ISSN 0030-5987. Orthopaedics, traumatology and prosthetics. 2022. № 3–4

УДК 616.718.5-001.5-089.2-007.2:613.25]:004.942](045)

DOI: http://dx.doi.org/10.15674/0030-598720223-445-51

The effectiveness of resistance to torsional loads of various options for osteosynthesis of bone fragments of the tibia for fractures in the upper third of the diaphysis (mathematical modeling)

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The treatment of patients with tibial fractures and overweight has certain peculiarities due to the increased load on the osteosynthesis device. Objective. To compare the stress-strain state of models of the lower leg with a fracture of the tibia in the upper third of the diaphysis under the influence of torsional load under different options of osteosynthesis depending on the patient's weight. Methods. Using the finite element method, a fracture in the upper third of the tibia and three types of osteosynthesis were modeled: using an external fixation device (EFD), a bone plate, and an intramedullary rod. A torque of 7 Nm and 12 Nm was applied to the tibial plateau. The results. The highest indicators of the stress level in the fracture zone (6.3–10.8 MPa) and on the metal structure (251.0–430.2 MPa) were determined in the model with a bony plate. In the model with osteosynthesis with the help of EFD, a fairly low stress level (0.2–0.3 MPa) was established in the fracture zone, but a high one in the proximal part of the tibia (6.7–11.5 MPa). The lowest values of stresses in the fracture zone (0.1–0.2 MPa) and the proximal fragment of the tibia (0.6–1.0 MPa) were determined under the conditions of reproduction of osteosynthesis using an intramedullary rod, but in the distal part of the tibia the stresses remained quite high — 11.1–19.0 MPa. Conclusions. The values of stresses in the fracture zone in the models with EFD and intramedullary rod were significantly lower than the values of the intact bone, with the periosteal plate - only at a load of 7 Nm. In the distal fragment of the tibia, the highest stress level was determined in the model with osteosynthesis with an intramedullary rod, in the proximal one — with EFD. Among the metal structures, the greatest stresses were found in the periosteal plate and around the fixing screws and rods under the conditions of its use. The function of the dependence of the amount of stress on the weight of the patient in the elements of the model turned out to be linear and directly proportional.

Лікування пацієнтів із переломами кісток гомілки та надмірною вагою має певні особливості через зростання навантаження на пристрій для остеосинтезу. Мета. Порівняти напружено-деформований стан моделей гомілки з переломом великогомілкової кістки у верхній третині діафіза під впливом навантаження на кручення за різних варіантів остеосинтезу залежно від ваги пацієнта. Методи. За допомогою методу скінченних елементів моделювали перелом у верхній третині великогомілкової кістки та три види остеосинтезу: з використанням апарата зовнішньої фіксації (АЗФ), накісткової пластини й інтрамедулярного стрижня. До плато великогомілкової кістки прикладали крутний момент величиною 7 Нм і 12 Нм. Результати. Найбільші показники рівня напружень в зоні перелому (6,3–10,8 МПа) та на металевій конструкції (251,0–430,2 МПа) визначено в моделі з накістковою пластиною. У моделі з остеосинтезом за допомогою АЗФ установлений досить низький рівень напружень (0,2–0,3 МПа) у зоні перелому, але високий — у проксимальному відділі великогомілкової кістки (6,7–11,5 МПа). Найнижчі показники напружень у зоні перелому (0,1–0,2 МПа) та проксимальному фрагменті великогомілкової кістки (0,6–1,0 МПа) визначені за умов відтворення остеосинтезу за допомогою інтрамедулярного стрижня, але в дистальному відділі великогомілкової кістки напруження залишилися досить високими — 11,1–19,0 МПа. Висновки. Величини напружень в зоні перелому в моделях з АЗФ та інтрамедулярним стрижнем були значно нижчими за показники неушкодженої кістки, із накістковою пластиною — лише за навантаження в 7 Нм. У дистальному фрагменті великогомілкової кістки найвищий рівень напружень визначений у моделі з остеосинтезом інтрамедулярним стрижнем, у проксимальному — з АЗФ. Серед металевих конструкцій найбільші напруження виявлені в накістковій пластині та навколо фіксувальних гвинтів і стрижнів за умов її використання. Функція залежності величини напружень від ваги пацієнта в елементах моделі виявилася лінійною та прямопропорційною. Ключові слова. Метод скінченних елементів, гомілка, перелом, кручення, остеосинтез.

