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Biomechanical validation of topographic patterns of new vertebral compression fractures after vertebroplasty using

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Despite the high clinical effectiveness of percutaneous vertebroplasty, the occurrence of new osteoporotic vertebral compression fractures after the procedure remains a significant clinical problem. One of the key mechanisms of recurrent fractures is believed to be the redistribution of mechanical loads within the spine caused by changes in geometry and stiffness after vertebral collapse and cement augmentation. Finite element analysis (FEA) is an appropriate tool for quantitative assessment of these biomechanical processes. The purpose. To provide biomechanical validation of topographic patterns of new vertebral fractures by analyzing the stress-strain state of a multisegment spinal model. Methods. Three-dimensional finite element models of the Th₁–L₁ spine were developed, taking into account osteoporotic bone properties, including an intact model and models with compression fractures at different vertebral levels. Additional models simulated post-vertebroplasty conditions with local replacement of cancellous bone by bone cement. Results. The simulations demonstrated that vertebral compression fractures lead to significant redistribution of stresses in adjacent and distant spinal segments, with the location of high-stress zones depending on the level of the primary fracture. Vertebroplasty reduced stress in the treated vertebra but did not eliminate elevated stresses in other spinal segments, where biomechanical conditions favorable for subsequent fractures persisted. Conclusion. These findings confirm that the level of the primary fracture determines the spatial pattern of load redistribution in the spine and may explain the topographic features of new fractures after vertebroplasty. Finite element analysis is an effective method for investigating mechanisms of cascade fractures and for supporting preventive strategies in patients with osteoporosis.

Незважаючи на високу клінічну ефективність пункційної вертебропластики, проблема виникнення нових остеопоротичних компресійних переломів хребців після втручання залишається актуальною. Одним із ключових механізмів розвитку повторних ушкоджень вважається перерозподіл механічних навантажень у хребті внаслідок зміни його геометрії та жорсткісних характеристик після компресійного перелому та цементування тіла хребця. Для кількісного оцінювання цих процесів доцільним є застосування методу скінченних елементів (МСЕ). Мета. Біомеханічне обґрунтування топографічних закономірностей виникнення нових компресійних переломів шляхом аналізу напружено-деформованого стану (НДС) багатосегментної моделі хребта. Побудовано тривимірні скінченно-елементні моделі хребта Th₁–L₁ з урахуванням остеопоротичних властивостей кісткової тканини, включно з інтактною моделлю та моделями з компресійними переломами тіл хребців різної локалізації. Окремо моделювалися варіанти після вертебропластики з локальним заміщенням губчастой кістки цементом. Результати. Виявлено, що компресійний перелом призводить до суттєвого перерозподілу напружень у суміжних і віддалених сегментах хребта, причому характер зон підвищеного напруження залежить від рівня первинного ушкодження. Вертебропластика його знижує в ушкодженому хребці, проте не усуває підвищеного навантаження в інших сегментах, де формуються біомеханічні передумови для розвитку повторних переломів. Висновки. Отримані результати підтверджують, що локалізація первинного перелому визначає просторову структуру перерозподілу навантажень у хребті та пояснює топографічні особливості виникнення нових переломів після вертебропластики. Ключові слова. Метод скінченних елементів; біомеханіка хребта; остеопороз; нові компресійні переломи хребців; вертебропластика; напружено-деформований стан.

Keywords. Finite element analysis; spinal biomechanics; osteoporosis; vertebral compression fractures; vertebroplasty; stress-strain state

Introduction

Osteoporotic vertebral compression fractures are among the most common causes of chronic pain syndrome, impaired functional activity, and reduced quality of life in elderly patients [1–3]. Percutaneous vertebroplasty is currently regarded as an effective minimally invasive method for fracture stabilization, enabling rapid pain relief and restoration of load-bearing capacity of the affected spinal segment [4, 5]. However, clinical studies indicate that there remains a significant risk of new vertebral compression fractures after vertebroplasty, which may form cascade injuries and lead to progressive spinal deformity [6–9].

Despite a substantial number of studies investigating risk factors for recurrent fractures after vertebroplasty, most research focuses on demographic, metabolic, or procedural technical factors, whereas spatial patterns of new fracture occurrence and their biomechanical mechanisms remain insufficiently explored [10–12]. There is a lack of publications analyzing the statistical identification of such patterns, and even fewer studies providing biomechanical justification.

Mathematical modelling is an important research tool widely used in complex biomechanical systems. Currently, the finite element method (FEM) is one of the most widely applied approaches for solving complex numerical modelling problems. One important application is the analysis of stress–strain distribution (SSD) in the spine when evaluating different models of spinal trauma and pathology. In the literature [13–15], research is predominantly focused on the lumbar spine. Fewer studies address the thoracolumbar region [16, 17], or the entire spine [18, 19], which is mainly due to the complexity of constructing geometric models and simulating their correct functional behavior.

Therefore, biomechanical modelling as a logical continuation of statistical analysis is highly relevant for substantiating the mechanisms of load redistribution in the spine after compression fractures and vertebroplasty, as well as for confirming topographic patterns of new injury occurrence. This approach not only helps explain the mechanisms of cascade fractures but also provides a scientific basis for developing individualized preventive and therapeutic strategies in patients with osteoporosis.

Aim: biomechanical substantiation of topographic patterns of new osteoporotic vertebral compression fractures through analysis of the stress–strain state of a multisegment spinal model.

Material and Methods

The study materials were reviewed by the Bioethics Commission of the SI “Professor M. I. Sytenko Institute of Spine and Joint Pathology of the NAMS of Ukraine” (Protocol No. 260 dated 23.02.2026).

The finite element modelling study was performed as a logical continuation of a previous stage of work, in which statistically significant topographic patterns of new osteoporotic vertebral compression fractures after percutaneous vertebroplasty were identified. The aim of the mathematical modelling was biomechanical substantiation and verification of the identified patterns through analysis of the stress–strain state of adjacent and distant spinal segments depending on the location of the primary fracture, namely: Th_{XI} — possible new deformation at Th_{VIII}; in the case of Th_{VII}–Th_{IX}, Th_{XII}, L_I; for Th_{XII}–Th_{XI}; for primary L_I — new Th_{XII}, L_{IV}, L_V [20].

