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Effectiveness of resisting torsional loads of various options for osteosynthesis of tibial fragments (according to the results of mathematical modeling)

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Recently, there has been a trend towards high statistical indicators of the number of bone fractures of the lower limbs (47.3%), of which diaphyseal fractures of the lower leg bones make up 45–56 %. Objective. Conduct a comparative analysis of the stress-strain state of leg models with a fracture of the tibia under the torsional loading combined with various options of osteosynthesis and depending on the patient's weight. Methods. A fracture was modeled in the middle third of the diaphysis of the tibia and three types of osteosynthesis — with the help of an external apparatus fixation (EAF), periosteal plate and intramedullary rod Bones were attached to the tibial plateau torque of 7 Nm and 12 Nm. Results. It was determined that the changes in stress levels in bone tissue depend linearly on the patient's weight. Under simulation conditions stabilization of the fracture with the help of EAF and intramedullary stress rod in the fracture area were found significantly lower than the level of indicators of intact bone. In this same zone in the model with a bony plate, the value stress levels were lower than the intact model bone, but with an increase in the patient's weight to 120 kg, these indicators almost leveled off. The highest stress level was recorded in the distal part of the tibia in the model with intramedullary rod osteosynthesis, and in the proximal one, the stresses that exceeded the parameters of the model with intact bone were determined under the conditions use of EAF. The largest in metal structures stress is detected in the periosteal plate. Conclusions. The highest stresses in the fracture zone (5.8–9.9 MPa) and on the metal structure (360.0–617.0 MPa) was recorded in a model with a bone plate. In the model with EAF in the zone of the fracture, the stresses were at the level of 0.1–0.2 MPa, in the proximal part of the tibia — 6.3–10.8 MPa, in the model with an intramedullary rod — 0.1–0.2 MPa and 0.5–0.9 MPa, respectively. In the distal part of the stress in the last model remained high — 11.7–20.1 MPa.

Останнім часом спостерігається тенденція до високих статистичних показників кількості переломів кісток нижніх кінцівок (47,3 %), із яких діафізарні переломи кісток гомілки становлять 45–56 %. Мета. Провести порівняльний аналіз напружено-деформованого стану моделей гомілки з переломом великогомілкової кістки під впливом навантаження на кручення за різних варіантів остеосинтезу та залежно від ваги пацієнта. Методи. Моделювали перелом у середній третині діафіза великогомілкової кістки та три види остеосинтезу — за допомогою апарата зовнішньої фіксації (АЗФ), накісткової пластини й інтрамедулярного стрижня. До великогомілкового плато кістки прикладали крутний момент величиною 7 Нм та 12 Нм. Результати. Визначено, що зміни величин напружень у кістковій тканині лінійно залежать від ваги пацієнта. За умов моделювання стабілізації перелому за допомогою АЗФ та інтрамедулярного стрижня напруження в ділянці перелому виявилися значно нижчими за рівень показників неушкодженої кістки. У цій самій зоні в моделі з накістковою пластиною значення рівня напружень були меншими за модель із неушкодженою кісткою, але зі збільшенням ваги пацієнта до 120 кг ці показники майже вирівнялися. У дистальному відділі великогомілкової кістки найвищий рівень напружень зафіксовано в моделі з остеосинтезом інтрамедулярним стрижнем, а в проксимальному — напруження, які перевищили показники моделі з неушкодженою кісткою, визначено за умов використання АЗФ. У металевих конструкціях найбільші напруження виявлено в накістковій пластині. Висновки. Найбільші напруження в зоні перелому (5,8–9,9 МПа) та на металевій конструкції (360,0–617,0 МПа) зафіксовано в моделі з накістковою пластиною. У моделі з АЗФ у зоні перелому напруження були на рівні 0,1–0,2 МПа, у проксимальному відділі великогомілкової кістки — 6,3–10,8 МПа, у моделі з інтрамедулярним стрижнем — 0,1–0,2 МПа та 0,5–0,9 МПа відповідно. У дистальному відділі напруження в останній моделі залишилися високими — 11,7–20,1 МПа. Ключові слова. Гомілка, перелом, кручення, остеосинтез.

Key words. Tibia, fracture, torsion, osteosynthesis

Introduction

Recently, there has been a steady trend towards high statistical indicators of the number of bone fractures of the lower limbs (47.3 %), and diaphyseal fractures of the lower leg bones make up 45–56 % of them [1]. According to the WHO, about 33 % of the population of Europe and America has a body mass index (BMI) of 25 or more points [2, 3].