Key words. Finite element method, shank, fracture, torsion, osteosynthesis

Introduction

The problem of overweight and obesity is one of the most widespread pandemics today. World statistics report that almost 40 % (2 billion people) of the world's population over the age of 18 are overweight, and 13 % suffer from obesity [1]. At the same time, the treatment of patients with fractures of the long bones of the tibia and accompanying excess weight creates certain peculiarities in the course of the disease, somewhat limiting the choice of an implant for high-quality osteosynthesis, as the load on the biomechanical structure increases [2, 3]. Currently, the specifics of the operation of various means of osteosynthesis of long bones under compression and bending are well studied [4], but torsional loads are tested on the tibial bones. They are the most dangerous because they are a complex combination of bending, stretching and compression loads.

The treatment of patients with tibial bone fractures and accompanying overweight or obesity has certain features: the choice of implant for high-quality osteosynthesis is limited, as the load on the biomechanical structure increases [3, 4].

In order to optimize the choice of implants and determine the advantages and disadvantages of various fracture fixation methods, we created a mathematical model of a tibial fracture in the upper third with various types of osteosynthesis under conditions of increasing torsional load on the «implant – bone» system and determined the stress level in the fracture model.

The purpose of the study: to carry out a comparative analysis of the stress-strain state of models of the lower leg with a fracture of the tibia in the upper third of the diaphysis under the impact of torsional loading in different options for osteosynthesis depending on the patient's weight.

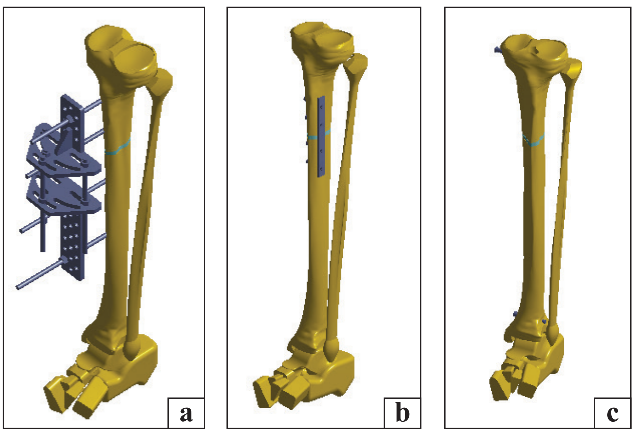


Fig. 1. Models of tibial fracture in the upper third with osteosynthesis: a) EFD; b) bone plate; c) intramedullary rod

Material and methods

In the biomechanics laboratory of the State Institution Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine we developed a basic finite-element model of the human lower leg [5], comprising the tibia and fibula bones, the bones of the foot. In all joints, a layer with the mechanical properties of cartilage tissue was made between the bone elements.

The basic model reproduces a fracture in the upper third of the tibia and three types of osteosynthesis with the help of an external fixation device (EFD), bone plate and an intramedullary rod. The gap between bone fragments in the fracture zone was filled with an element that imitated bone regeneration (Fig. 1).

The material is assumed to be homogeneous and isotropic. A 10-node tetrahedron with a quadratic approximation is chosen as a finite element. All materials from which the models were made were assigned appropriate mechanical properties — Young's modulus of elasticity and Poisson's ratio [6–9] (Table 1).

The models were tested under the impact of torsional loading, typical for patients weighing 70 kg and 120 kg. For this, a torque of 7 Nm and 12 Nm was applied to the tibial plateau. The feet of the models were rigidly fixed. The load diagram is shown in Fig. 2.

To compare the stress-strain state (SSS) of the models, the maximum stress values were determined in the proximal and distal fragments of the tibia, the fracture zone, the metal structure, and the bone tissue around the fixing screws. Indicators of stress values at control points of the model were taken from our previous study [5]. Models were evaluated using the finite element method. Mises stress [10] was used as a criterion for assessing SSS.

Modeling was performed using the SolidWorks automated design system; the stress-strain state of the models was calculated with the CosmosM software complex [11].

