Original article

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Impact of transpedicular fixation on thoracolumbar junction burst fracture stability: a biomechanical perspective

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Introduction. The treatment of burst fractures at the thoracolumbar junction remains a contentious issue in vertebrology. Despite a broad array of surgical interventions available, many surgeons favor isolated posterior stabilization, which can be performed using either minimally invasive or open approaches. However, the biomechanical properties of these methods have not been thoroughly investigated.

Objective: This study aims to evaluate the biomechanical stability of the thoracolumbar junction following transpedicular stabilization of a burst fracture at the Th12 vertebra, under different system configurations influenced by lateral flexion.

Materials and Methods: A mathematical finite element model of the human thoracolumbar spine, featuring a burst fracture at the Th12 vertebra, was developed. The model included a transpedicular stabilization system with eight screws, simulating "long" stabilization. We examined four variants of transpedicular fixation using both mono- and bicortical screws, with and without the inclusion of two cross-links.

Results: The study found that the load borne by the damaged Th12 vertebral body varied depending on the fixation system employed. Specifically, stress levels were 24.0 MPa, 27.3 MPa, 18.4 MPa, and 25.8 MPa for models with short screws without cross-links, long screws without cross-links, short screws with cross-links, and long screws with cross-links, respectively. At the screw entry points in the vertebral arch, the highest stress values were recorded at the L2 vertebra, showing 11.8 MPa, 14.0 MPa, 9.4 MPa, and 13.4 MPa for each respective model. Among the metal construct elements, the connecting rods consistently exhibited the highest stress, with values of 226.7 MPa, 313.4 MPa, 212.4 MPa, and 293.98 MPa, respectively.

Conclusion: The results underscore that utilizing cross-links in the stabilization of burst fractures at the thoracolumbar junction, which is only feasible through an open installation, somewhat mitigates stress within the stabilized spinal segment. Meanwhile, the modeling of lateral flexion revealed only minimal differences in stress values between open and minimally invasive installations.

Keywords: *burst fracture; thoracolumbar junction; transpedicular stabilization; finite element analysis; biomechanical properties; minimally invasive surgery*

Introduction. The first detailed morphological description of burst fractures (BF) was provided by Sir Frank Wild Holdsworth in 1963 [1]. Based on his dual-column theory, Holdsworth proposed that such injuries are stable, as the posterior support complex remains intact. In 1983, Francis Denis expanded on this by introducing a three-column theory of spinal stability [2]. According to Denis, the posterior column comprises the posterior support complex, including bone structures and ligaments; the anterior column consists of the anterior longitudinal ligament, the anterior part of vertebral body, and the intervertebral disc; and the middle column is defined by the vertebral body's posterior wall and the fibrous ring of the intervertebral disc, along with the posterior longitudinal ligament. Under this framework, BF that compromise two of the three columns are considered unstable. Despite extensive clinical data and a wealth of experimental research, the stability of BF remains an open question. Thus, the management strategies for patients with BF in the thoracolumbar spine continue to be highly debated [3].

A trend of the last few decades has been the active promotion and adherence to the principles of evidence-based medicine. Modern healthcare, particularly in relation to traumatic spinal injuries, faces two seemingly contradictory objectives. On one hand, the effectiveness of therapy is determined by the duration of disability, where surgical methods clearly have an advantage as they generally allow for a reduction in the duration of functional limitations under comparable conditions [4].

On the other hand, the economic aspect favors conservative methods as they are less costly [5].

The thoracolumbar junction is the most vulnerable region of the spine regarding traumatic injuries [6]. It is known that over 50% of all spinal injuries occur in the Th11-L2 vertebrae [7]. BF account for about 15-20% of these injuries. Due to the biomechanical characteristics of this section and the high frequency of injuries, therapeutic approaches to BF in this area are highly varied [8]. Posterior, anterior, combined, and hybrid surgical methods are commonly used. It should be noted that in cases where there are no neurological disorders and significant compression of the spinal canal—which is observed in 60-70% of all BF—the primary goal of surgical intervention is the preservation and, in some cases, correction of the spinal axis, and the elimination of instability until the consolidation of bone fragments [4]. So, the need for stabilization of such injuries is often temporary, and several authors have noted the appropriateness of removing metal constructs to remobilize previously fixed segments, which naturally leads to reduced pain and improved quality of life. This is why most practicing surgeons prefer isolated posterior transpedicular fixation as it is less traumatic during installation and more accessible for removal [9].

