfully address most challenges in restoring the supportive capability of the damaged vertebral-motor segment [4]. Surgical interventions developed for the TLJ area are performed using classical posterior, anterior, and combined approaches [5]. However, based on the principle that the maximum result should be achieved with minimal intervention, classical posterior approaches are predominantly used. Moreover, the role of anterior approaches in treating TLJ trauma, traditionally used in oncological practice, remains controversial [6].

The first publication of results for thoracolumbar spine stabilization using the transpedicular system, presented in 1986 by R. Roy-Camille and colleagues, can indeed be considered a significant milestone in the evolution of spinal stabilization methods [7]. Transpedicular fixation, compared to earlier methods, has a number of undeniable advantages as it easily modulates the necessary spinal axis over any length and does not depend on the degree of damage to the bone structures of the posterior support complex [8]. The further introduction of modern intraoperative visualization methods into practical healthcare has allowed some modifications to the installation technique and, in some cases, minimized surgical trauma through the use of minimally invasive percutaneous methods of transpedicular fixation. The technique, first used in the treatment of thoracolumbar spine injuries in 2004 by R. Assaker, significantly reduces surgical trauma to soft tissues, reduces blood loss, minimizes the risks of postoperative complications, reduces pain syndrome, and generally shortens the duration of hospital stays, which undoubtedly has both medical and economic benefits [9–11].

As a result, there is now a trend toward the active use of minimally invasive stabilization methods for thoracolumbar spine injuries in all cases where open decompression is not necessary [12]. However, despite the apparent benefits of this approach at first glance, some authors note that minimally invasive stabilization, compared to the open installation of the system, shows worse results in terms of maintaining the spinal axis [13].

In a detailed biomechanical analysis of the discussed methods, a fundamental difference that could theoretically result in varying outcomes is specifically the presence of crosslinks, which are not included in the percutaneous installation technique, and to some extent, the length of the transpedicular screws [14, 15]. However, the literature review focused on assessing the load on bone structures and the components of the metal construct, installed due to the traumatic injury TLJ that does not require decompression, does not allow for a definitive conclusion on this aspect of the problem. This work is part of a broader study aimed at investigating the load distribution on the stabilized thoracolumbar junction in the event of a traumatic injury.

The aim: To investigate the stress-strain state of the thoracolumbar spine model with a burst fracture of the Th12 vertebra under various transpedicular fixation scenarios subjected to rotational loading.

2. Materials and methods

In the Biomechanics Laboratory of the Sitenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine, a mathematical finite-element model of the human thoracolumbar spine was developed, incorporating a burst fracture of the Th12 vertebra. The model also includes a transpedicular stabilization system with eight screws implanted in the vertebrae Th10, Th11, L1, and L2. A full description and characteristics of the model are detailed in previous publications [16, 17].

To simulate the burst fracture, the body of the Th12 vertebra was divided into separate fragments along several planes (Fig. 1). The gaps between the fragments were filled with a material simulating interfragmentary regeneration.

Four variants of transpedicular fixation were modelled using short fixing and long screws that pass through the anterior surface of the vertebral body, both with and without two crosslinks (Fig. 2).