In constructing the computational models, a geometric spinal model developed at the Biomechanics Laboratory of the SI “Professor M. I. Sytenko Institute of Spine and Joint Pathology of the NAMS of Ukraine” was used as a basis. The following modifications were introduced:

1. unchanged geometry, while bone tissue properties were defined as osteoporotic tissue (intact model).
2. a 15° compression fracture of the Th_{XI} vertebra was simulated, taking osteoporosis into account. In addition, in the models, a one-third replacement of the vertebral body (trabecular bone tissue) with a material containing bone cement (16 %) was performed:
 - a) in the anterior, middle, and posterior parts of the Th_{XI} vertebra;
 - b) in the anterior part of the Th_{XII} vertebra;
 - c) in the anterior part of the L_I vertebra;
 - d) in the anterior part of the Th_{VII} vertebra.

The computational models are shown in Fig. 1.

Material properties

In this study, the material was assumed to be homogeneous and isotropic. When selecting the properties of bone structures and biological tissues, we relied on data most frequently reported in the literature. Osteoporotic changes in bone tissue were taken into account [21–24]. The material properties, including Young’s modulus (E) and Poisson’s ratio (ν), are summarized in Table 1.

The *loading scheme* was considered under conditions of upright standing. To calculate load magnitudes, several authors [25–28] investigated muscle forces that compensate for the effect of the weight of individual body components applied at their centers of mass. Accordingly, the force values used in this study are summarized in Table 2.

The location and direction of the forces are shown in Fig. 2. The model is fixed at the inferior surface of the vertebral body and at the articular surfaces of L_V.

Results and discussion

Model of the intact Th_V–L_V vertebral block

The computational model is shown in Fig. 3.

Analysis of the simulation results for the osteoporotic vertebral model under normal conditions (Fig. 4) showed that the stress level in the Th_V–L_V vertebral block ranged from 1 to 3.2 MPa. It was demonstrated that the lumbar spine (L_I–L_V) is more stressed, with a maximum stress level of 3.2 MPa. In the thoracic region, the most stressed segment was the Th_V–Th_{VIII} block, where the stress level reached 1.6 MPa. A comparison of stress distribution across vertebrae in the model is presented in Fig. 5.

From the calculations, the following conclusions can be drawn:

- in the Th_V–L_V block, the SSD is non-uniform. The lumbar spine is the most stressed region;
- in the Th_V–Th_{XI} segment, vertebral bodies are more stressed in their anterior portion;
- in the L_I–L_V segment, the posterior load-bearing complex is more stressed.

The model with a compression fracture of the Th_{XI} vertebra is shown in Fig. 6.

Analysis of the computational results (Fig. 7) compared with the intact model demonstrated that the pat-

tern of SSD in the Th_V–L_V spinal block changed, with an overall increase in stress levels. In the L_I–L_V segment, stress reached 3.7 MPa (3.2 MPa in the intact model), while in the Th_V–Th_{VIII} segment it reached 2.1 MPa (1.6 MPa in the intact model). The maximum von Mises stress in the Th_{XI} vertebral body in the computational model was 1.3 MPa (1.0 MPa in the intact model).

A comparison of stress distribution in the vertebrae of the intact model and the compression fracture model is shown in Fig. 8.

From the calculations, the following conclusions can be drawn:

Table 2

Magnitudes of loads on the T_V–L_V vertebrae

Upper surface of the vertebral body	Perpendicular to the upper surface of the vertebral body (N)	In the plane of the upper surface of the vertebral body (N)
Th _V	182.7	35
Th _{VI}	9.1	5
Th _{VII}	9.8	5
Th _{VIII}	10.5	5
Th _{IX}	11.2	3
Th _X	14.0	3
Th _{XI}	14.7	0
Th _{XII}	17.5	0
L _I	16.8	10
L _{II}	16.8	8
L _{III}	16.1	7
L _{IV}	18.2	5
L _V	18.2	0

Table 1

Mechanical properties of the materials used

Material	Elastic modulus E (MPa)	Ποιcσov□σ pαtio v
Osteoporotic cortical bone [21]	3066.00	0.30
Osteoporotic cancellous bone [21]	132.00	0.30
Intervertebral disc	4.20	0.45
Cartilage	5.58	0.45
Mixture of cancellous bone and bone cement (16 %)	2200.00	0.34

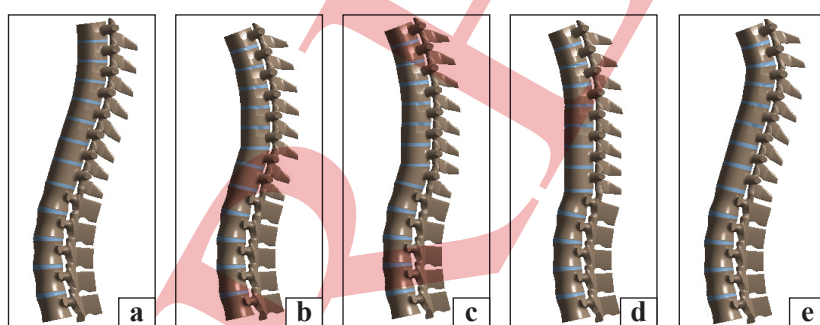


Fig. 1. Computational models: (a) normal model with osteoporotic bone tissue; models with compression fractures: (b) Th_{XI} vertebra; (c) Th_{XII}; (d) L_I; (e) Th_{VII} and bone cement in the posterior part.

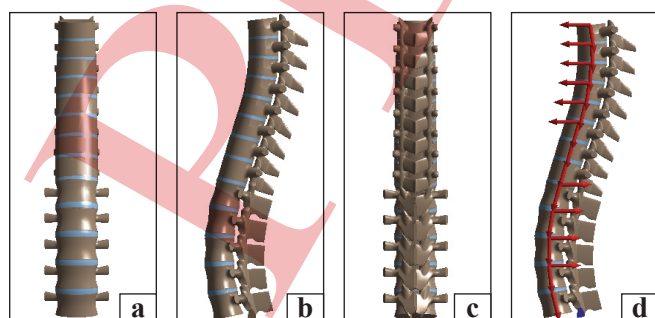


Fig. 2. Intact computational model, views: (a) anterior; (b) left; (c) posterior; (d) loading and fixation in the computational model.