The ability to avoid open decompression of the spinal canal facilitates the widespread adoption of minimally invasive techniques for the placement of pedicle screws. This technique significantly reduces blood loss, shortens the duration of surgery, and consequently decreases the risks of postoperative complications and the length of hospital stays [10]. Most researchers report identical orthopedic outcomes using either minimally invasive or open screw placement methods [11]. However, some publications note a greater loss of spinal axis correction and vertebral body height specifically with minimally invasive screw placement [12, 13]. Such differences may be solely related to the features of the stabilization system, as minimally invasive placement does not involve the use of cross-links, which undoubtedly affects the load distribution in the stabilized section of the spine and may have specific clinical manifestations [14]. Meanwhile, a review of the literature reveals no studies evaluating the differences in BF stabilization with or without cross-links; moreover, the assessment of the depth of pedicle screw placement in the treatment of BF has also not been studied.

Objective: To analyze the load distribution in the thoracolumbar junction with a burst fracture of the Th12 vertebra under various modifications of the stabilizing transpedicular system influenced by lateral flexion.

Materials and Methods: In the Biomechanics Laboratory of Sytenko Institute of Spine and Joint Pathology, National Academy of Medical Sciences of Ukraine, a mathematical finite element model of the human thoracolumbar spine with a burst fracture at the Th12 vertebra was developed. The model incorporated a transpedicular stabilization system. An eight-screw “long” stabilization was simulated. Detailed descriptions and characteristics of the model have been provided in previous publications [15, 16].

To simulate the BF, the body of the Th12 vertebra was divided by several planes into separate fragments ***(see Fig. 1)***. The gaps between the fragments were filled with a material that simulated interfragmentary regenerate, to replicate the conditions of a real burst fracture.

Four variants of transpedicular fixation were modeled using both short fixation screws and long screws that pass through the anterior wall of the vertebral body, with and without the use of two cross-links ***(see Fig. 2)***.

In the simulation, the material was assumed to be homogeneous and isotropic [17]. A 10-node tetrahedral finite element with quadratic approximation was selected for the analysis. The mechanical properties of biological tissues (cortical and cancellous bone, intervertebral discs) for the mathematical modeling were chosen based on data from references [18, 19]. The material for the metal construct elements was titanium. Mechanical characteristics of artificial materials were selected according to technical literature [20]. For the analysis, characteristics such as the Young's modulus (E) and the Poisson's ratio (ν) were used. Data on the mechanical properties of the materials are presented in ***Table 1***.

The stress-strain state of the models was investigated under the influence of a bending load acting from right to left, simulating a leftward tilt of the torso, with the distal surface of the L5 disc being rigidly fixed. The load was applied to the body of the Th9 vertebra and the right facet joint. The load magnitude was 350 N. The loading scheme for the models is shown in ***Fig. 3a***.

For the convenience of studying changes in the stress-strain state of the models depending on the method of transpedicular fixation, the stress magnitude was determined at multiple control points ***(see Figs. 3b, c, d)***.

The stress-strain state of the models was investigated using the finite element method. The criterion for assessing the stress state of the models was von Mises stress [21]. The modeling was performed using the SolidWorks computer-aided design system (Dassault Systèmes, France). Calculations of the stress-strain state of the models were carried out using the CosmosM software suite [22].