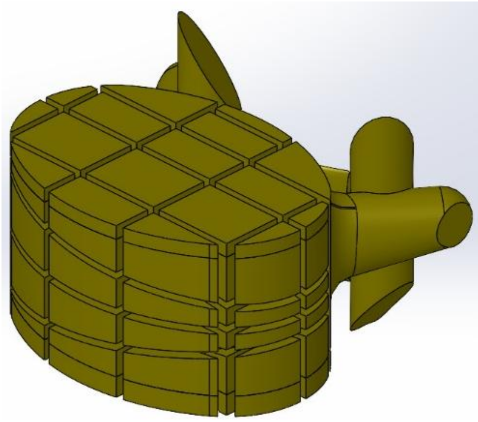

Fig. 1. Model of the Th12 vertebra

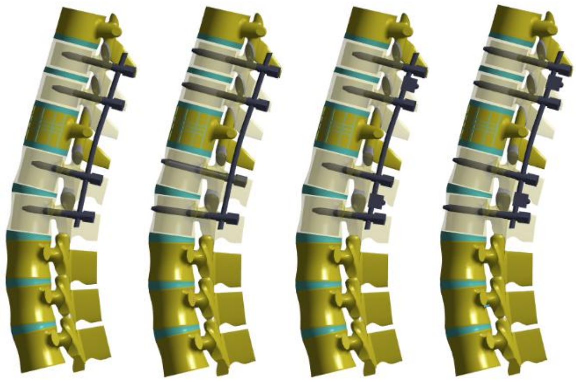

Fig. 2. Models with different variants of transpedicular fixation: *a* – short screws without crosslinks; *b* – long screws without crosslinks; *c* – short screws with crosslinks; *d* – long screws with crosslinks

During modelling, it was assumed that the material was homogeneous and isotropic. A 10-node tetrahedral element with quadratic approximation was used as the finite element. The mechanical properties of biological tissues, such as cortical and cancellous bone and intervertebral discs, were selected based on literature data [18, 19]. Titanium was used for the elements of the metal construct, with its mechanical characteristics chosen from technical literature [20]. The analysis employed parameters such as Young's modulus (E) and Poisson's ratio (ν). Information about the mechanical properties of the materials is presented in Table 1.

Table 1

Mechanical Properties of Materials Used in Modeling

Material	Young's Modulus (MPa)	Poisson's Ratio
Cortical Bone	10.000	0.3
Cancellous Bone	450	0.2
Articular Cartilage	10.5	0.49
Intervertebral Discs	4.2	0.45
Interfragmentary Regenerate	1.0	0.45
Titanium VT-16	110.000	0.3

The investigation of the stress-strain state of the models was performed under rotational loading. For this purpose, a torque of 10 Nm was applied to the Th9 vertebra body. The model was rigidly fixed along the distal surface of the L5 vertebral disc. The loading scheme for the models can be seen in Fig. 3a.

To analyze the impact of the transpedicular fixation method on the stress-strain state of the models, a series of control points were selected where the stress magnitude was measured. These points are located in strategically important areas of the model, which are crucial for assessing the level of stress. The control points play a key role in identifying weak zones in the construction and the effectiveness of transpedicular fixation. The placement of these points, their detailed positioning, and distribution on the model are shown in Fig. 3, b, c, d.