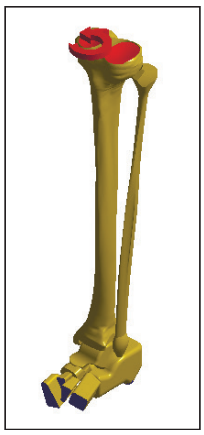


Fig. 2. Model loading scheme

Results and their discussion

The first stage of the study involved an assessment of the SSS of models of the lower leg with a fracture of the tibia in the upper third under the impact of a torsional load of 7.0 Nm.

In osteosynthesis with an EFD, a torque of 7.0 Nm was shown to cause maximum stresses of 6.7 MPa at the proximal end of the tibia. In the departments located below, the entire load was taken over by the EFD, the stress on which reached 197.1 MPa. Also, a high level of stress (31.5 MPa) was observed on the fixation screws and in the bone tissue around them. Therefore, it is possible to remove stresses from the distal fragment, where they were determined at the level of 0.3 MPa, and, what is especially important, from the fracture zone, where they did not exceed 0.2 MPa (Fig. 3).

Let us consider the SSS model of the lower leg with a fracture of the tibia in the upper third and osteosynthesis with a bone plate under a torsional load of 7.0 Nm (Fig. 4).

The use of a bone plate for osteosynthesis of the tibia for a fracture in the upper third under the impact of a torsional load of 7.0 Nm was found to trigger an increase in the stress value in the fracture zone to 6.3 MPa, in the distal fragment to 6.6 MPa compared with EFD osteosynthesis. At the same time, there was a decrease to 4.3 MPa in the stress level in the proximal fragment. A very high stress level of 251.0 MPa was determined on the plate itself, with 57.0 MPa on the fixing screws.

Table 1

Mechanical characteristics of materials used in modeling

Material	Young's modulus (E), MPa	Poisson's ratio, ν
Cortical bone	18350	0.29
Spongy bone	330	0.30
Cartilaginous tissue	10.5	0.49
Interfragmental regenerate	1.00	0.45
Сталь	$2.1 \cdot 10^5$	0.2

Table 2

Values of the maximum stresses in the elements of models of the lower leg with a fracture of the tibial bone for various options of osteosynthesis under the impact of a torsional load of 7.0 Nm

Model element	Stress, MPa			
	norm	EFD	plate	rod
Fragment of the tibia:				
– proximal;	4.1	6.7	4.3	0.6
– distal	9.5	0.3	6.6	11.1
Fracture zone	6.0	0.2	6.3	0.1
Construction	—	197.1	251.0	250.0
Entry of screws	—	31.5	51.7	13.6

Fig. 5 shows the distribution of stresses in the tibia model with a fracture of the tibia in the upper third and osteosynthesis with an intramedullary rod under a torsional load of 7.0 Nm. Under these conditions, the intramedullary rod provided significant resistance to torsional loads. This resulted in a decrease in stress in the fracture zone to 0.1 MPa and in the proximal fragment of the tibia to 0.6 MPa. Instead, a rather high stress level (11.1 MPa) was determined in the distal fragment. The stress on the rod reached 250.0 MPa, with 13.6 MPa on the fixing screws.

The maximum values of the relative deformations in the elements of the models of the lower leg with a fracture of the tibial bone under various options of osteosynthesis under a torsional load of 7.0 Nm are given in Table 2.

The second stage of the study involved an assessment of the processes in the models in case of increasing the load to 12.0 Nm, corresponding to the patient's weight of 120 kg.

The study showed that in the presence of a fracture of the tibia in the upper third and its osteosynthesis with an EFD, an increase in the patient's weight and, accordingly, the value of the torsional load triggered an increase in the values of stresses in all elements of the model. The biggest changes were found on structural elements (337.8 MPa) and fixing rods (54.0 MPa) (Table 3). In the bone tissue, the highest stress level was determined in the proximal fragment of the tibia — 11.5 MPa, but in the distal fragment and the fracture zone it remained quite low — 0.5 and 0.3 MPa, respectively (Fig. 6).

Fig. 7 shows the SSS of the lower leg model with a fracture of the tibia in the upper third and osteosynthesis with a bone plate under a torsional load of 12.0 Nm. It was found that an increase in the patient's weight did not change the nature of the stress distribution in the model under these conditions. Namely, an increase in the stress level was noted in all its elements: in the fracture zone and distal fragment — 10.8 and 11.3 MPa, respectively, in the proximal fragment — 7.4 MPa. The bone plate was the most stressed element — 430.2 MPa, on the fixing screws it increased to 97.7 MPa (Table 3).