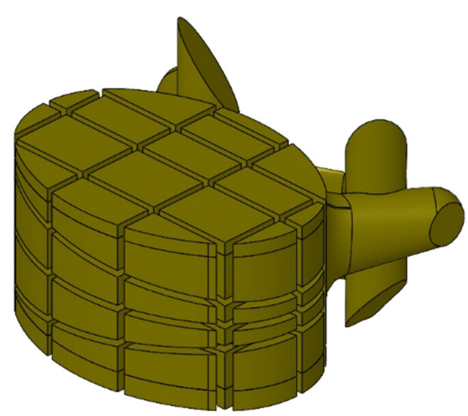

Fig. 1. *Th12 Vertebra Model*

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

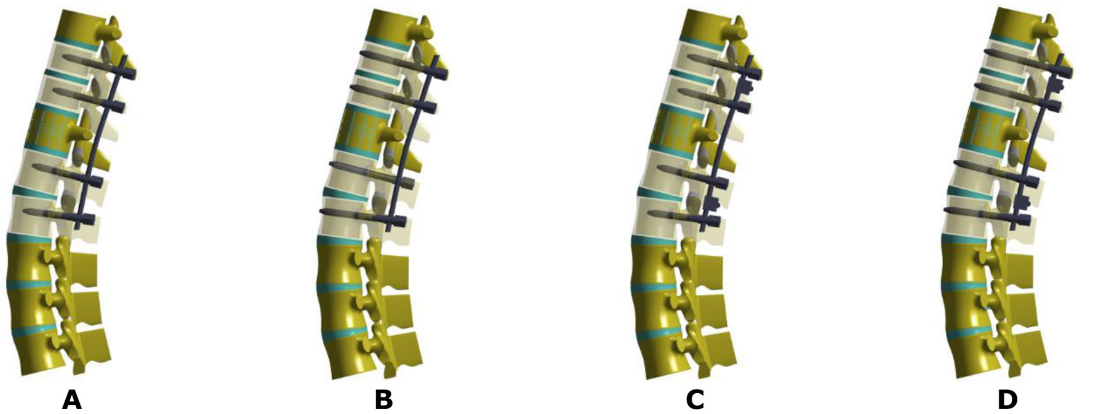

Fig. 2. Models with different variants of transpedicular fixation: a - short screws without cross-links; b - long screws without cross-links; c - short screws with cross-links; d - long screws with cross-links

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

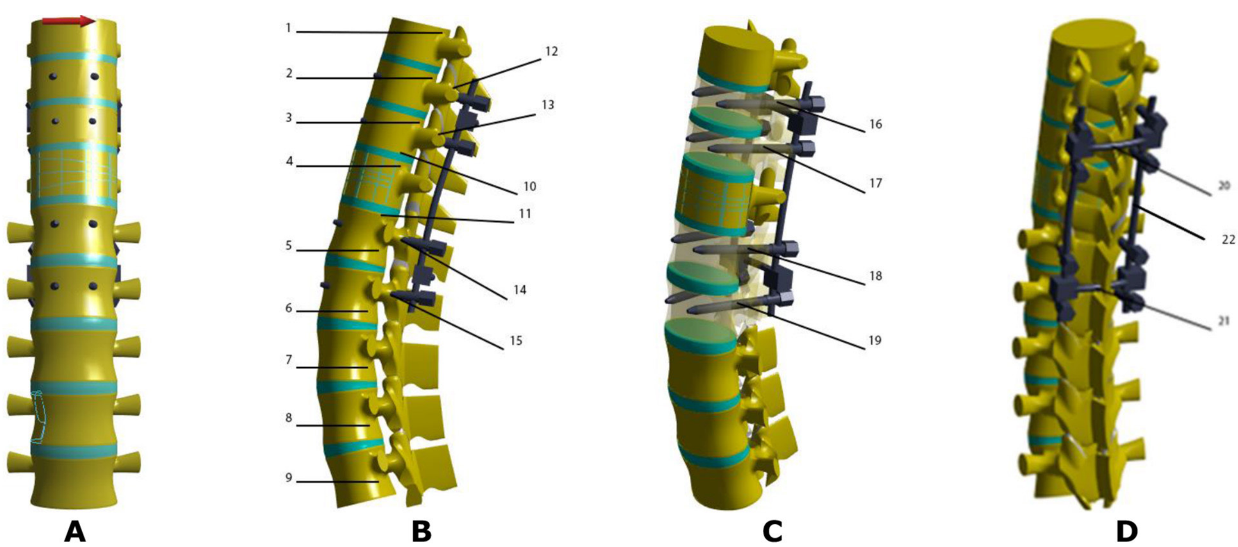

Fig. 3. Load scheme of models (a) and locations of control points (b, c, d): 1 - body of Th9 vertebra; 2 - body of Th10 vertebra; 3 - body of Th11 vertebra; 4 - body of Th12 vertebra; 5 - body of L1 vertebra; 6 - body of L2 vertebra; 7 - body of L3 vertebra; 8 - body of L4 vertebra; 9 - body of L5 vertebra;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

Results

In the model using transpedicular fixation with short screws without cross-links ***(see Fig. 4)***, the maximum stress values of 24.0 MPa were identified in the body of the Th12 vertebra. High stress levels of 21.5 and 20.1 MPa were also recorded in the bodies of the L2 and L3 vertebrae, respectively. Around the fixing screws, the highest stress value of 11.8 MPa was determined in the arches of the L2 vertebra. The stress around the screws in other vertebrae did not exceed 5.4 MPa.