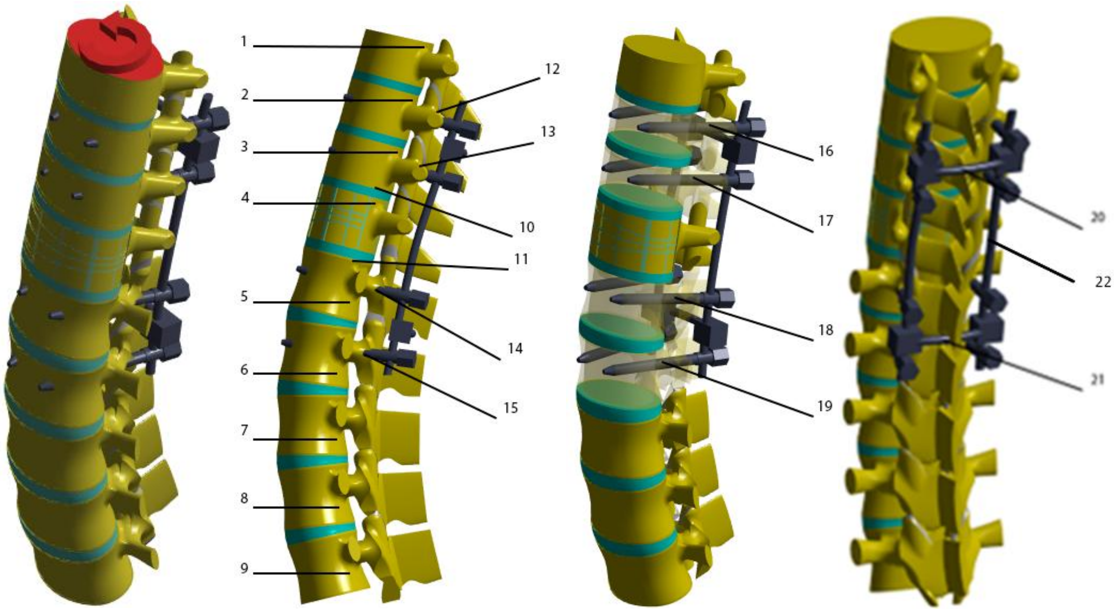

Fig. 3. Loading scheme of the models (a) and location of control points (b, c, d): 1 – body of vertebra Th9; 2 – body of vertebra Th10; 3 – body of vertebra Th11; 4 – body of vertebra Th12; 5 – body of vertebra L1; 6 – body of vertebra L2; 7 – body of vertebra L3; 8 – body of vertebra L4; 9 – body of vertebra L5; 10 – lower endplate of vertebra Th11; 11 – upper endplate of vertebra L1; 12 – entry of screws into the arch of vertebra Th10; 13 – entry of screws into the arch of vertebra Th11; 14 – entry of screws into the arch of vertebra L1; 15 – entry of screws into the arch of vertebra L2; 16 – screws in the body of vertebra Th10; 17 – screws in the body of vertebra Th11; 18 – screws in the body of vertebra L1; 19 – screws in the body of vertebra L2; 20 – crosslinks between screws in the bodies of vertebrae Th10 and Th11; 21 – crosslinks between screws in the bodies of vertebrae L1–L2; 22 – rods

The investigation of the stress-strain state of the models was conducted using the finite element method. The von Mises stress, an effective evaluative measure for determining the degree of deformation and stress in materials under load, was chosen as the primary criterion for assessment [21]. The modelling was carried out using SolidWorks, an automated design system developed by the French company Dassault Systemes. Calculations were performed using the CosmosM software suite, part of this software package [22].

3. Results

In the initial phase of the study, the stress-strain state of the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under rotational loading was analyzed. In this case, short screws were used for transpedicular fixation without crosslinks. The distribution of stresses in the model is shown in Fig. 4.

During torsional loading of the model with transpedicular fixation using short screws without crosslinks, the maximum stress observed was 33.2 MPa in the body of the Th12 vertebra. High-stress values were also recorded around the fixing screws in the arches of the L1 vertebra – 27.6 MPa and the Th11 vertebra – 14.7 MPa. In these vertebral bodies, the maximum stress recorded was 13.0 MPa in L1 and 10.2 MPa in Th11. The least stressed were the bodies of the Th9 and L5 vertebrae, where stress levels were measured at 5.4 MPa and 6.5 MPa, respectively. Among the metal construct elements, the highest stress value (56.0 MPa) was observed on the screws in the Th11 vertebra, with the lowest (13.3 MPa) on the screws in the L2 vertebra. Additionally, one of the most critical elements of the stabilization system – the support rods – drew attention. The analyzed modification shows the highest stress indicator among all considered models, measuring 582.0 MPa.