The last step was to study the distribution of stresses in the developed model under the impact of a torsional load of 12.0 N in osteosynthesis with an intramedullary rod (Fig. 8). It was established that the introduction of an intramedullary rod in the case of increased patient weight and torsional load made it possible to maintain a low level of stress both in the fracture zone (0.2 MPa) and in the proximal fragment of the tibia (1.0 MPa). In the distal fragment, the stresses

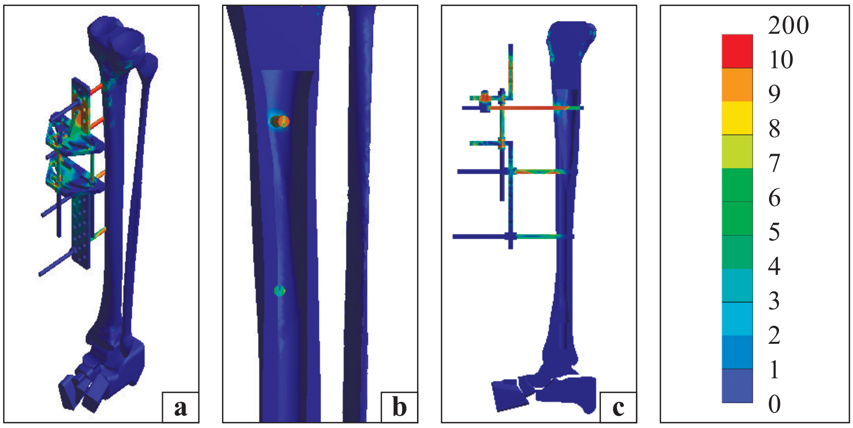


Fig. 3. Pattern of stress distribution in the lower leg model with a fracture of the tibia in the upper third (osteosynthesis with an EFD) under a torsional load of 7.0 Nm: a) general view; b) fracture zone; c) intersection of the tibia

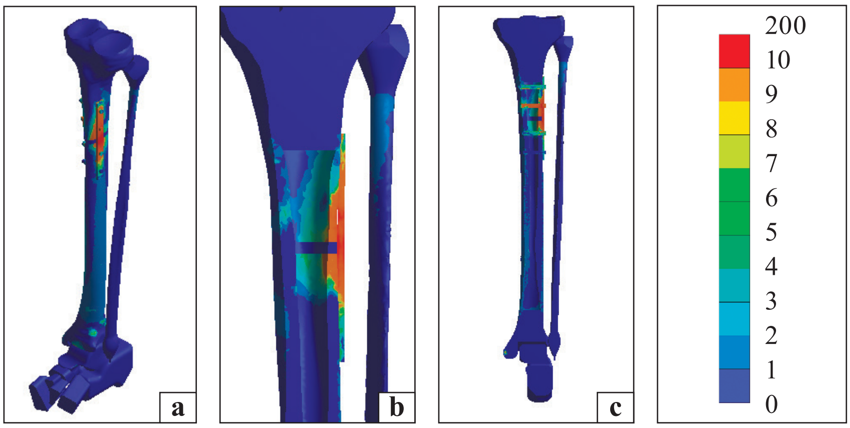


Fig. 4. Pattern of stress distribution in the lower leg model with a fracture of the tibia in the upper third (osteosynthesis with a bone plate) under a torsional load of 7.0 Nm: a) general view; b) fracture zone; c) intersection of the tibia