According to the published analysis of complications in the treatment of diaphyseal fractures of long bones, according to the data of Kharkiv Traumatological Medical Social Expert Committee, more than half of them are related to fractures of the tibia. The rate of primary disability due to injuries of the bones of the lower limbs was up to 27.9 %. Unfortunately, traditional tactics and permanent approaches to the treatment of this category of patients lead to long-term disability in 5 %, which determines the social and economic significance of this issue [4].

Biomechanical features of the interaction in the «implant-bone» system determine the approaches to the tactics of surgical treatment and rehabilitation. Torsional loads are the most dangerous in view of the development of complications in the treatment of tibial bone fractures [5].

We have planned and carried out mathematical modeling by the finite element method taking into account not only excess weight, but also the possibilities of various methods of osteosynthesis with the use of modern implants in the conditions of rotational tests.

Purpose: to conduct a comparative analysis of the stress-strain state of models of the lower leg with a tibial fracture under the influence of torsional load under various options of osteosynthesis depending on the patient's weight.

Material and methods

The materials of the study were discussed and approved at the meeting of the Bioethics Committee at the State Institution «Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Sciences of Ukraine» (Protocol No. 10 of 02.10.2019).

Premises of the biomechanics laboratory of the State Institution «Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Sciences of Ukraine» were used to elaborate a basic finite element model of the human lower leg. The general appearance of the model is shown in Fig. 1.

The model consists of tibia and fibula bones, bones of the foot. In all joints, a layer with the mechanical properties of cartilaginous tissue has been created between the bone elements.

On the basic model, a fracture in the middle third of the tibia and three types of osteosynthesis were simulated with the help of an external fixation device (EFD), a bone plate and an intramedullary rod. The gap between bone fragments in the fracture zone was filled with an element that imitated bone regenerate with the mechanical properties of collagen. The appearance of models with a fracture in the middle third of the tibia and various types of osteosynthesis is shown in Fig. 2.

The material was considered homogeneous and isotropic. A 10-node tetrahedron with quadratic approximation was chosen as the finite element. All materials from which the models were made were given the appropriate mechanical properties, namely Young's modulus of elasticity and Poisson's ratio (Table 1). Mechanical properties of biological tissues were selected from special literature [6–9], metal structures from technical literature [10].

The models were tested under the influence of torsional loads, which were simulated for patients weighing 70 kg and 120 kg. For this, a torque of 7.0 and 12.0 Nm was applied to the tibial plateau. The feet of the models were rigidly fixed. The loading scheme of the models is shown in Fig. 3.

The fracture zone, the metal structure and the bone tissue around the fixing screws were determined to compare the stress-strain state of the models, the maximum values of stresses in the proximal and distal fragments of the tibia.

The model was studied using the finite element method. The von Mises stress [11] was used as a criterion for assessing the stress-strain state of the models.

Modeling was performed using the SolidWorks automated design system; calculations of the stress-strain state of the models were carried out using the CosmosM software complex [12].

Results and their discussion

The first stage of the study assessed the stress-strain state of models of the lower leg with a fracture of the tibia in the middle third under various options of osteosynthesis under the influence of a torsional load of 7.0 Nm. It was determined that under the influence of this load on the intact leg, stresses occurred in the tibia, increasing in the direction from top to bottom. In particular, the lowest stresses of 4.1 MPa were determined in the proximal part of the tibia and its middle third 6.0 MPa, the highest (9.5 MPa) at the distal end (Fig. 4).

In the tibia model with a fracture of the tibia in the middle third of its diaphysis, stabilized with the help of EFD, under a torsional load of 7.0 Nm,