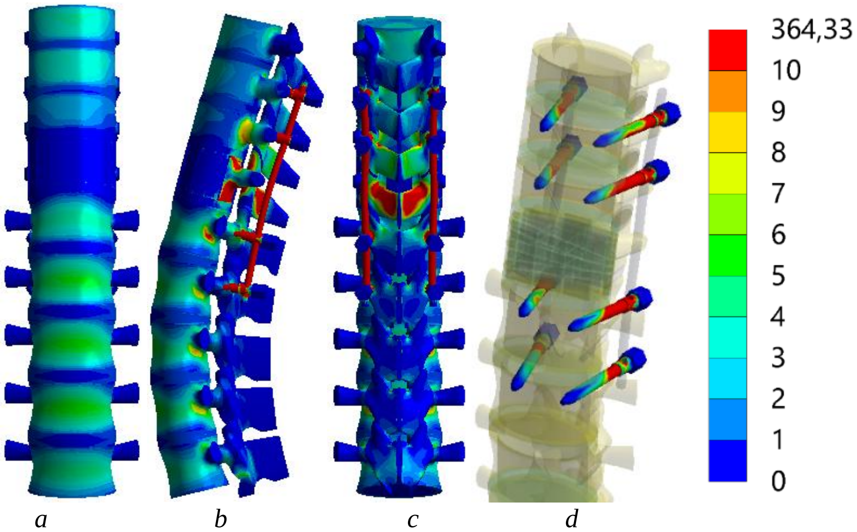

Fig. 4. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under rotational loading. Transpedicular fixation with short screws without *crosslinks: a* – front view; *b* – side view; *c* – rear view; *d* – screws

The use of long transpedicular screws without crosslinks during torsional loads leads to reduced stress levels in all vertebral bodies (Fig. 5). The exception is the lower endplate of the Th11 vertebral body, where stress levels increased to 5.8 MPa. The stress levels around the screws themselves also decrease, except for the screws in the Th10 vertebra, where they rise to 15.0 MPa. This is due to the fact that the stress on the screws in the Th10 vertebra increases to 72.6 MPa, while stress on the screws in other vertebrae significantly decreases. Additionally, a significant decrease in stress (by 12 %) is observed on the support rods, which amounts to 512.5 MPa. The impact of crosslinks on the stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under torsional loading was investigated (Fig. 6).

The simulation results demonstrated that the use of crosslinks in combination with short screws under torsional loads reduces the stress level at all control points on the bone elements of the model. Exceptions are the lower endplate of the Th11 vertebra and the upper endplate of the L1 vertebra, which are in contact with the damaged vertebra. Stress in these areas increased to 4.8 MPa and 14.1 MPa, respectively. On the fixing screws in the bodies of the Th11, L1, and L2 vertebrae, a significant reduction in stress levels was observed, with a minor increase (up to 30.4 MPa) on the screws in the Th10 vertebra. Stress on the upper and lower crosslinks was 30.1 MPa and 22.8 MPa, respectively.

The load on the rods essentially matches that of the previously considered model and is measured at 512.6 MPa.

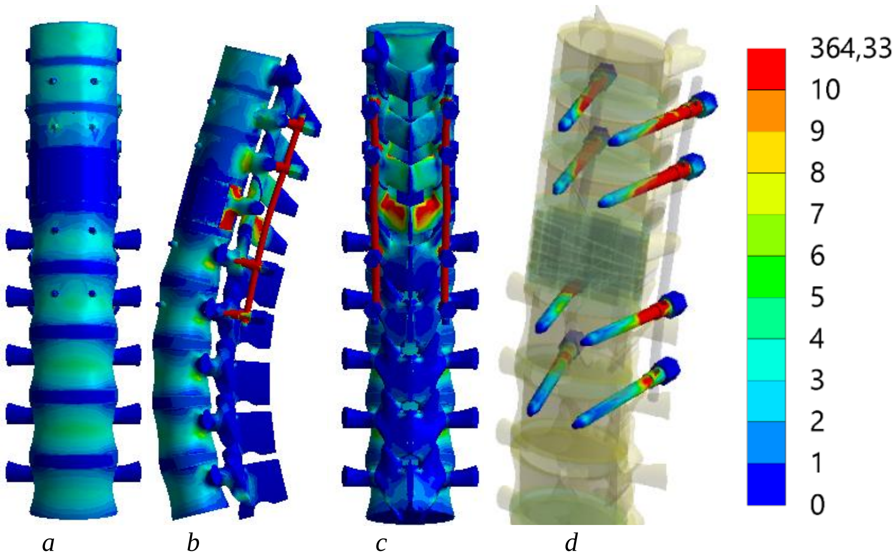

Fig. 5. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under torsional loading. Transpedicular fixation using long screws without crosslinks:
a – front view; *b* – side view; *c* – rear view; *d* – screws