– the pattern of SSD distribution in the Th_V-L_V spinal block changed compared with the intact model. The greatest increase in stress was observed in the $Th_{VII}-Th_{XI}$ segment;

– stress levels in the $Th_{IX}-Th_X$ vertebrae increased by 60 %, while in the Th_{VII} , Th_{VIII} , and Th_{XI} vertebrae the increase was 30 %;

– in other vertebrae, stress levels increased by 10–20 %.

Model with a compression fracture of Th_{XI} and bone cement augmentation in the anterior portion

In the computational model, bone cement (16 %) was added to the osteoporotic trabecular bone in the anterior part of the Th_{XI} vertebral body (Fig. 9).

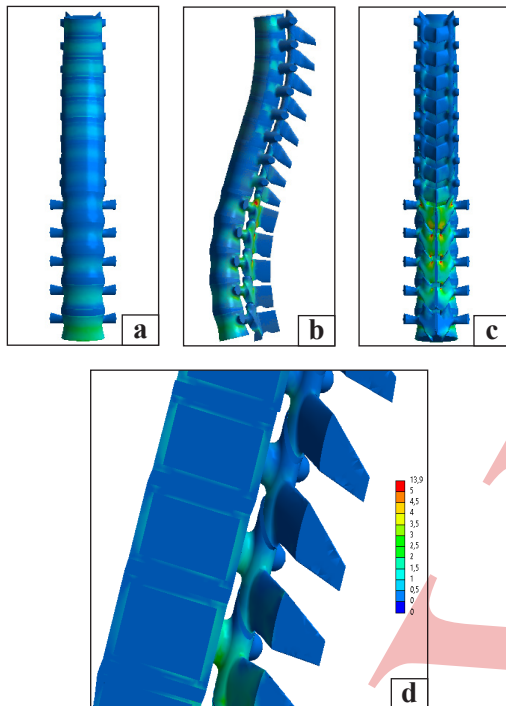


Fig. 3. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior; (d) sagittal section of the Th_X-Th_{XII} vertebral block.

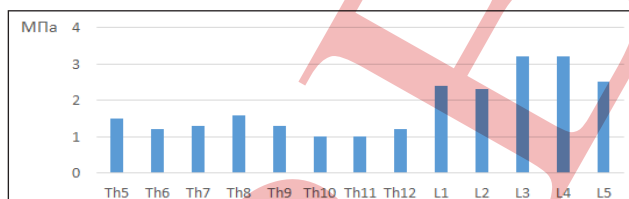


Fig. 4. Magnitude of von Mises stress in the Th_V-L_V vertebrae.

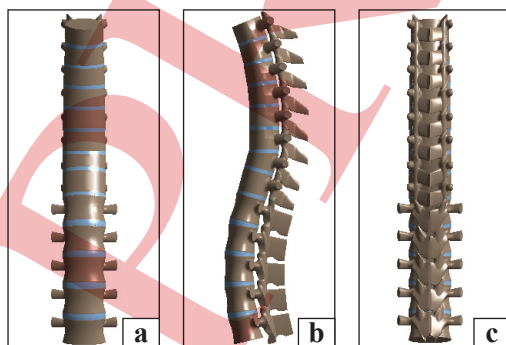


Fig. 5. Computational model with compression fracture of the Th_{XI} vertebral body, views: (a) anterior; (b) left; (c) posterior.

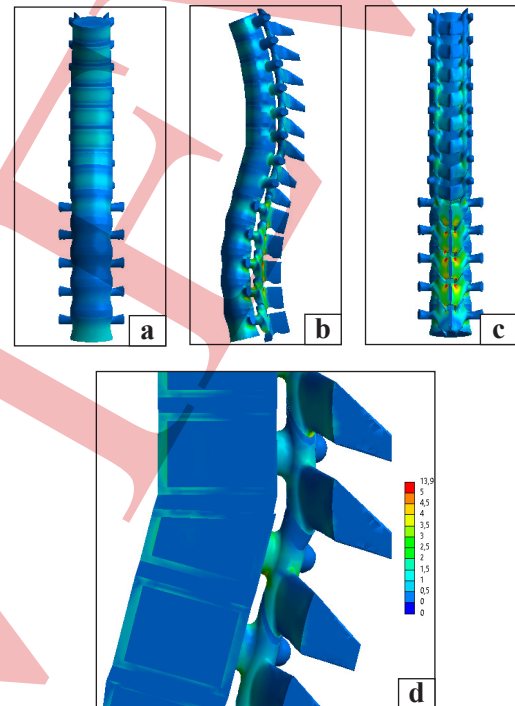


Fig. 6. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior; (d) sagittal section of the Th_X-Th_{XII} vertebral block.

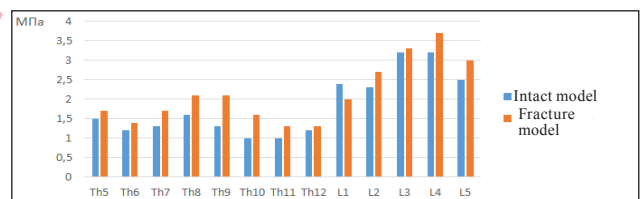


Fig. 7. Magnitude of von Mises stress in the Th_V-L_V vertebrae in the intact model and in the compression fracture model.

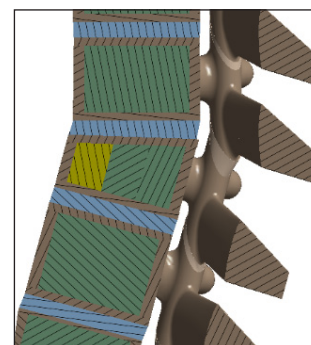


Fig. 8. Sagittal section of the Th_X-Th_{XII} vertebral block of the computational model.

Analysis of the computational results (Fig. 10) compared with the model without bone cement showed that the overall pattern of SSD in the Th_V–L_V spinal block did not change, except for the Th_{XI} vertebra.