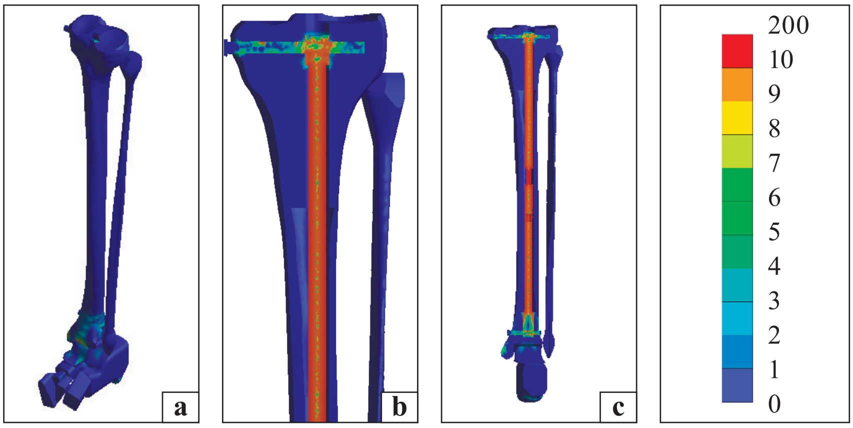


Fig. 5. Pattern of stress distribution in in the lower leg model with a fracture of the tibia in the upper third and osteosynthesis with an intramedullary rod under a torsional load of 7.0 Nm: a) general view; b) fracture zone; c) intersection of the tibia

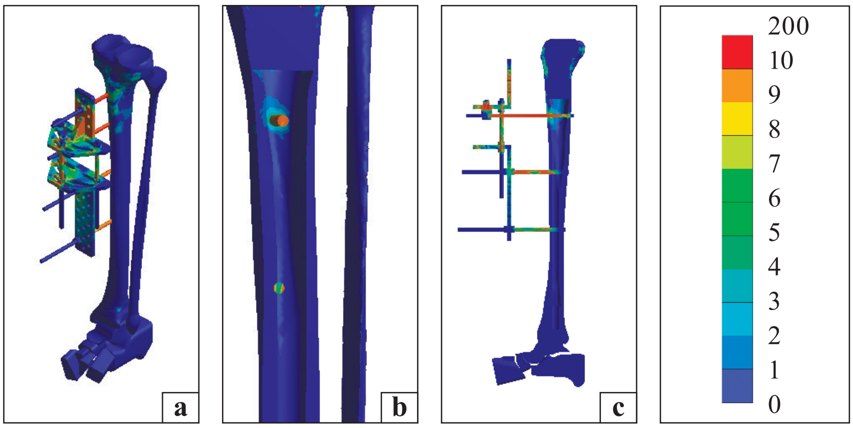


Fig. 6. Pattern of stress distribution in the lower leg model with a fracture of the tibia in the upper third under a torsional load of 12.0 Nm, EFD osteosynthesis: a) general view; b) fracture zone; c) intersection of the tibia

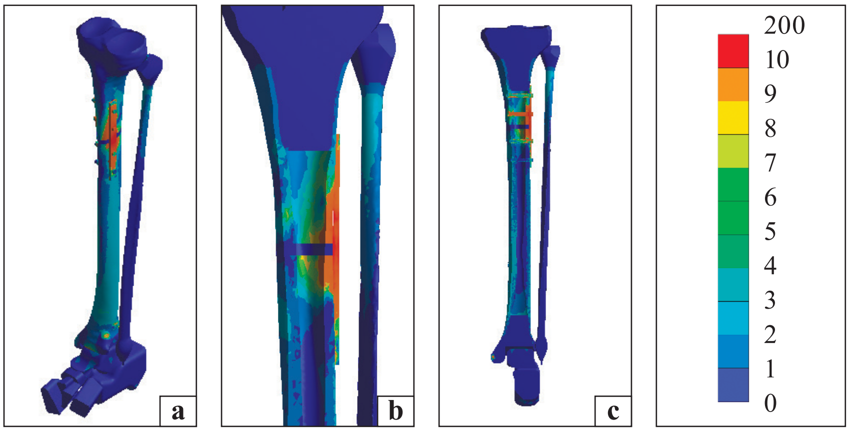


Fig. 7. SSS in the lower leg model with a fracture of the tibia in the upper third under a torsional load of 12.0 Nm, osteosynthesis with a bone plate: a) general view; b) fracture zone; c) intersection of the tibia