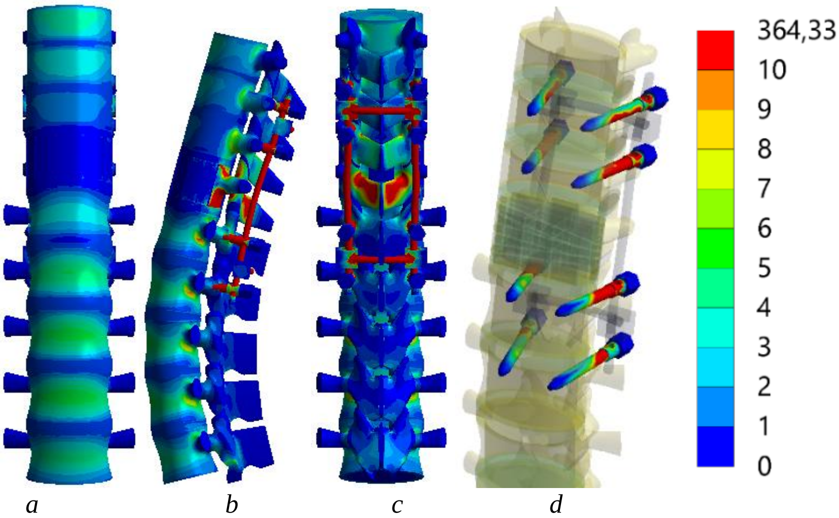

Fig. 6. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under torsional loading. Transpedicular fixation using short screws with crosslinks:
a – front view; *b* – side view; *c* – rear view; *d* – screws

The use of long bicortical transpedicular screws in combination with crosslinks demonstrates a reduction in loads across almost all elements of the model compared to the model with short screws (Fig. 7). Specifically, this indicator decreases directly in the posterior elements of the damaged vertebral body to 24.5 MPa. Similar values are only registered in the model with long screws without crosslinks at 26.7 MPa, while using short screws results in stress values exceeding 30 MPa in the damaged body, regardless of the presence of crosslinks. The advantages of this model modification are also observed concerning the loading of the stabilized vertebral bodies. For instance, average indicators are 23 % lower compared to the "short screws + crosslinks" model and 14.6 % lower compared to "long screws without crosslinks". Overall, it should be noted that under the considered stabilization method and loading pattern, the stress indicators in the bodies of stabilized vertebrae are quite high. The screw entry zone into the arch of the fixed vertebrae, when using bicortical screws and crosslinks, also features the lowest stress indicators among all considered modifications and does not exceed 10 MPa, except for the Th10 vertebra where the analyzed stress value is calculated at 12.1 MPa. The contact area of adjacent vertebrae Th11 and L1 with the damaged one also shows certain advantages in terms of loading, measuring 5.2 and 3.8 MPa, respectively. The closest values are only noted in the model with long screws and without crosslinks. The support rods exhibit a clear advantage of the considered modification – 452.7 MPa, which is 11.7 % less than in the model with short screws and crosslinks.

Information on the stress magnitude at all control points of the models for all transpedicular fixation options is presented in Table 2.