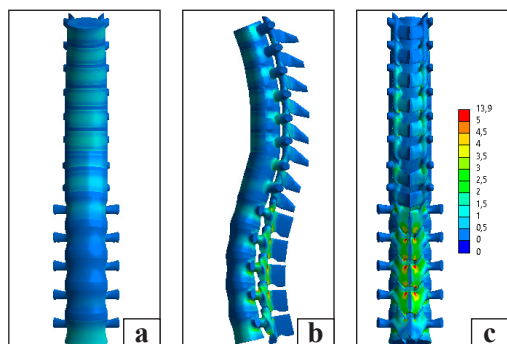


Fig. 9. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior.

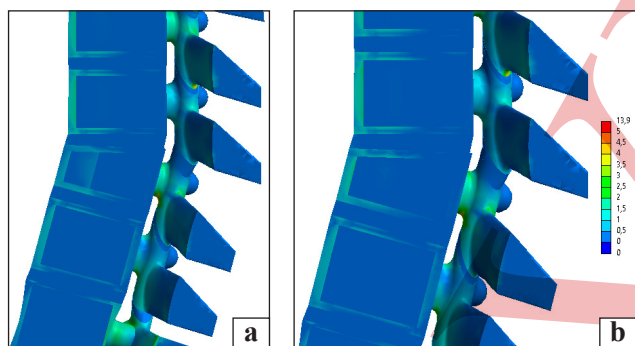


Fig. 10. von Mises stress in the ThXI vertebral body: (a) computational model; (b) model without bone cement.

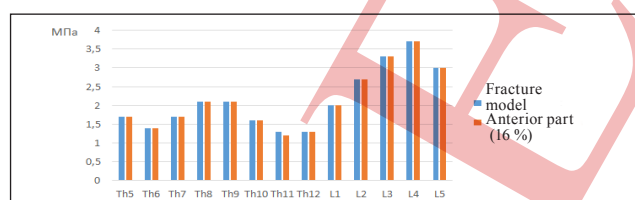


Fig. 11. Distribution of von Mises stresses in the computational models without and with bone cement augmentation.

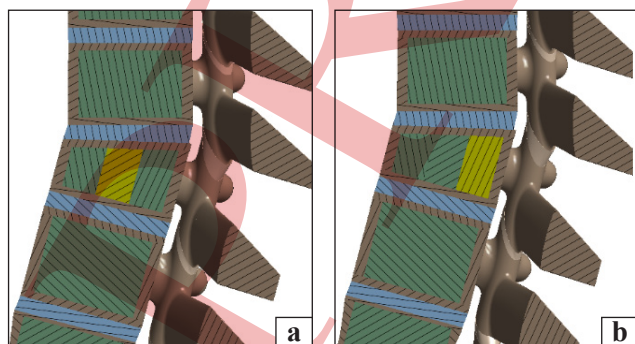


Fig. 12. Sagittal section of the Th_X–Th_{XII} vertebral block of the computational model with bone cement augmentation: (a) middle part of the Th_{XI} vertebra; (b) posterior part of the Th_{XI} vertebra.

Stress in the cortical layer of the Th_{XI} vertebral body (Fig. 11) was 1.2 MPa (1.3 MPa in the model without bone cement). For the trabecular bone in the cemented region, the stress was 0.6 MPa (0.3 MPa in the model without bone cement).

The diagram (Fig. 12) shows a comparison of maximum von Mises stress values for vertebral bodies in the models with and without bone cement augmentation.

From the calculations, the following conclusions can be drawn:

- the pattern of the SDS distribution in the Th_V–L_V spinal block compared with the model without bone cement did not change;
- a decrease in the stress state within 10 % occurred in the cortical layer of the surface of the Th_{XI} vertebral body;

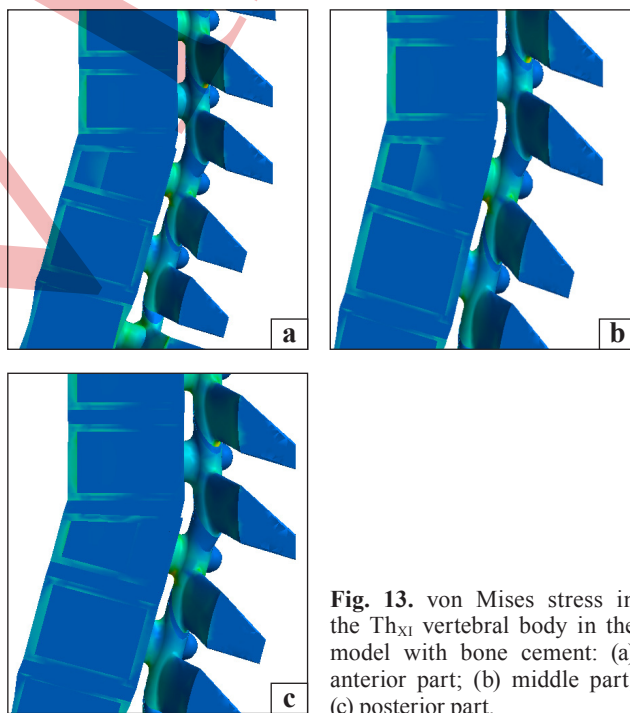


Fig. 13. von Mises stress in the Th_{XI} vertebral body in the model with bone cement: (a) anterior part; (b) middle part; (c) posterior part.

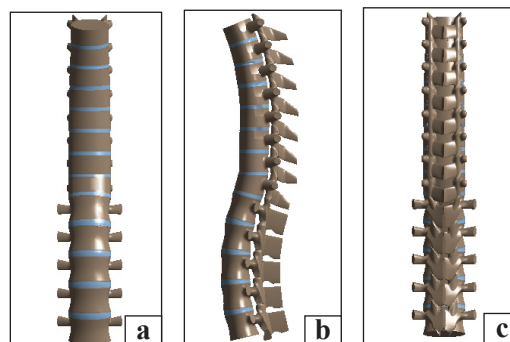


Fig. 14. Computational model with compression fracture of the Th_{XII} vertebral body, views: (a) anterior; (b) left; (c) posterior.