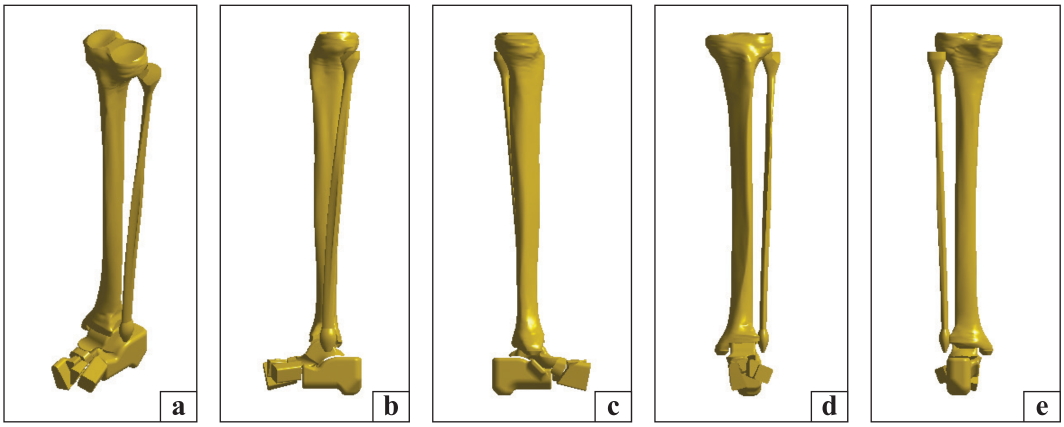


Fig. 1. Basic finite-element model of the tibia: general view (a), from the medial (b) and lateral (c) sides, anterior (d), posterior (e)

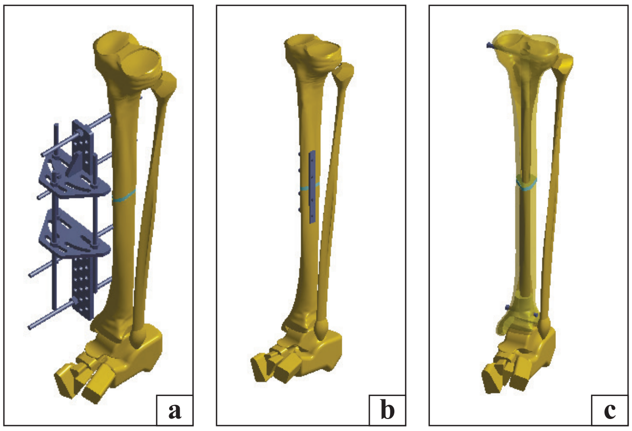


Fig. 2. Models of tibial fracture in the middle third with osteosynthesis: a) EFD; b) bony plate; c) intramedullary rod

Fig. 3. Model loading scheme

Table 1

Mechanical characteristics of materials used during modeling

Material	Young's modulus (E), MPa	Poisson's ratio, ν
Cortical bone	18350.0	0.29
Spongy bone	330.0	0.30
Cartilaginous tissue	10.5	0.49
Collagen	1.0	0.45
Titanium VT-16	$1.1 \cdot 10^5$	0.20

the maximum stresses (6.3 MPa) were set at the proxial end of the tibia.

In the lower sections, the whole load fell on the EFD, the stress on which reached 195.5 MPa. Also, a high level of stress (23.0 MPa) was found on the fixation screws and in the bone tissue around them. However, the study of the mathematical model showed that EFD helped to remove stresses from the distal fragment of the tibia, where they were determined at the level of 0.3 MPa, and, most importantly, from the fracture zone, where they did not exceed 0.1 MPa (Fig. 5).

The stress-deformed state of the tibia model with a fracture of the tibia in the middle third of the diaphysis, fixed by a bone plate, under the action of a torsional load of 7.0 Nm was considered (Fig. 6). On the finite element model the use of this type of osteosynthesis resulted in an increase in the amount of stress in the fracture zone to 5.8 MPa and in the distal fragment of the tibia to 6.1 MPa. At the same time, stress level in the proximal fragment of the tibia decreased to 3.4 MPa. A very high stress level of 360.0 MPa was determined on the plate itself, while the fixing screws remained unstressed.

Fig. 7 shows stress distribution in the model of the lower leg with a fracture of the tibia in the middle third of the diaphysis in osteosynthesis with an intramedullary rod under the influence of a torsional load of 7.0 Nm. According to the results of mathematical analysis, the intramedullary rod under these conditions provided significant resistance to torsional loads. This resulted in a decrease in stress in the fracture zone to 0.1 MPa, in the proximal fragment of the tibia to 0.5 MPa. On the other hand, in the distal fragment, a fairly high level of stress of 11.7 MPa was determined. The stress on the rod itself reached 243.0 MPa, and 10.5 MPa on the fixing screws.

