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BIOMECHANICAL FEATURES OF SINGLE-BONE OSTEOSYNTHESIS OF DIAPHYSEAL FRACTURES IN CHILDREN BY THE TITANIUM ELASTIC NAILS

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The purpose of the study was to investigate the changes in stress-strain in the forearm bones in diaphyseal fracture of both bones when fixing a fracture of only one bone with titanium elastic nails compared to normal and to determine the type of fixation that best provides conditions for optimal fracture consolidation. We used the finite elements method for numerical analysis of the stress-strain state in the forearm bones. The model was based on tomographic sections of bone. A transverse fracture in the middle of the diaphysis of the ulna and radius was modeled and variants of the model with osteosynthesis with titanium elastic fracture nails of either the ulna only or the radial bone were constructed. The developed biomechanical model "Diaphysis of the forearm bones – metal fixator" demonstrates a moderate increase in internal stress at the fracture site using titanium elastic nails , which can help create optimal conditions for reparative osteogenesis; the greatest changes in the stress-strain state in both types of osteosynthesis in comparison with the norm occurred in the simulation of torsion, especially in the ulna. A significant increase in the stress-strain state in the fracture area of the ulna with its isolated osteosynthesis can lead to complications in the form of delayed union or the formation of a nonunion (even a break of the fixator with the wrong selection of its diameter). Thus, in the case of a fracture of both bones of the forearm, even with a stable fracture of the radial bone, it is not recommended to fix only the ulna. It is better to fix both bones according to standard methods. In addition, in the case of both forearm bones' fracturing with a stable fracture of the ulna, you can limit osteosynthesis of the radial bone only.

Key words: children, fracture of forearm bones, biomechanics, osteosynthesis, stress-strain state.

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БІОМЕХАНІЧНІ ОСОБЛИВОСТІ SINGLE-BONE ОСТЕОСИНТЕЗУ ДІАФІЗАРНИХ ПЕРЕЛОМІВ КІСТОК ПЕРЕДПЛІЧЧЯ У ДІТЕЙ ІЗ ЗАСТОСУВАННЯМ ТИТАНОВИХ ЕЛАСТИЧНИХ СТРИЖНІВ

Метою роботи було вивчення змін напружено-деформованого стану в кістках передпліччя при діафізарному переломі обох кісток при фіксації перелому лише однієї кістки за допомогою титанових еластичних стрижнів в порівнянні з нормою та визначити тип фіксації, який найкраще забезпечує умови для оптимального зрощення перелому. Для чисельного аналізу напружено-деформованого стану у кістках передпліччя нами був використаний метод скінчених елементів. Модель будувалася на основі томографічних зрізів кістки. Було змодельовано поперечний перелом у середині діафіза ліктьової та променевої кісток та побудовані варіанти моделі з остеосинтезом титановими еластичними стрижнями перелому або тільки ліктьової або тільки променевої кістки. Розроблена біомеханічна модель «діафіз кісток передпліччя – металевий фіксатор» демонструє помірне збільшення внутрішнього напруження в місці перелому при використанні титанових еластичних стрижнів, що може сприяти створенню оптимальних умов для репаративного остеогенезу; найбільші зміни напружено-деформованого стану при обох видах остеосинтезу в порівнянні з нормою відбувалися при моделюванні кручення, особливо в ліктьовій кістці. Значне збільшення напружено-деформованого стану в ділянці перелому ліктьової кістки при її ізольованому остеосинтезі може призводити до ускладнень у вигляді сповільненого зрощення або формування несправжнього суглобу (навіть перелому фіксатора при неправильному підборі його діаметру). Таким чином, у випадку перелому обох кісток передпліччя навіть при стабільному переломі променевої кістки, не рекомендується фіксація лише ліктьової кістки. Краще виконати фіксацію обох кісток за стандартною методикою. А у випадку перелому обох кісток передпліччя зі стабільним переломом ліктьової кістки можна обмежитися остеосинтезом лише променевої кістки.

Ключові слова: діти, перелом кісток передпліччя, біомеханіка, остеосинтез, напружено-деформований стан.

Analysis of modern literature sources [11] showed that the problem of osteosynthesis of forearm bones diaphyseal fractures in children is extremely relevant.

For the surgical treatment of diaphyseal fractures of the forearm bones in children, minimally invasive intramedullary osteosynthesis using titanium elastic rods (TER), which in our opinion is an effective method of surgical treatment, has lately become widespread.

When using the classical method of intramedullary osteosynthesis, it is necessary to fix both bones [4, 11] to prevent secondary displacement of fragments of unfixed bone. However, additional surgery is an additional soft tissue injury that can cause neuropathy, infectious complications (including osteomyelitis) and compartment syndrome [3, 9, 13]. The radiation exposure to the patient and staff also increases [12].

Therefore, there have been many recent publications on intramedullary fixation of only one bone (more displaced) with a stable fracture without displacement of the second (single-bone fixation) [4, 5, 15].