– in the cement injection zone, an increase in the stress state was observed, which is explained by the higher stiffness of bone cement compared to cancellous bone.

Model of Th_{XI} compression fracture with bone cement in the middle and posterior parts

For the construction of the computational models, bone cement (16 %) was added to the osteoporotic cancellous bone tissue in the middle and posterior parts of the Th_{XI} vertebral body (Fig. 13).

Analysis of these models (Fig. 14) compared with the model with bone cement in the anterior part showed that the pattern of SDS distribution in the Th_V–L_V spinal block did not change. In the Th_{XI} vertebra, changes in SDS were also negligible.

The stress level in the cortical layer of the Th_{XI} vertebral body (Fig. 14) was 1.2 MPa in the model with bone cement in the anterior part of the vertebral body and 1.1 MPa in the middle and posterior parts. For the cancellous bone in the cement zone, the values were 0.6 MPa, 0.7 MPa, and 0.4 MPa, respectively.

From the calculations, the following conclusion can be made: the location of bone cement in different regions of the Th_{XI} vertebral body does not affect the SDS distribution in the Th_V–L_V spinal block.

The model of Th_{XII} compression fracture with bone cement is shown in Fig. 15. Analysis of the computational model (Fig. 16) compared with the intact model showed that the pattern of SDS distribution in the Th_V–L_V spinal block changed and the stress level increased. The stress level in the L_I–L_V spinal block reached 3.8 MPa (3.2 MPa in the intact model), and in the Th_V–Th_{XII} block it reached 2.4 MPa (1.6 MPa in the intact model). The maximum von Mises stress in the Th_{XII} vertebral body in the computational model was 1.3 MPa (1.2 MPa in the intact model).

Comparison of stress states in the vertebrae of the intact and compression fracture models is shown in Fig. 17.

From the calculations, the following conclusions can be made:

- the pattern of SDS distribution in the Th_V–L_V spinal block compared with the intact model changed. The increase in stress was most pronounced in the Th_{VII}–Th_{XI} and L_{IV}–L_V blocks;
- the stress level in the Th_{VIII} vertebra increased by 50 %, in the Th_{VII}, Th_{IX}, and Th_{XI} vertebrae by 40–46 %;
- in the L_I and L_{IV} vertebrae, the increase was 19 % and 21 %, and in the L_V vertebra by 24 %;
- in other vertebrae, the stress level increased within 4–8 %.

Model of Th_{XII} compression fracture with bone cement in the anterior part

In the computational model, bone cement (16 %) was added to the osteoporotic cancellous bone tissue in the anterior part of the Th_{XII} vertebral body (Fig. 18).

Analysis of the computational model (Fig. 19) compared with the model without bone cement showed that the pattern of SDS distribution in the Th_V–L_V spinal block did not change, except for the Th_{XII} vertebra.

The stress level in the cortical layer of the Th_{XII} vertebral body (Fig. 20) is 1.2 MPa (1.3 MPa in the model without bone cement). For the cancellous bone in the cement injection zone, it is 0.6 MPa (0.2 MPa in the model without bone cement).

Figure 21 shows a comparison of the maximum von Mises stress values for vertebral bodies in the models with and without bone cement.

From the calculations: the pattern of the SDS distribution in the Th_V–L_V spinal block compared with the model without bone cement did not change; a decrease in the stress state within 10 % occurred in the cortical layer of the surface of the Th_{XII} vertebral body; in the cement injection zone, an increase in stress was observed, which is explained by the higher stiffness of bone cement compared to cancellous bone.

Model of L_I compression fracture (Fig. 22)

Comparing the computational model (Fig. 23) with the intact model revealed that the pattern of SDS distribution in the Th_V–L_V spinal block changed and the stress level increased.

The stress level in the L_I–L_V spinal block reached 3.4 MPa (3.2 MPa in the intact model), and in the Th_V–Th_{XII} block it was 2.0 MPa (1.6 MPa in the intact model). The maximum von Mises stress in the L_I vertebral body in the computational model was 2.0 MPa (2.4 MPa in the intact model).

Comparison of stress states in the vertebrae of the intact and compression fracture models is shown in Fig. 24.

From the calculations, the following follows:

- the pattern of SDS distribution in the Th_V–L_V spinal block compared with the intact model changed. The increase in stress was more pronounced in the Th_{VII}–Th_{IX} block and in the L_V vertebra;
- the stress level in the Th_{IX} vertebra increased by 31 %. In Th_{VII} and Th_{VIII}, by 23 % and 25 %, respectively;
- in the L_V vertebra, by 16 %;
- in other vertebrae, the increase in stress did not exceed 10 %.

Model of L_1 compression fracture with bone cement in the anterior part

In the computational model, bone cement (16 %) was added to the osteoporotic cancellous bone tissue in the anterior part of the L_1 vertebral body.

Analysis of the computational model (Fig. 26) compared with the model without bone cement

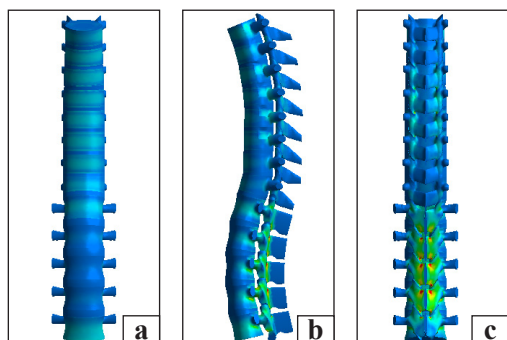


Fig. 15. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior; (d) sagittal section of the Th_{XII} – L_1 vertebral block.

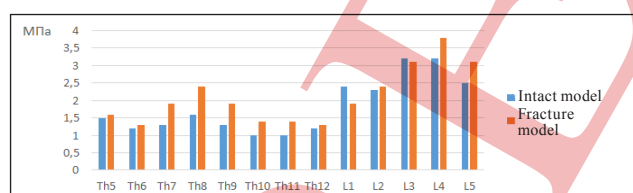


Fig. 16. Magnitude of von Mises stress in the Th_V – L_V vertebrae in the intact model and in the compression fracture model.