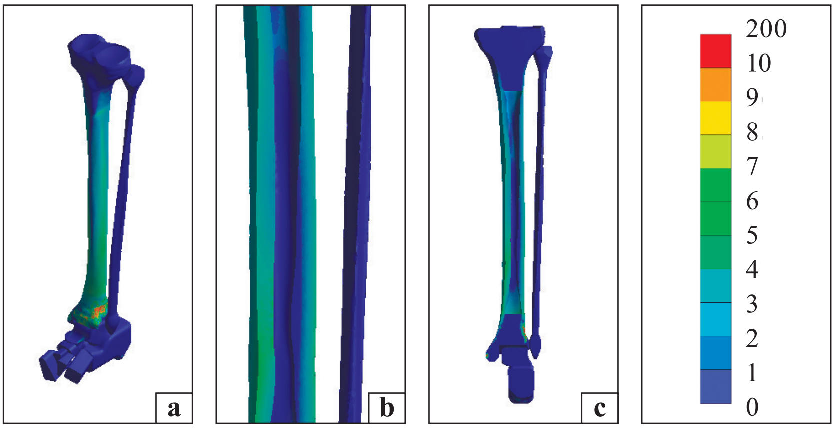


Fig. 4. Pattern of stress distribution in the model of a normal lower leg under the action of a torsional load of 7.0 Nm: a) general view; b) the middle of the diaphysis; c) section of the tibia

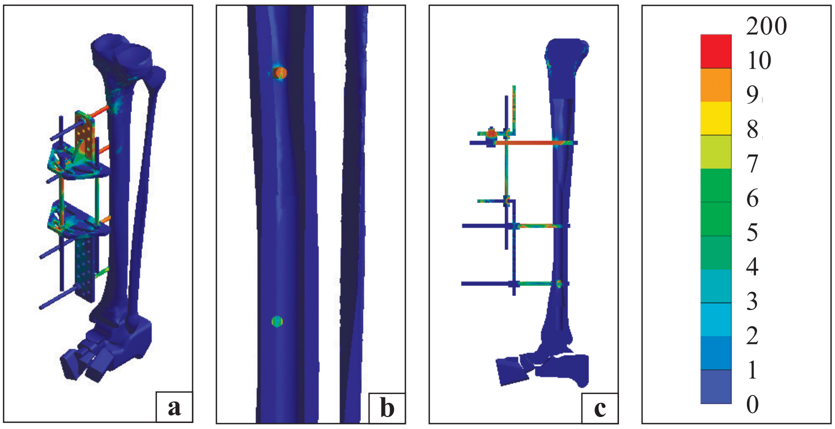


Fig. 5. Pattern of stress distribution in the model of a lower leg with a fracture of the tibia in the middle third and EFD osteosynthesis under a torsional load of 7.0 Nm: a) general view; b) fracture zone; c) section of the tibia

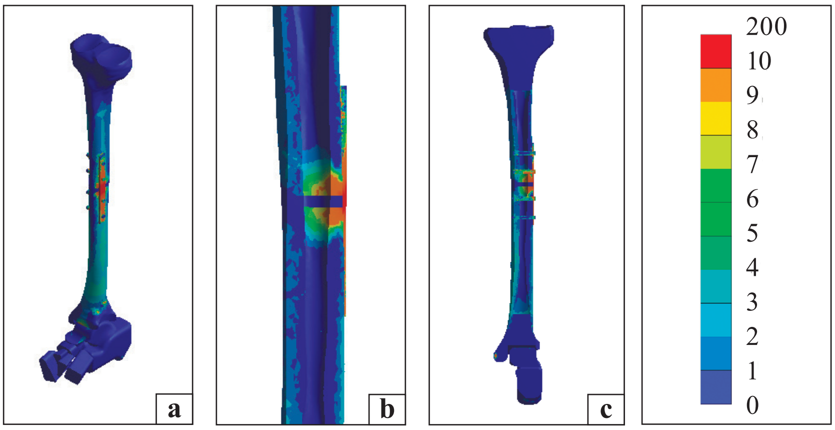


Fig. 6. Pattern of stress distribution in the model of a lower leg with a fracture of the tibia in the middle third of the diaphysis and osteosynthesis with a bone plate under the action of a torsional load of 7.0 Nm: a) general view; b) fracture zone; c) section of the tibia