In the metal structure components, the rods were the most stressed, experiencing stress levels of 226.7 MPa, indicating that they bear the primary load. Among the fixation screws, the maximum stress value of 27.3 MPa was observed in screws at the L2 vertebra, while the minimum was 14.3 MPa at the L1 vertebra. Screws in the thoracic vertebrae experienced uniform stress levels—22.1 MPa and 20.6 MPa at Th10 and Th11 vertebrae, respectively.

Using long screws without cross-links in the stabilization system ***(see Fig. 5)*** slightly reduced the stress levels in the bodies of intact vertebrae, whereas in the body of the Th12 vertebra, the stress increased to 27.3 MPa. Around the transpedicular screws, an increase in stress levels was also observed. The most significant doubling of stress was seen in the arches of the Th10 vertebra, where it was recorded at 9.0 MPa. In the arches of the Th11 and L2 vertebrae, stresses increased to 6.0 and 14.0 MPa, respectively. These findings correspond to the pattern of stress distribution changes on the transpedicular screws at Th10, Th11, and L2 vertebrae, where they also increased to values of 38.6 MPa, 20.3 MPa, and 34.8 MPa, respectively. The increased load on the transpedicular screws is transmitted to the rods, causing an increase in their stress levels to 313.4 MPa.

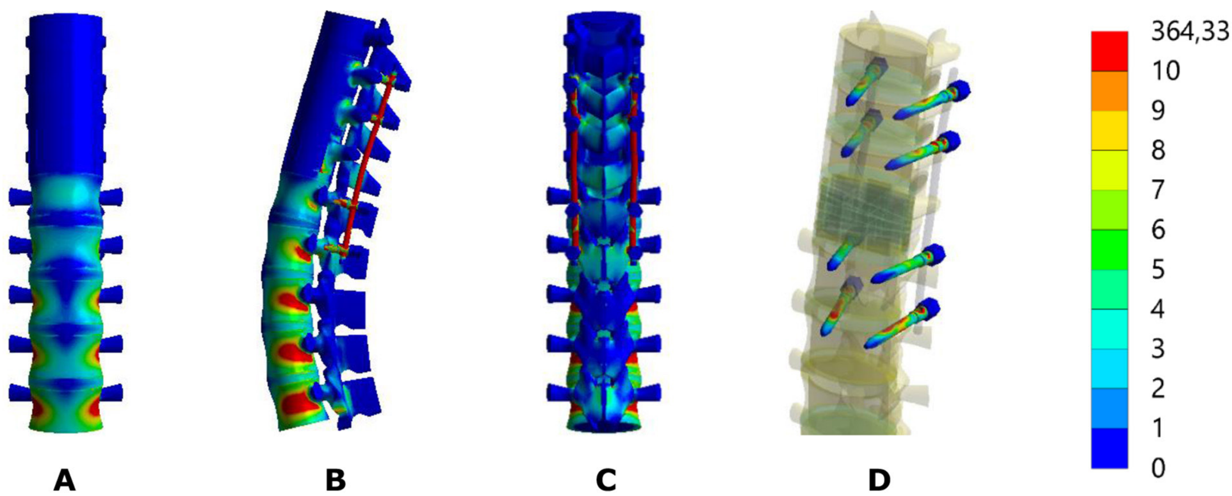

Fig. 4. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under load simulating leftward trunk tilt. Transpedicular fixation with short screws without crosslinks (model modification No. 1): a - front view; b - side view; c - rear view; d - screws