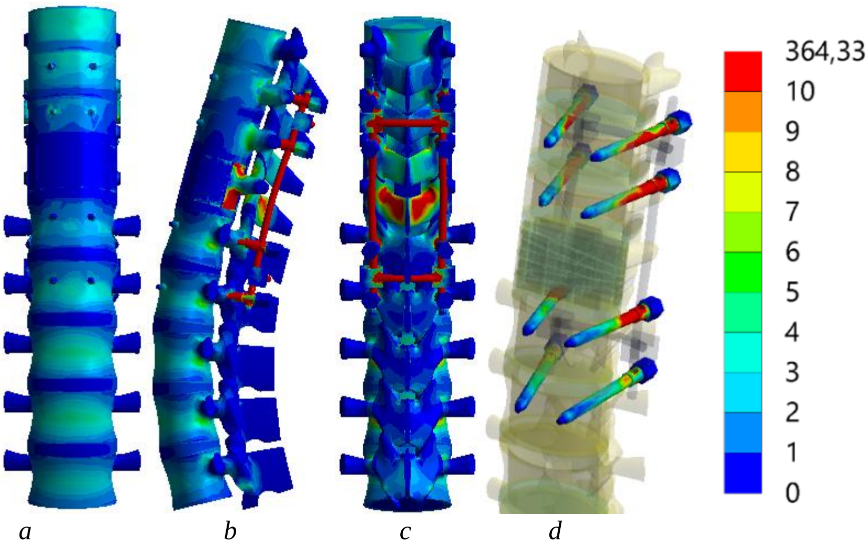

Fig. 7. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under torsional loading. Transpedicular fixation using long screws with crosslinks:
a – front view; *b* – side view; *c* – rear view; *d* – screws

Table 2

Stress under torsional loading in models of the thoracolumbar spine with a burst fracture of the Th12 vertebra for various transpedicular fixation options

No	Control Points		Stress, MPa			
			Model without Crosslinks		Model with Crosslinks	
			Short Screws	Long Screws	Short Screws	Long Screws
1	Bone Tissue	Th9 Vertebra Body	5.4	4.9	5.4	4.8
2		Th10 Vertebra Body	9.0	8.6	8.3	7.6
3		Th11 Vertebra Body	10.2	8.9	7.1	6.2
4		Th12 Vertebra Body	33.2	26.7	30.1	24.2
5		L1 Vertebra Body	13.0	8.4	10.9	7.1
6		L2 Vertebra Body	9.3	6.8	10.0	7.0
7		L3 Vertebra Body	9.6	7.4	8.9	6.5
8		L4 Vertebra Body	9.2	7.3	8.5	6.3
9		L5 Vertebra Body	6.5	4.5	5.1	4.0
10		Lower Endplate of Th11	3.3	5.8	4.8	5.2
11		Upper Endplate of L1	8.4	4.4	14.1	3.8
12		Entry of Screws into Arch of Th10	8.4	15.0	6.6	12.1
13		Entry of Screws into Arch of Th11	14.7	11.7	11.0	9.0
14		Entry of Screws into Arch of L1	27.6	13.3	20.0	9.9
15		Entry of Screws into Arch of L2	9.5	8.1	5.8	7.8
16	Metal Constructs	Screws in Th10 Body	26.3	72.6	30.4	63.7
17		Screws in Th11 Body	56.0	44.7	38.1	32.4
18		Screws in L1 Body	24.0	17.2	17.2	12.1
19		Screws in L2 Body	13.3	10.0	15.7	10.6
20		Crosslinks between Th10 and Th11 Screws	-	-	30.1	10.8
21		Crosslinks between L1 and L2 Screws	-	-	22.8	10.7
22		Connecting rods	582.0	512.5	512.6	452.7