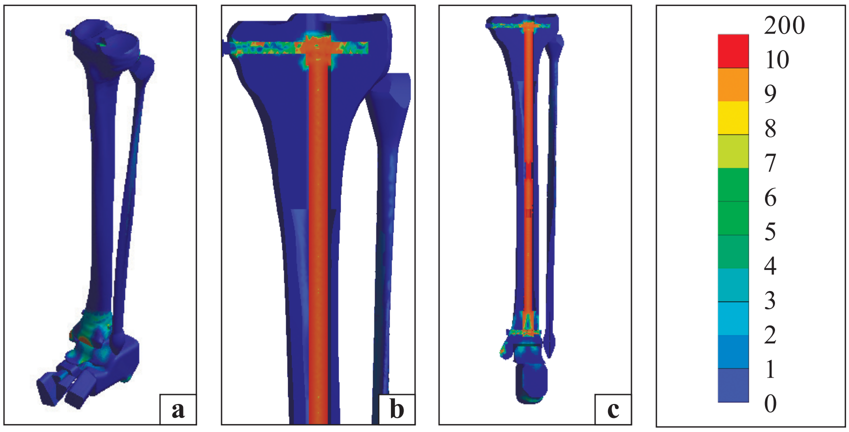


Fig. 8. SSS in the lower leg model with a fracture of the tibia in the upper third under a torsional load of 12.0 Nm, osteosynthesis with an intramedullary rod: a) general view; b) fracture zone; c) intersection of the tibia

Table 3

Values of the maximum stresses in the elements of models of the lower leg with a fracture of the tibial bone for various options of osteosynthesis under the impact of a torsional load of 12.0 Nm

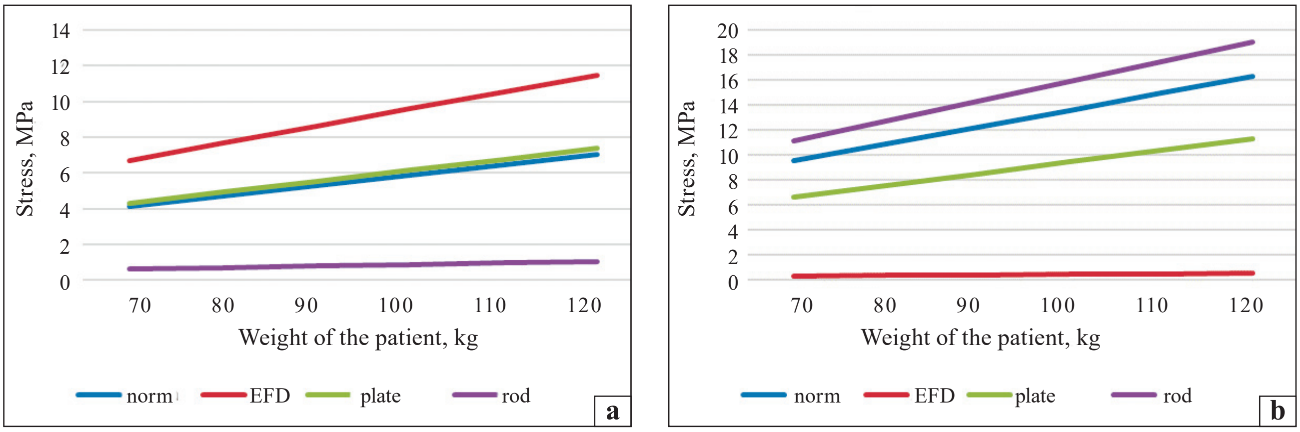
Model element	Stress, MPa			
	norm	EFD	plate	rod
Fragment of the tibia:				
– proximal;	7.0	11.5	7.4	1.0
– distal	16.3	0.5	11.3	19.0
Fracture zone	10.3	0.3	10.8	0.2
Construction	—	337.5	430.2	428.5
Entry of screws	—	54.0	97.7	23.3

increased to the level of 19.0 MPa. The highest stress level of 428.5 MPa was determined on the rod, and 23.3 MPa on the fixing screws (Table 3).

Thus, the use of an EFD and an intramedullary rod was found to ensure the minimum level of stress in the tibial fracture zone in models under the action of a torsional load of 12.0 Nm. Under the conditions of osteosynthesis with a bone plate, no significant stress reductions were found in any area of the tibia, with the exception of the fixing screws, where the stresses were equal to zero. As for the values of stresses on the elements of metal structures, in this case they are again the highest under the conditions of using a bone plate.