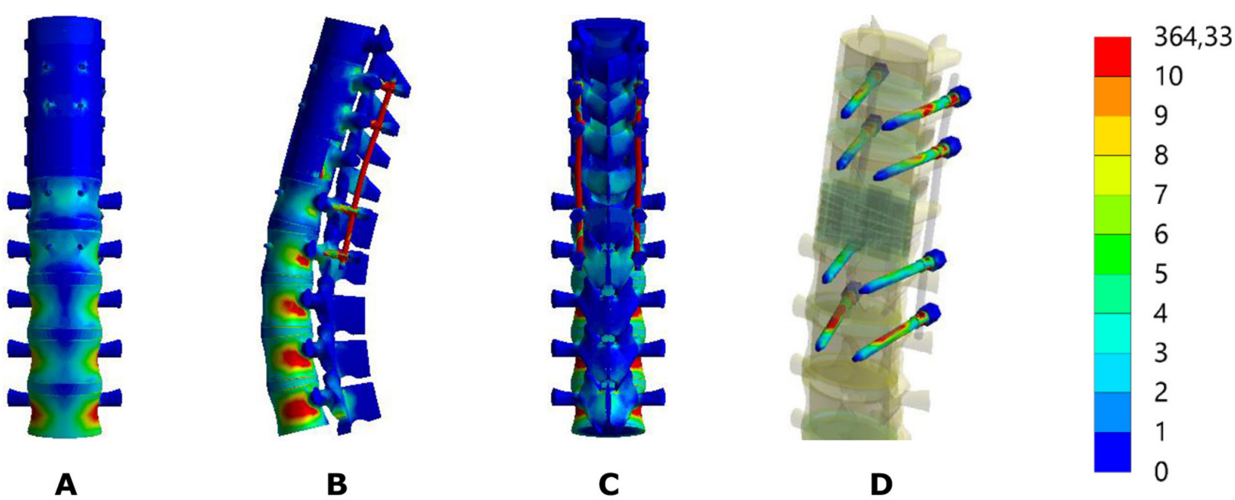

Fig. 5. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under load simulating leftward trunk tilt. Transpedicular fixation with bicortical screws without crosslinks (model modification No. 2): a - front view; b - side view; c - rear view; d - screws

The use of short fixation screws in combination with crosslinks, as shown in ***(Fig. 6)***, allowed for a reduction in the maximum stress values at all control points of the model and, most importantly, in the damaged Th12 vertebra, down to 18.4 MPa. A reduction in stress levels was also observed in all elements of the metal structure. The most significant changes occurred in the connecting rods, where stresses decreased to 212.4 MPa. The stresses on the crosslinks themselves were determined to be 7.8 MPa and 10.6 MPa at the upper and lower crosslinks, respectively.

The combination of crosslinks with long fixation screws ***(Fig. 7)*** during lateroflexion, compared to the model without crosslinks, also reduces stresses at all control points of the model, both in bone and metal components. However, compared to the model using short screws, the stress levels remain higher. The exception is the crosslinks themselves, where stress decreases to levels of 6.2 MPa and 5.4 MPa for the upper and lower crosslinks, respectively.

Data on the stress values at all control points of models with transpedicular fixation are presented in ***Table 2***.

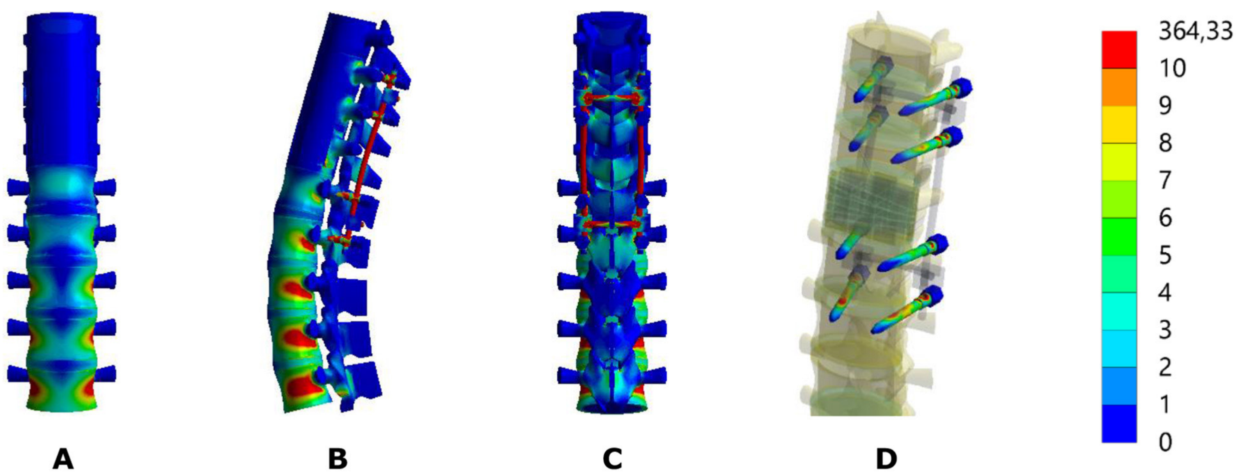

Fig. 6. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under load simulating leftward trunk tilt. Transpedicular fixation with monocortical screws and the presence of crosslinks in the system (model modification No. 3): a - front view; b - side view; c - rear view; d – screws