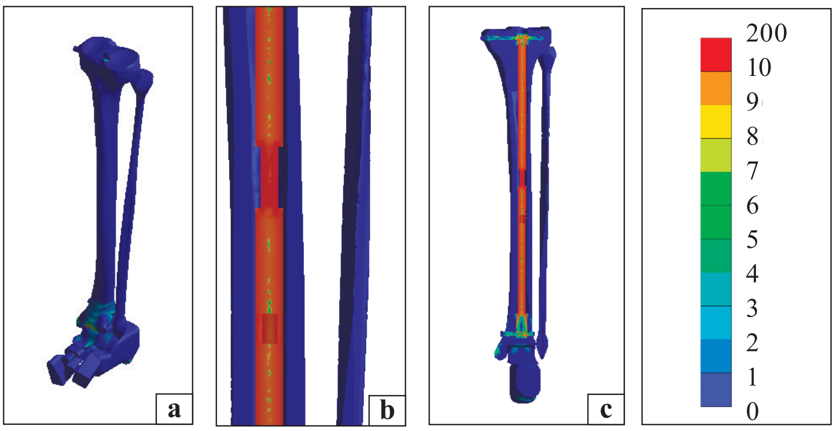


Fig. 7. Pattern of stress distribution in the model of a lower leg with a fracture of the tibia in the middle third of the diaphysis and osteosynthesis with an intramedullary rod under the action of a torsional load of 7.0 Nm: a) general view; b) fracture zone; c) section of the tibia

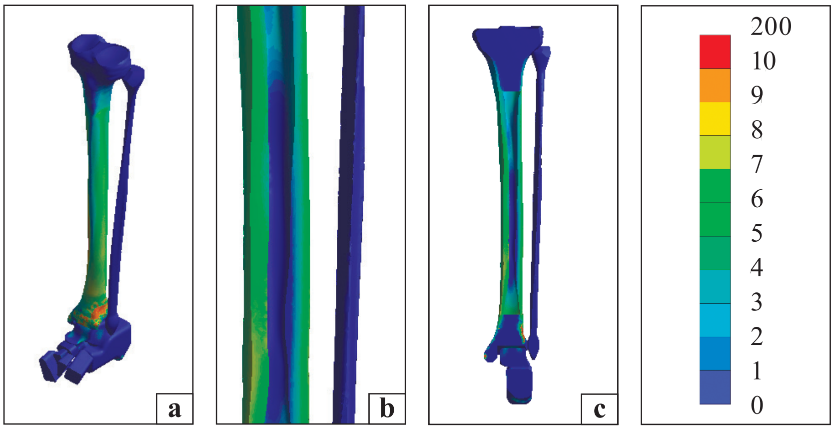


Fig. 8. Pattern of stress distribution in the model of a normal lower leg under the action of a torsional load of 12.0 Nm: a) general view; b) the middle of the diaphysis; c) section of the tibia

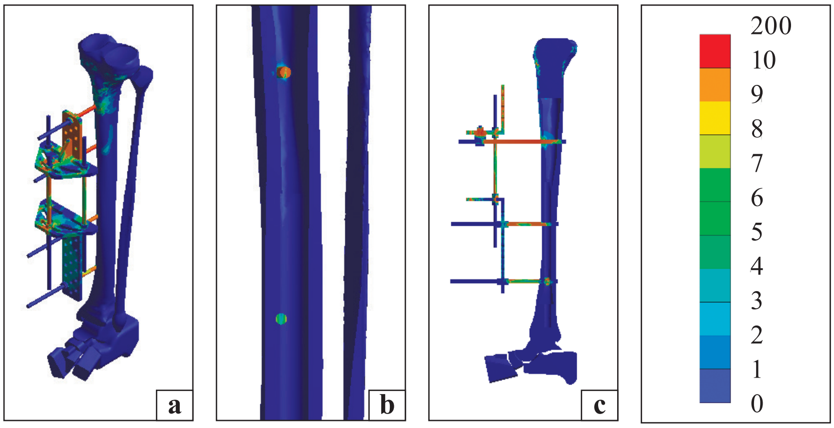


Fig. 9. Pattern of stress distribution under the action of a torsional load of 12.0 Nm in the model of a lower leg with a fracture of the tibia in the middle third of the diaphysis, osteosynthesis with EFD: a) general view; b) fracture zone; c) section of the tibia

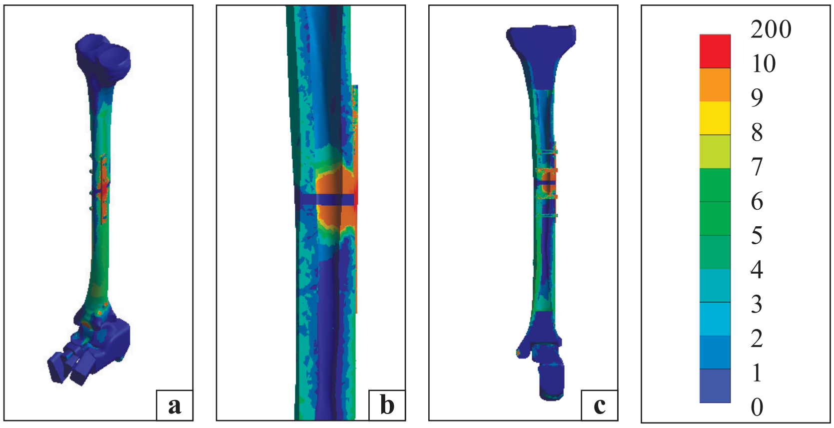


Fig. 10. Pattern of stress distribution under the action of a torsional load of 12.0 Nm in the model of a lower leg with a fracture of the tibia in the middle third of the diaphysis, osteosynthesis with a bone plate: a) general view; b) fracture zone; c) section of the tibia