4. Discussion

Analyzing the results obtained in this study, along with previously conducted modelling of other types of surgical interventions for traumatic injuries to the thoracolumbar area, several distinctive features should be noted [23]. For instance, rotational loading in the case of a burst fracture of one of the vertebral bodies shows quite high load indicators, with peak loads in some cases exceeding those in models with a completely resected body replaced by a titanium implant. No similar comparative studies have been found in the literature. At the same time, several researchers note that rotational instability is the most critical aspect in the case of burst fractures [24]. Significant load indicators on the connecting rods also draw attention. For example, in modelling transpedicular fixation using monocortical screws without installing crosslinks, load indicators on the rods approach the strength limit of AISI 316L surgical steel, which does not exceed 600 MPa [20]. The use of titanium, typical in modern stabilization systems, seems more advantageous as the strength limit of VT16 titanium ranges from 1030 MPa to 1225 MPa [25]. Nevertheless, our modelling results provide some explanation for instances of fragmentation of the connecting beams in the transpedicular stabilization system, as reported in the literature and also observed in our clinical practice [26]. Furthermore, substantial loading indicators are also observed on the transpedicular screws themselves – the second most commonly damaged element in the metal construct. Researchers have noted that in most cases, fragmentation is most likely to occur at the most cranial or caudal screws [27, 28]. Our study shows that under rotational loads, it is precisely the screws in the most cranial positions (in our model, installed in the bodies of Th10) that exhibit peak loads.

The second significant finding from the analysis, which directly corresponds to the goals of the research, is that minimally invasive stabilization using monocortical screws has certain disadvantages compared to methods that involve the installation of crosslinks. Clinical observations described by several researchers are confirmed in our biomechanical analysis. For instance, Shengtao Dong and colleagues, analyzing the results of minimally invasive percutaneous stabilization of the thoracolumbar spine due to the presence of a burst fracture in one of the vertebrae, report that in 35.3 % of cases, there is negative radiological progression [13]. Researchers identified risk factors including the presence of intervertebral disc damage, surgically corrected kyphotic deformation, significant pre-surgical kyphotic deformation of the segment, and an expanded interpedicular distance. Hazem M. Alkosha and co-authors, evaluating the effectiveness of stabilization based on the Thoracolumbar Injury Classification and Severity Score (TLICS), note that minimally invasive stabilization is suitable for TLICS-4 injuries, while more severe injuries require open interventions [29, 30]. On the other hand, a considerable number of studies do not find significant differences when using the considered methods [12, 31].

Our results partially explain this discrepancy. Detailed analysis of load indicators, presented in Table 2, shows that the use of long screws without crosslinks yields values close to those of the model with short screws and crosslinks, suggesting that the clinical outcomes of open and minimally invasive stabilization should be comparably effective. Moreover, it should be noted that only the model with bicortical screws and crosslinks allows for the maximum reduction of load in the "bone tissue-metal construct" system. This fact must be considered when performing surgical interventions in patients with osteoporosis. Meanwhile, literature analysis finds clinical confirmation for this assertion [14, 32].

Overall, characterizing the data obtained in this work, it is clear that the biomechanical modelling conducted is corroborated by clinical observations, indicating the validity of the model. At the same time, a conclusion about the appropriateness of using a particular method of pedicle screw fixation, considering all risks and benefits, can be made after analyzing all classic loading patterns, which requires further research.

Study limitations. It should be noted that in constructing the model, the material was considered homogeneous and isotropic, and the poroviscoelastic nature of the spinal tissues was not taken into account. This assumption was made because all loads were applied under quasi-static loading conditions. This approach is commonly used in most finite element models of morphologically complex and heterogeneous systems, such as the human spine. By disregarding individual characteristics determined by anatomical variability, this method allows for the identification of basic principles of load distribution that have the greatest clinical significance.

Prospects for further research. The ultimate goal of the ongoing study is to identify the optimal method for stabilizing the damaged spinal motion segment at TLJ area. A definitive conclusion can only be reached by analyzing the results of finite element modelling under all loading patterns. This constitutes the primary objective for future research.

5. Conclusions

The conducted analysis demonstrates that in modelling rotational loading, the model with monocortical screws without crosslinks shows the highest peak loads at control points, while the model with bicortical screws and crosslinks shows the minimum. Meanwhile, models with short screws and crosslinks and long screws without crosslinks show comparable results. Extrapolating the results to clinical practice, it can be suggested that in most clinical cases, the use of long bicortical screws installed minimally invasively will demonstrate an adequate radiological outcome. However, such a statement requires an analysis of the entire spectrum of possible loading patterns and clinical comparison.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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