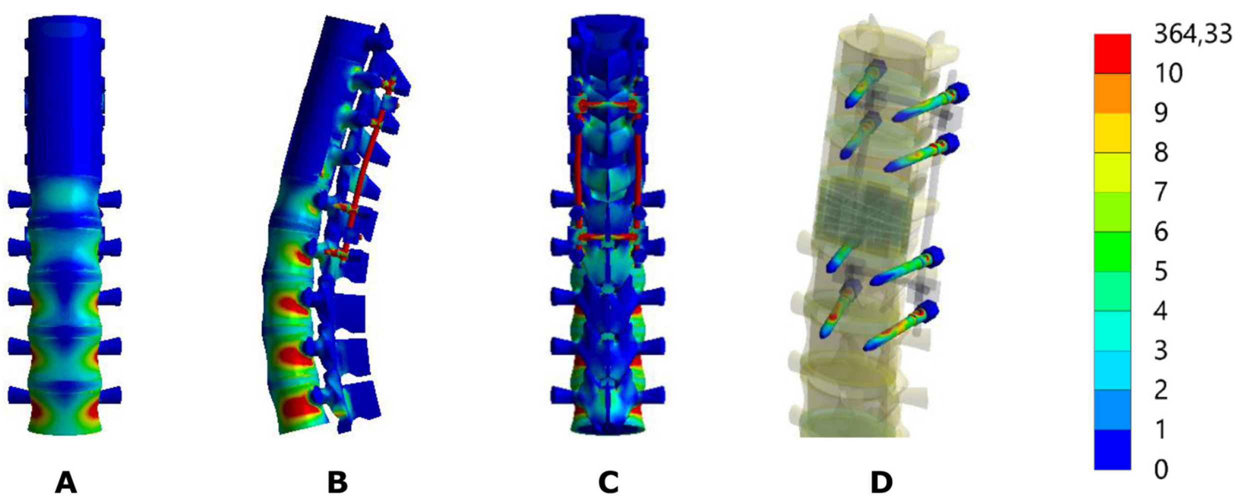

Fig. 7. Stress distribution in the model of the thoracolumbar spine with a burst fracture of the Th12 vertebra under load simulating leftward trunk tilt. Transpedicular fixation with bicortical screws and the presence of crosslinks in the system (model modification No. 4): a - front view; b - side view; c - rear view; d - screws

Table 2. Stress under load simulating leftward trunk tilt in models of the thoracolumbar spine with a burst fracture of the Th12 vertebra under 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	1.1	1.0	1.1	1.0
2		Th10 Vertebra Body	10.4	7.6	10.2	5.8
3		Th11 Vertebra Body	6.5	5.4	6.3	5.2
4		Th12 Vertebra Body	24.0	27.3	18.4	25.8
5		L1 Vertebra Body	10.3	9.3	9.7	8.7
6		L2 Vertebra Body	21.5	18.2	20.0	17.6
7		L3 Vertebra Body	20.1	17.0	19.8	16.1
8		L4 Vertebra Body	25.0	21.1	23.8	20.5
9		L5 Vertebra Body	15.4	14.7	17.3	14.3
10		Lower Endplate of Th11	3.4	3.1	3.2	2.9
11		Upper Endplate of L1	5.8	5.3	5.5	4.9
12		Entry of Screws into Arch of Th10	4.1	9.3	3.8	9.0
13		Entry of Screws into Arch of Th11	5.4	3.6	4.5	3.5
14		Entry of Screws into Arch of L1	5.3	6.0	2.9	5.8
15		Entry of Screws into Arch of L2	11.8	14.0	9.4	13.4
16	Metal Constructs	Screws in Th10 Body	22.1	38.6	19.8	38.6
17		Screws in Th11 Body	20.6	20.3	20.3	19.9
18		Screws in L1 Body	14.3	15.5	11.4	13.2
19		Screws in L2 Body	27.3	34.8	26.5	33.0
20		Crosslinks between Th10 and Th11 Screws			7.8	6.2
21		Crosslinks between L1 and L2 Screws			10.6	5.4
22		Connecting rods	226.7	313.4	212.4	293.98

When conducting a comparative analysis of the obtained results, the following key features can be identified:

1. Stress Reduction Effectiveness:

- Crosslinks consistently reduce stress across all configurations, particularly beneficial in models involving both short and long screws. This effect is prominent in critical areas such as the fractured Th12 vertebra, where the reduction of stress can be crucial for stability and healing.