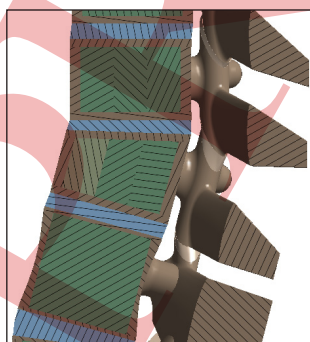


Fig. 17. Sagittal section of the Th_{XI} – L_1 vertebral block of the computational model.

showed that the pattern of SDS distribution in the Th_V – L_V spinal block did not change, except for the L_1 vertebra.

The stress level in the cortical layer of the L_1 vertebral body (Fig. 27) is 1.9 MPa (2.0 MPa in the model

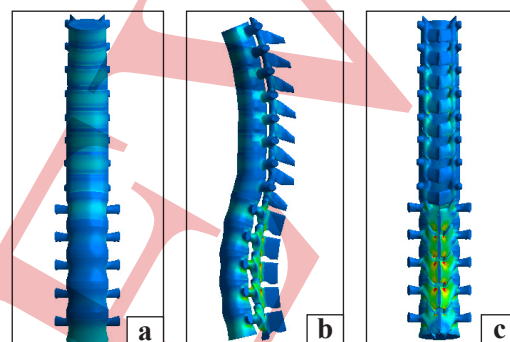


Fig. 18. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior.

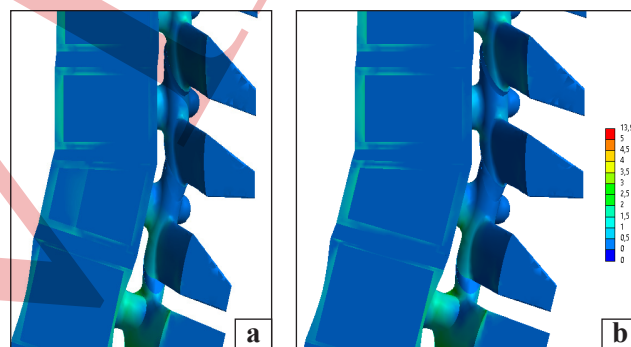


Fig. 19. von Mises stress in the Th_{XII} vertebral body: (a) computational model; (b) model without bone cement.

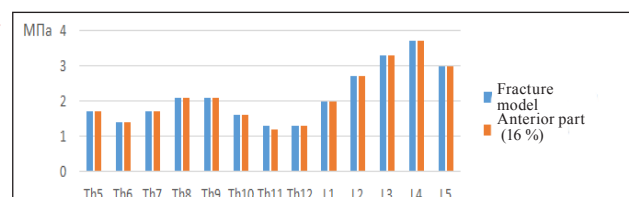


Fig. 20. Distribution of von Mises stresses in the computational models without and with bone cement augmentation.

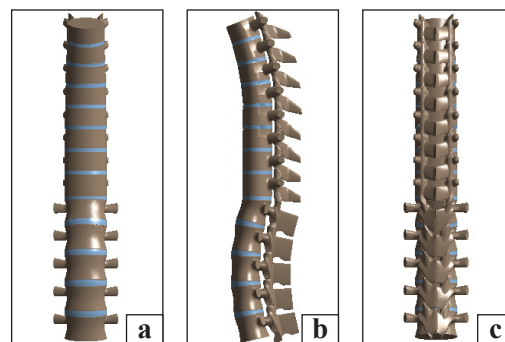


Fig. 21. Computational model with compression fracture of the L_1 vertebral body, views: (a) anterior; (b) left; (c) posterior.

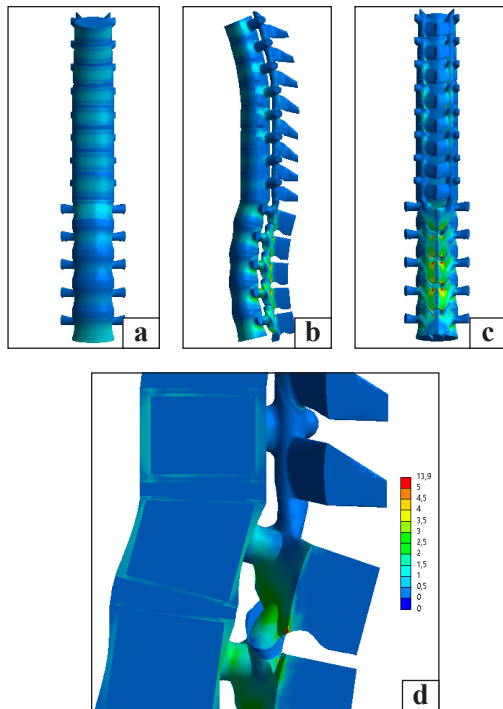


Fig. 22. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior; (d) sagittal section of the Th_{XII}–L_{II} vertebral block.

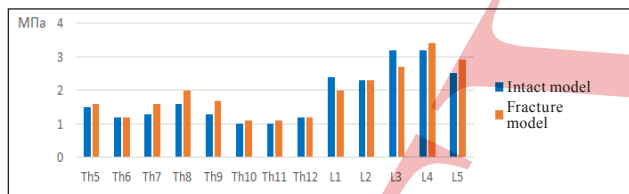


Fig. 23. Magnitude of von Mises stress in the Th_V–L_V vertebrae in the intact model and in the compression fracture model.

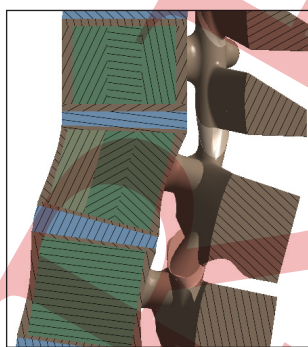


Fig. 24. Sagittal section of the Th_{XII}–L_{II} vertebral block of the computational model.

without bone cement). For the cancellous bone in the cement zone, it is 0.5 MPa (0.2 MPa in the model without bone cement).

Figure 28 shows a comparison of the maximum von Mises stress values for vertebral bodies in the models with and without bone cement.