For a visual representation of the changes in the amount of stress in the elements of the tibial bone during its fractures in the upper third and various types of osteosynthesis, graphs are drawn based on the patient's weight (Fig. 9). Conducted mathematical studies have shown that changes in stress values in bone tissue are linearly dependent on the patient's weight. At the same time, the EFD and the intramedullary rod ensure stress values in the fracture zone that are significantly lower than those for an intact bone. In the distal part of the tibia, the highest stress level was determined in the model where an intramedullary rod was used for osteosynthesis. In the proximal part of the tibia, stresses exceeding the parameters of the model with an intact bone were recorded in the case of using an EFD.

The graphs shown in Fig. 10, demonstrate the dependence of the stress values in the elements of the metal structures of the models depending on the patient's weight. In the same way as in bone tissue, in metal structures, the stress values were directly proportional to the patient's weight. The greatest



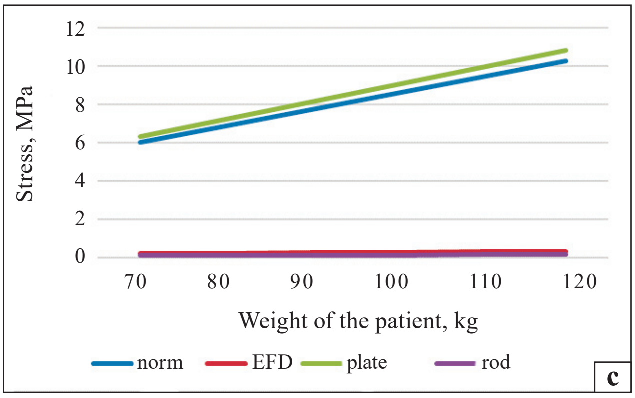


Fig. 9. Graphs of the dependence of stress values on the patient's weight in models of the tibia with fractures in its upper third and various types of osteosynthesis: proximal (a) and distal (b) fragments; fracture zone (c)

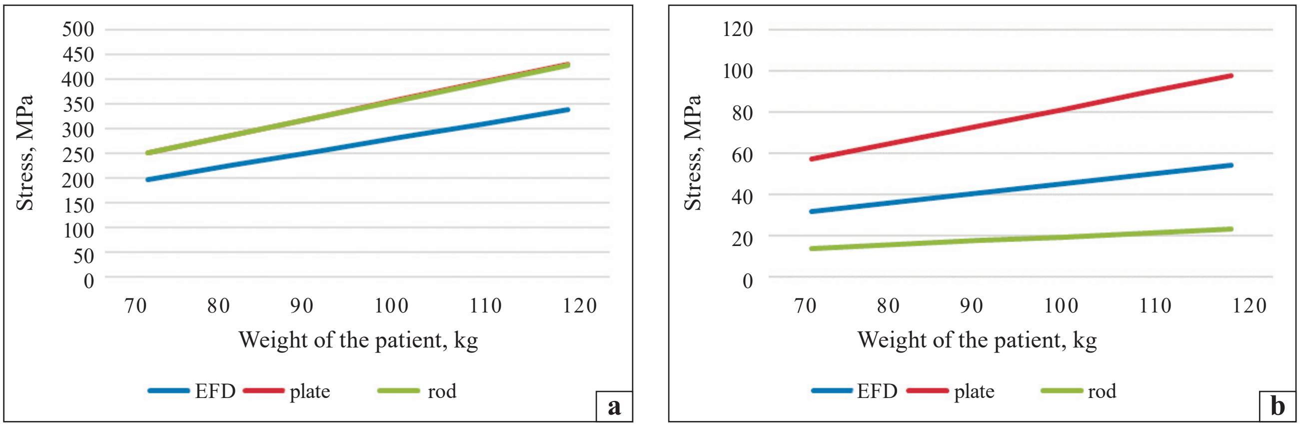


Fig. 10. Graphs of the dependence of stress values on the weight of the patient in the elements of metal structures (a) and around the fixing screws and rods (b) in the tibia after its fracture in the upper third and various types of osteosynthesis

stresses were found in the bone plate. The same occurred around fixation screws and rods in osteosynthesis with a bone plate, where the highest stresses were determined compared to other designs.

Conclusions

The highest stress levels in the fracture zone (from 6.3 to 10.8 MPa) and on the metal structure (from 251.0 to 430.2 MPa) were determined in the model using the bone plate.

A fairly low stress level (0.2–0.3 MPa) in the fracture zone was established in the mathematical model with osteosynthesis using an EFD, but the disadvantage was a high stress level in the proximal part of the tibia (6.7–11.5 MPa).