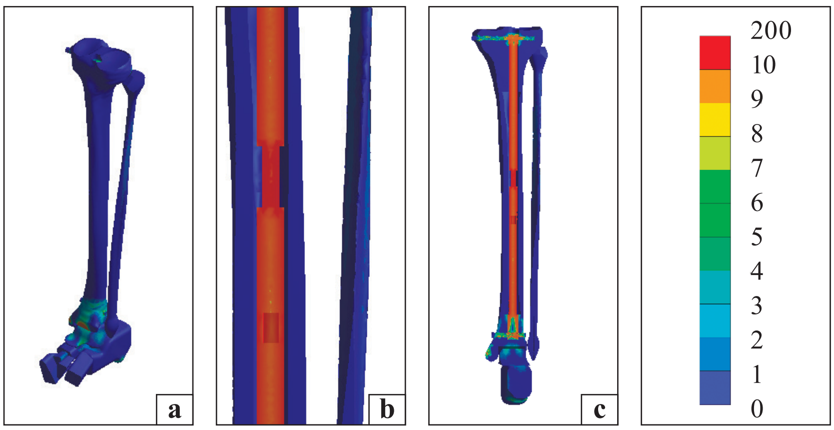


Fig. 11. Pattern of stress distribution under the action of a torsional load of 12.0 Nm in the model of a lower leg with a fracture of the tibia in the middle third of the diaphysis, osteosynthesis with an intramedullary rod: a) general view; b) fracture zone; c) section of the tibia

Table 2 compares the maximum stress values in the elements of different models of the lower leg (normal, with a fracture in the middle third of the diaphysis under the conditions of various types of osteosynthesis) under the action of a torsional load of 7.0 Nm.

Second stage of the study considered how the created leg models behave under the conditions of increased torsional load from 7.0 to 12.0 Nm, which corresponded to the patient's weight of 120 kg.

The study showed the following stresses in the tibia under the conditions of a torsional load of 12.0 Nm: 7.0 MPa in the proximal part, 16.3 MPa in the distal part, 10.3 MPa in the middle third (Fig. 8).

Analysis of the model of the lower leg with a fracture of the tibia in the middle third of the diaphysis, stabilized with the help of EFD, revealed an increase in the values of stresses in all elements of the model. The biggest changes were observed in the structural elements, where the stresses reached 335.1 MPa, and 39.4 MPa in the fixing rods. In the bone tissue, the highest stress level was determined in the proximal fragment of the tibia — 10.8 MPa, but in the distal fragment and the fracture zone, the stress values remained rather low — 0.5 and 0.2 MPa, respectively (Fig. 9).

Fig. 10 shows the stress-deformed state of the tibia model with a fracture of the tibia in the middle third of the diaphysis, fixed by a bone plate, under the influence of a torsional load of 12.0 Nm. Mathematical calculations of this model determined that an increase in the patient's weight did not change the nature of the stress distribution compared to the action of a load of 7 Nm. So, we observed an increase in the stress level on all elements of the model: in the fracture zone and the distal fragment of the tibia up to 9.9 and 10.5 MPa, respectively, in the proximal fragment – up to 5.8 MPa. The bone plate was the most stressed element — 617.0 MPa, and the fixing screws remained unstressed.

Analysis of stress distribution in the finite-element model of the lower leg with a fracture of the tibia at the level of the middle third of the diaphysis, stabilized with the help of an intramedullary rod, under a torsional load of 12.0 Nm, established that the low level of stress was also maintained in the fracture zone (0.2 MPa), and in the proximal fragment of the tibia (0.9 MPa). In the distal fragment, the stresses increased to 20.1 MPa. The highest stress level (416.5 MPa) was determined on the rod itself; on the fixing screws they were equal to 18.0 MPa (Fig. 11).