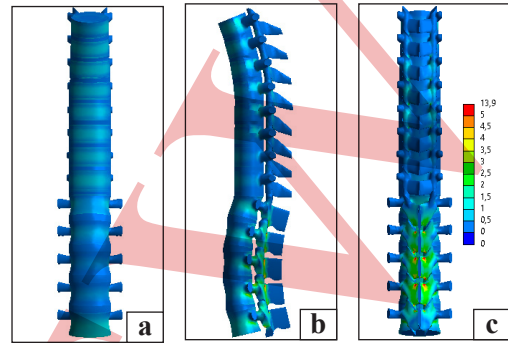


Fig. 25. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior.

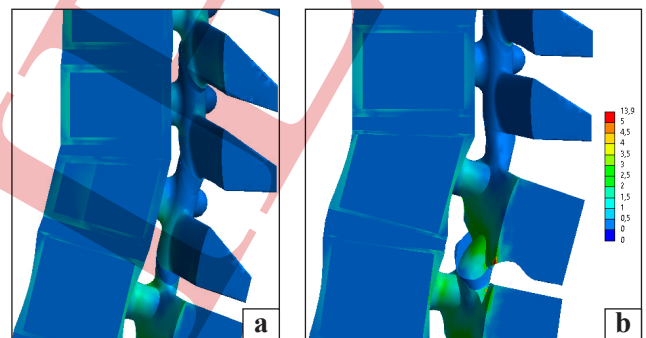


Fig. 26. von Mises stress in the L_I vertebral body: (a) computational model; (b) model without bone cement.

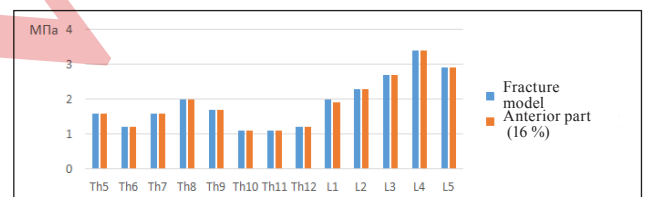


Fig. 27. Distribution of von Mises stresses in the computational models without and with bone cement augmentation.

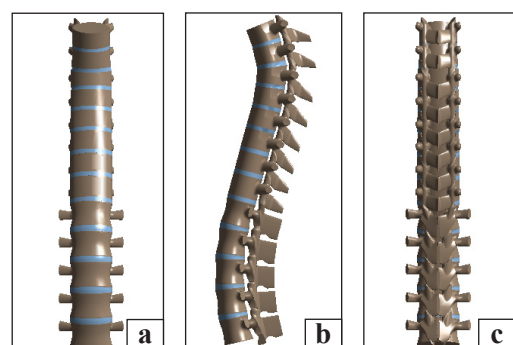


Fig. 28. Computational model with compression fracture of the Th_{VII} vertebral body, views: (a) anterior; (b) left; (c) posterior.

From the calculations: the pattern of SDS distribution in the Th_V–L_V spinal block compared with the model without bone cement did not change; a decrease in the stress state within 10 % occurred in the cortical layer of the L_I vertebral body surface; in

Table 3

Degree of increase in stress–strain state (SSE) in the Th_V–L_V vertebral block

Fracture location	Up to 10 %	From 10 to 30 %	More than 30 %
Th _{VII}	Th _V , L _{II} –L _{IV}	Th _{VIII} , L _I	Th _{VI} , Th _{VII}
Th _{XI}	Th _{XII} , L _{III}	Th _V , Th _{VI} , L _{II} , L _{IV} , L _V	Th _{VII} –Th _{XI}
Th _{XII}	Th _V , Th _{VI} , Th _{XII} , L _{II}	L _{IV} , L _V	Th _{VII} –Th _{XI}
L _I	Th _V , Th _X , Th _{XI} , L _{IV}	Th _{VII} , Th _{VIII} , L _V	Th _{IX}

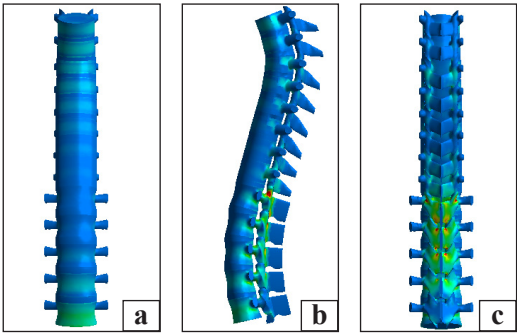


Fig. 29. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior; (d) sagittal section of the Th_{VI}–Th_{VIII} vertebral block.

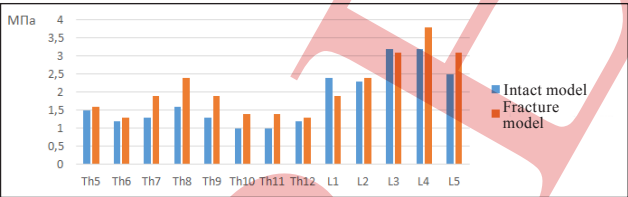


Fig. 30. Magnitude of von Mises stress in the Th_V–L_V vertebrae in the intact model and in the compression fracture model.

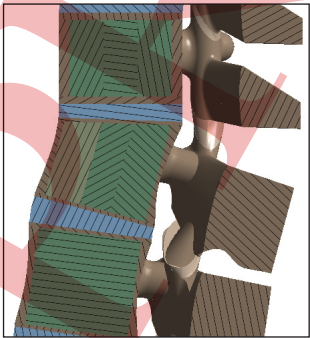


Fig. 31. Sagittal section of the Th_{VI}–Th_{VIII} vertebral block of the computational model.

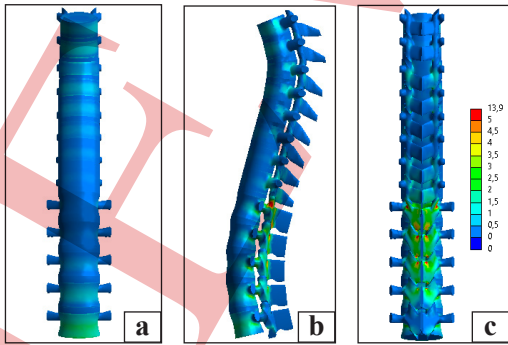


Fig. 32. von Mises stress in the computational model, views: (a) anterior; (b) left; (c) posterior.