2. Screw Length:

- Long Screws with crosslinks tend to reduce stress more effectively than short screws without crosslinks, especially in thoracic vertebrae (Th10 and Th11). This suggests that for areas requiring robust stabilization, long screws with crosslinks might be more beneficial.

- However, in the case of the fractured Th12 vertebra, short screws with crosslinks show the best performance by significantly lowering the stress, illustrating that the optimal screw length may vary depending on the specific requirements of the fracture and anatomical location.

3. Load Distribution:

- Metal Constructs: Long screws without crosslinks exhibit the highest stress levels, particularly at critical points like in the Th10 vertebra body. This underscores the potential for higher mechanical loads leading to increased risk of screw loosening or breakage. The inclusion of crosslinks helps mitigate this risk by better distributing the load.

- Endplates and Screw Entry Points: The use of crosslinks not only reduces the stress on the vertebral bodies but also at the structural interfaces where screws enter the bone, enhancing the overall integrity of the fixation.

4. Rods:

The connecting rods, an integral part of the metal construct, show significantly reduced stress when crosslinks are used. This reduction highlights the importance of crosslinks in preventing overloading of the beams, which can prevent structural failure under load.

5. General Observations:

- The pattern of stress distribution suggests that while long screws are generally effective, the addition of crosslinks is critical for achieving optimal outcomes. This combination seems to provide the best balance between stability and stress reduction.

- The consistent reduction of stress in models with crosslinks, regardless of screw length, suggests that crosslinks could be a universally beneficial addition to spinal fixation systems, especially in cases of severe trauma or instability.

It should be noted that the results we obtained are generally predictable and corroborated by a range of clinical and experimental biomechanical studies. For instance, it is indisputable that the use of crosslinks in transpedicular stabilization provides a more uniform distribution of loading across various sections of the stabilized spine, reducing the risks of fixation failure [23]. The data regarding the impact of the length of transpedicular screws on critical load indicators in the bone tissue-metal construct system also find their clinical confirmation. It is known, for example, that the modification with bicortical placement of screws is more preferable in osteoporotic spine [24, 25]. In our study, the loading of the vertebral bodies when using long transpedicular screws with crosslinks is minimal, which to some extent confirms the validity and informativeness of the finite element model we used.

However, when extrapolating these results to clinical practice, it's important to note that despite the clear advantages of models with crosslinks, the stress values obtained are not so critical as to favor open stabilization unequivocally. For example, even the most heavily loaded elements of the metal constructs—the connecting rods —show a maximum stress level of 313.4 MPa, while the calculated strength threshold for the titanium alloy VT16 ranges from 1030 MPa to 1225 MPa [26]. The empirical data suggest that, despite apparent biomechanical challenges, lateroflexion does not induce critical overloads at any of the control points analyzed, rendering an eight-screw fixation somewhat excessive. However, these findings are specific to the examined loading pattern, and conclusions regarding the suitability of any particular stabilization type can only be drawn after exploring all loading scenarios as well as modeling shorter fixation methods, which will be addressed in our future research. Moreover, based on the data, it should be noted that in cases with additional risks of fixation failure and non-consolidation of the fractured vertebral body, opting for an open installation of a transpedicular system enhanced with crosslinks may still be more advisable.

Conclusion: The results obtained illustrate that the use of crosslinks in the stabilization of burst fractures in the thoracolumbar junction, which is feasible only through open installation, contributes to a reduction in stress within the stabilized spinal segment. Meanwhile, in the modeling of lateroflexion, the difference in stress values between open and minimally invasive installations is minimal.

Information disclosure

Conflict of interest

The authors declare no conflict of interest.

Ethical standards

This article does not contain any studies involving humans or animals.

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