Table 2

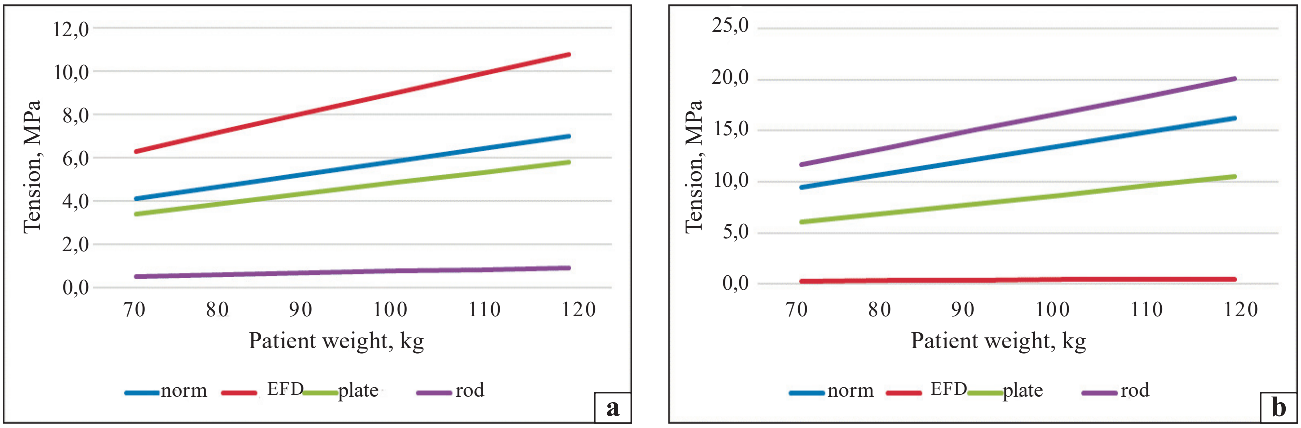
Maximum stresses (MPa) in sections of different finite-element models of a lower leg under the action of a torsional load of 7.0 Nm

Zone	Model			
	Normal values	Osteosynthesis device		
		EFD	plate	rod
Tibia:				
– proximal fragment;	4.1	6.3	3.4	0.5
– distal fragment	9.5	0.3	6.1	11.7
Fracture zone	6.0	0.1	5.8	0.1
Construction	—	195.5	360.0	243.0
Entry of screws	—	23.0	0.0	10.5

Таблиця 3

Максимальні напруження (МПа) в ділянках різних скінченно-елементних моделей гомілки під дією навантаження на кручення величиною 12,0 Нм

Zone	Model			
	Normal values	Osteosynthesis device		
		EFD	plate	rod
Tibia:				
– proximal fragment;	7.0	10.8	5.8	0.9
– distal fragment	16.3	0.5	10.5	20.1
Fracture zone	10.3	0.2	9.9	0.2
Construction	—	335.1	617.0	416.5
Entry of screws	—	39.4	0.0	18.0



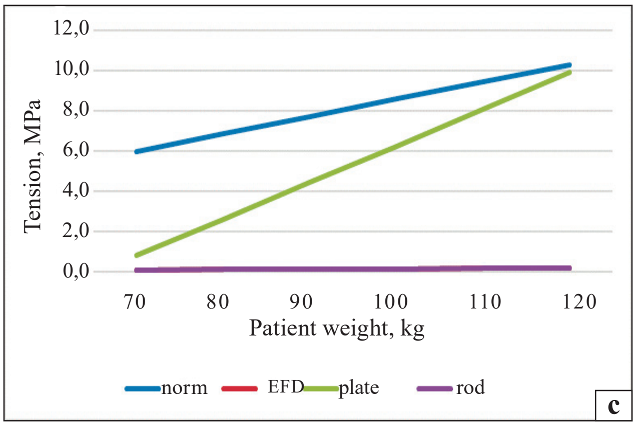


Fig. 12. Graphs of the dependence of stress values on the patient's weight in the model of a tibia with its fracture in the middle third of the diaphysis, stabilized with the help of various types of osteosynthesis: proximal (a) and distal (b) fragments, fracture zone (c)