The lowest values of stresses in the fracture zone (0.1–0.2 MPa) and the proximal fragment of the tibia (0.6–1.0 MPa) were determined in osteosynthesis using an intramedullary rod, but in the distal part of the tibia the stresses remained quite high — 11.1–19.0 MPa.

The function of the dependence of the amount of stress on the weight of the patient in the elements of the model was found to be linear and directly proportional.

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

References

1. WHO. Obesity and overweight [Web source]. — Available from : https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight
2. Pelypenko O. Analysis of the causes of mechanical complications after osteosynthesis of the limbs / Pelypenko O., Kovalov O. // The problems of traumatology and osteosynthesis (Ukraine). — 2020. — Vol. 1 (19). — P. 47–59.
3. Stoyko I. V. Analysis of stress-strain state of the distal tibia and foot in pilon injuries under external fixation using rod devices / I. V. Stoyko, G. V. Bets, M. Yu. Karpinsky, I. G. Bets // Trauma (Ukraine). — 2014. — Vol. 15 (1). — P. 41–49. — DOI: 10.22141/1608-1706.1.15.2014.81263.
4. Mechanical Complications after Limb Osteosynthesis: Analysis of Etiologic Factors in 42 Cases / M. Traore, R. Gogoua, M. Kouame [et al.] // Open Journal of Orthopedics. — 2017. — Vol. 7. — P. 43–52. — DOI: 10.4236/ojo.2017.72006.
5. Jupiter J. B. The complications and difficulties of management of nonunion in the severely obese / J. B. Jupiter, D. Ring, H. Rosen // Journal of Orthopaedic Trauma. — 1995. — Vol. 9 (5). — P. 363–370. — DOI: 10.1097/00005131-199505000-00001.
6. Effectiveness of resisting torsional loads of various options for osteosynthesis of tibial fragments (according to the results of mathematical modeling) / M. Karpinsky, M. Stroiev, M. Berezka [et al.] // Orthopaedics, Traumatolgy and Prjsthetics. — 2022. — No. 1–2. — P. 34–42. — DOI: 10.15674/0030-598720221-234-42. (in Ukrainian)
7. Berezovsky V. A. Biophysical characteristics of human tissues: Handbook / V. A. Berezovsky, N. N. Kolotilov. — Kyiv : Naukova dumka, 1990. — 224 p. (in russian)
8. Mathematical modeling of options for osteosynthesis of distal tibial metaphyseal fractures type C1 [Matematychne modelyuvannya variantiv osteosyntezu perelomiv dystal′noho metaepifiza velykohomilkovoyi kistky typu S1] / V. L. Vasyuk, O. A. Koval, M. Yu. Karpinsky, O. V. Yaresko // Trauma (Ukraine). — 2019. — Vol. 20 (1). — P. 37–46. — DOI: 10.22141/1608-1706.1.20.2019.158666. (in Ukrainian)
9. Mathematical modeling of the influence of the deformation of the lower leg bones on the load on the joints of the lower limb [Matematychne modelyuvannya vplyvu deformatsiyi kistok homilky na navantazhennya suhlobiv nyzhn′oyi kintsivky] / M. O. Korzh, K. K. Romanenko, D. V. Prozorovsky [et al.] // Trauma (Ukraine). — 2016. — Vol. 17 (3). — P. 23–24.
10. Gere J. M. Mechanics of Material / J. M. Gere, S. P. Timoshenko. — 1997. — P. 912.
11. Zenkevich O. K. Finite element method in engineering / O. K. Zenkevich. — Moscow : Mir, 1978. — 519 p. (in russian)
12. Alyamovsky A. A. SolidWorks/COSMOSWorks. Engineering analysis by the finite element method / A. A. Alyamovsky. — Moscow : DMK Press, 2004. — 432 p. (in russian)

The article has been sent to the editors 26.10.2022

THE EFFECTIVENESS OF RESISTANCE TO TORSIONAL LOADS OF VARIOUS OPTIONS FOR OSTEOSYNTHESIS OF BONE FRAGMENTS OF THE TIBIA FOR FRACTURES IN THE UPPER THIRD OF THE DIAPHYSIS (MATHEMATICAL MODELING)

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