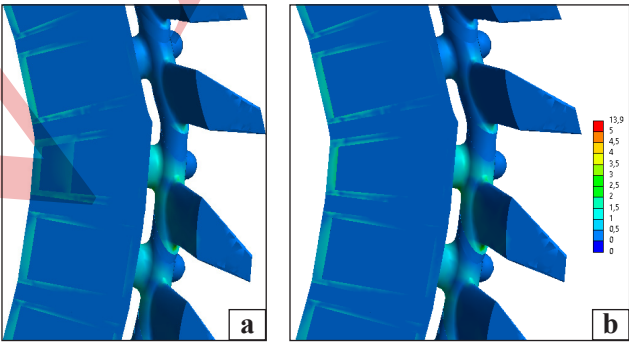


Fig. 33. von Mises stress in the Th_{VII} vertebral body: (a) computational model; (b) model without bone cement.

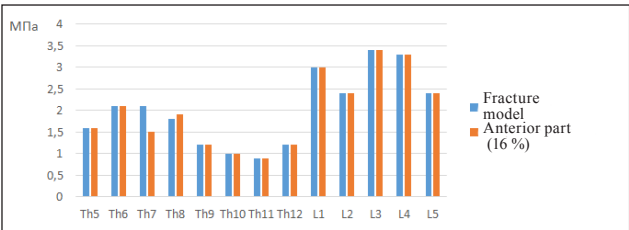


Fig. 34. Distribution of von Mises stresses in the computational models without and with bone cement augmentation.

the cement injection zone, an increase in stress was observed, which is explained by the higher stiffness of bone cement compared to cancellous bone.

Model of Th_{VII} compression fracture (Fig. 29)

Analysis of the computational model (Fig. 30) compared with the intact model showed that the pattern of SDS distribution in the L_I–L_V spinal block changed only slightly. The maximum stress level in

the L_{III} vertebra was 3.4 MPa (3.2 MPa in the intact model). In the Th_V–Th_{XII} spinal block, both the distribution pattern and stress levels changed. For example, in the Th_{VI} vertebra it reached 2.1 MPa (1.2 MPa in the intact model). The maximum von Mises stress in the Th_{VII} vertebral body in the computational model was 2.1 MPa (1.3 MPa in the intact model).

Comparison of stress states in the vertebrae of the intact and compression fracture models is shown in Fig. 31.

From the calculations, it follows:

- the pattern of the SDS distribution in the Th_V–Th_{XII} spinal block compared with the intact model changed. The increase in stress state was mainly observed in the Th_{VI} and Th_{VII} vertebral blocks;
- the stress level in the Th_{VI} vertebra increased by 75 %, and in Th_{VII} by 62 %;
- in the L_I–L_V spinal block, it remained almost unchanged;
- in other vertebrae, the stress level changed within 3–8 %.

Model of Th_{VII} compression fracture with bone cement in the anterior part

In the computational model, bone cement (16 %) was added to the osteoporotic cancellous bone tissue in the anterior part of the Th_{VII} vertebral body (Fig. 32).

Analysis of the computational model (Fig. 33) compared with the model without bone cement showed that the pattern of SDS distribution in the Th_V–L_V spinal block did not change, except for the Th_{VII} vertebra.

The stress level in the cortical layer of the Th_{VII} vertebral body (Fig. 34) was 1.5 MPa (2.1 MPa in the model without bone cement). For the cancellous bone in the cement zone, it was 0.6 MPa (0.2 MPa in the model without bone cement).

Figure 35 shows a comparison of the maximum von Mises stress values for vertebral bodies in the models with and without bone cement.

From the calculations, it follows:

- the pattern of SDS distribution in the Th_V–L_V spinal block compared with the model without bone cement did not change;
- a decrease in the stress state within 28 % occurred in the cortical layer of the surface of the Th_{VII} vertebral body. In percentage terms, this represents the greatest reduction in stress among vertebrae with compression fractures after cement augmentation;
- in the cement injection zone, an increase in stress was observed, which is explained by the higher stiffness of bone cement compared to cancellous bone.

In summary, Table 3 presents the results of increased stress in the Th_V–L_V spinal block depending on the location of the fracture.

The obtained results of mathematical modeling are consistent with previously established clinical

and statistical patterns and confirm that the location of the primary compression fracture determines the pattern of stress redistribution in the spine, creating prerequisites for the occurrence of new fractures in predicted segments [20].

Conclusions

Biomechanical modeling confirmed that a vertebral compression fracture leads to a significant redistribution of stresses in adjacent and distant spinal segments, forming zones of increased load that correspond to the clinical topography of new fractures identified in our previous study. Vertebroplasty reduces local stresses in the treated area but does not eliminate global changes in the stress–strain state of the spinal motion segment.

The obtained results explain the mechanisms of cascade fracture development and justify the feasibility of preventive interventions in vulnerable segments of high-risk patients. Thus, biomechanical modeling confirms the clinical and statistical patterns identified in the previous study.

Study limitations. The finite element biomechanical model is static and considers only vertical loading in the standing position. It does not include dynamic movements, individual muscle activity, age-related postural changes (progressive thoracic kyphosis, forward trunk inclination, shift of the center of mass), degenerative changes in intervertebral discs, the influence of the thoracic cage, ribs, and abdominal muscles, as well as the individual spinal geometry of a specific patient. These simplifications limit the full reproduction of the real multicomponent biomechanics of the spine in elderly patients with osteoporosis.

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

Prospects for further research. The perspective of further studies is prospective clinical validation of the confirmed patterns, with assessment of their predictive value, reproducibility, and practical applicability. The obtained data may serve as a basis for improving risk assessment algorithms, individualized selection of vulnerable vertebrae, and implementation of preventive approaches in clinical practice.

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BIOMECHANICAL VALIDATION OF TOPOGRAPHIC PATTERNS OF NEW VERTEBRAL COMPRESSION FRACTURES AFTER VERTEBROPLASTY USING

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