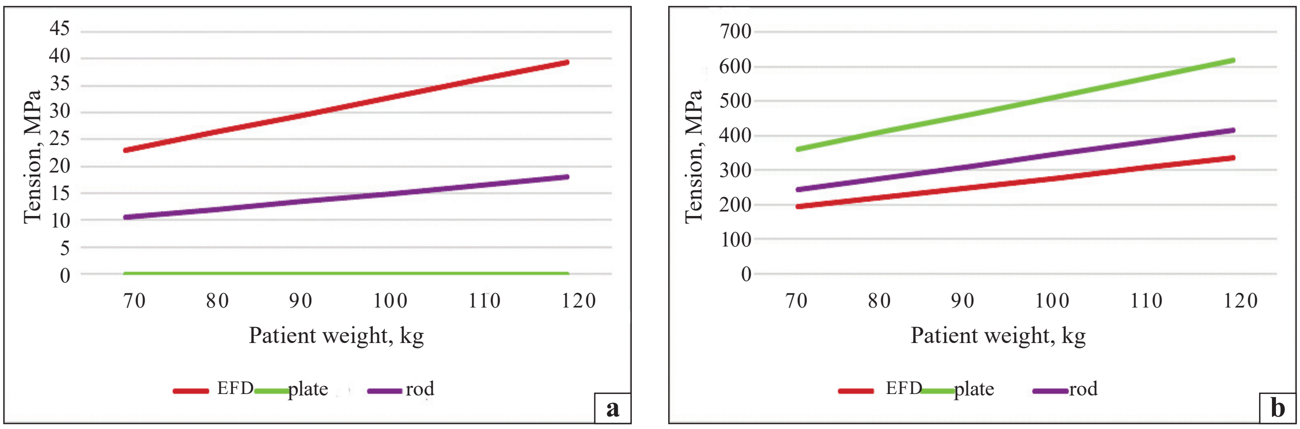


Fig. 13. Graph of the dependence of the stress values around the fixing screws (a) and in the elements of the metal structures (b) used to simulate osteosynthesis of fractures at the level of the middle third of the diaphysis of the tibia, on the patient's weight

Table 3 compares the values of the maximum stresses in the elements of the created models of the lower leg (normal, with a fracture of the tibia at the level of the middle third of the diaphysis for various options of osteosynthesis) under the action of a torsional load of 12.0 Nm.

Thus, the EFD and the intramedullary rod ensured the minimum stress level in the fracture zone under torsional load conditions. Osteosynthesis with a bone plate did not lead to significant stress reductions in any of the areas of the tibia, with the exception of the fixing screws, where the stresses were equal to 0. As for the stress values on elements of metal structures, the bone plate again led in this case.

Graphs of the patient's weight were drawn for a visual representation of changes in the amount of stress in the elements of the tibia after its fracture in the middle third of the diaphysis, fixed with the help of various devices (Fig. 12).

The conducted studies showed that the changes in the stress levels in the bone tissue depended linearly on the patient's weight. At the same time, in simulation of fracture stabilization with the help of EFD and intramedullary rod, the stresses in the fracture area were significantly lower than the level of indicators of the intact bone. In the same area, the stress level values in the model with a bone plate were lower than in the model with intact bone, but as the patient's weight increased to 120 kg, these values almost leveled off. In the distal part of the tibia, the highest stress level was determined in the model with osteosynthesis with an intramedullary rod, and in the proximal part, stresses that exceeded the parameters of the model with an intact bone were determined under the conditions of using EFD.

The graphs shown in Fig. 13, demonstrate the dependence of stress values in elements of metal structures, used in models for fixing a fracture in the middle third of the tibial diaphysis, on the patient's weight.

In the same way as in bone tissue, the stress values in metal structures directly depended on the patient's weight. They were the highest in the periosteal plate, but near the fixation screws and rods around it, the stresses were minimal. The highest values of stresses on structural elements were found in the model with EFD.

Conclusions

The highest stress levels in the fracture zone (from 5.8 to 9.9 MPa) and on the metal structure (from 360.0 to 617.0 MPa) were determined in the model with a bone plate.

The analysis of the model, where EFD was used for osteosynthesis of a tibial fracture at the level of the middle of the diaphysis, revealed a rather low level of stress (from 0.1 to 0.2 MPa) in the fracture zone, but the disadvantage was a high level of stress in the proximal part of the bone (from 6.3 to 10.8 MPa).

The lowest values of stresses in the fracture zone (from 0.1 to 0.2 MPa) and the proximal fragment of the tibia (from 0.5 to 0.9 MPa) were determined in osteosynthesis with an intramedullary rod, but in the distal part of the bone, the stresses remained quite high, from 11.7 to 20.1 MPa.

The dependence function of the magnitude of stresses in the elements of the considered model is linear and directly proportional.

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

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EFFECTIVENESS OF RESISTING TORSIONAL LOADS OF VARIOUS OPTIONS FOR OSTEOSYNTHESIS OF TIBIAL FRAGMENTS (ACCORDING TO THE RESULTS OF MATHEMATICAL MODELING)

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