Given this, we want to dwell on some biomechanical aspects of osteosynthesis.

According to some authors [10, 11], hematoma around the fracture is the main source of the formation of periosteal callus. Its formation is facilitated by micromovements in the fracture area [11]. Periosteal callus is the main and is formed faster in the presence of periosteum, which in children is thicker and better vascularized than in adults [11]. The process of bone remodeling after fracture consists of resorption of the primary callus by osteoclasts and the formation of mature lamellar bone tissue by osteoblasts [10, 11]. Plate bone trabeculae are located along the lines of mechanical force [10, 11]. This fact is interesting from the point of view of callus formation biomechanics.

Analysis of the bone beams and plates location indicates that the architectonics of bone tissue corresponds to the lines of force stress that occurs in the bone under load [8].

In view of this, osteosynthesis should provide [1] preservation of the axis of the affected segment and elastic deformations in the fracture zone and restoration of bone tension due to elastic deformation of the fracture site under cyclic loads in the presence of preserved hematoma at the fracture site [10, 11].

In our opinion, flexible metal intramedullary fixators, namely TENs, meet these requirements the most. In the literature we have studied, there are opposite recommendations for osteosynthesis of diaphyseal fractures of the forearm bones in children. Mandatory osteosynthesis of both bones is preferred, but there are a number of articles on the fixation of one bone only without a clear biomechanical justification for the use of each of these methods of surgical treatment, which became the basis for this work.

The purpose of the study was to investigate the changes in the stress-strain state in the forearm bones in diaphyseal fracture of both bones when fixing the fracture of one bone only with titanium elastic nail in comparison with the norm. Based on the study, determine the type of fixation that provides the best conditions for optimal fracture fusion.

Materials and methods. For the numerical analysis of the stress-strain state (SSS) in the forearm bones, we used the finite element method (FEM). To build a calculated biomechanical model based on the model of the ulna and radial bones, which were developed in the laboratory of biomechanics of the Sytenko Institute. The model was based on tomographic sections of the bone, which were performed in 0.5–1 cm for irregular areas (proximal and distal parts) and 1–3 cm for areas with simpler geometry (diaphysis). Additional geometric dimensions of the forearm bones, which were necessary to build a geometric model of the forearm in children, were taken from the work [14].

Based on the constructed geometric model, we simulated a fracture in the middle of the diaphysis of the ulnar and radial bones and variants of the model with osteosynthesis of TENs were built (with isolated osteosynthesis of fractures of the ulnar or radial bones).

Features of materials.

The studies took into account different types of biological tissues: compact and spongy bone, cartilage. In this study, the material was considered homogeneous and isotropic. When choosing the properties of bone structures, we based on the data most common in the literature [6], for fixators the properties of materials were taken from [7]. The obtained characteristics are summarized in table 1.

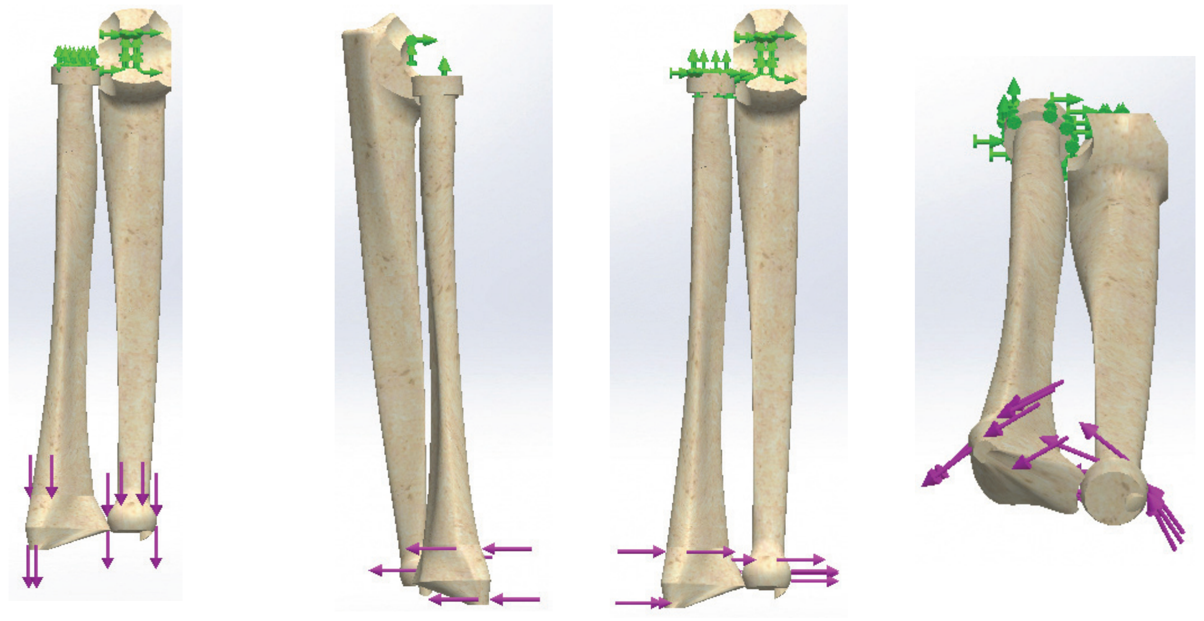
Table 1

Mechanical characteristics of materials used

Tissue	E (MPa)	□
Compact bone	18350	0.3
Spongy bone	330	0.3
Cartilage	10.5	0.49
Callus	50	0.3
Titanium	120000	0.33

The scheme of loading and fastening. The main purpose of the study was to determine the stress-strain state of the forearm bones in different types of osteosynthesis. To do this, we considered the load on the bones of the forearm in the area of the radial wrist joint with a force of 10 N in different directions, and also considered the torsion of 1 Nm. In the area of the elbow joint, the forearm bones are fixed. In fig. 1 on the example of the model in the norm the direction of loads and fixing the model is shown.

As an assessment of the stress state, von Mises stresses are selected as the most informative type of the general stress state. The obtained computational model consists of 23,722 three-dimensional tetraidal isoparametric FEs and has 38,820 nodes. The calculations were performed in the SOLIDWORKS software. Database management of the study, data processing and tabulation were maintained using Microsoft Excel 2013 software.



a b c d

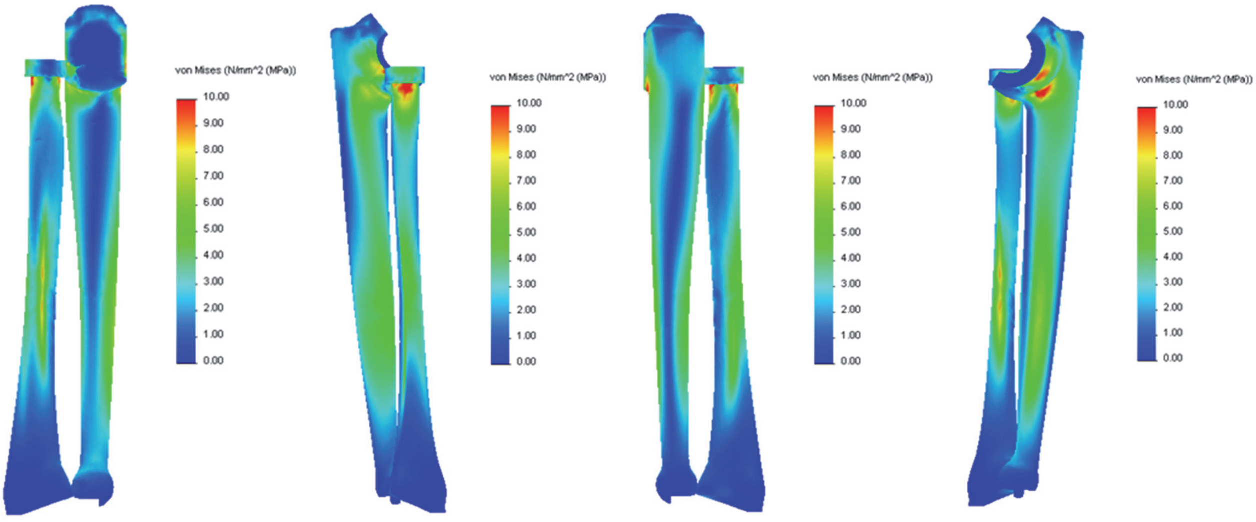
Fig.1 The direction of loading and fixing of the model: a) tensile load; b) load in the sagittal plane, directed front to back; c) load in the frontal plane, directed from outside to inside; d) torsion.

Results of the study and their discussion. Analysis of the results of the SSS study of the forearm bones in the norm in the simulation of vertical tensile load showed that the level of stress remains low. The stress in the middle of the diaphysis was 0.16 MPa for the ulna and – 0.05 MPa for the radial bone. Next, the SSS was calculated for the load located in the sagittal plane and directed from front to back. Analysis of this study results showed that the stress in the middle of the diaphysis was 1.64 MPa for the radial bone and 0.58 MPa for the ulna.

Analyzing the changes in SSS in the simulation of the load located in the frontal plane and directed from the outside to the inside, we can say that the stress in the middle of the diaphysis is 0.77 MPa for the radial bone, and more stress occurs in the ulna (0.92 MPa, respectively).

In the latter version, 1 Nm of torque applied to the radial wrist joint was used for loading. Analysis of the results showed that in the middle of the diaphysis the stress was the highest compared to previous versions and was 2.14 MPa for the radial bone and 2.43 MPa for the ulna. This version of the study was the most interesting for us, given the significant increase in bone tension.

Graphically, the changes in SSS in the simulation of torsion are presented in fig. 2, where the color scale from blue to red colors indicate the stresses arising in the bones of the forearm. Blue indicates the minimum von Mises stress, and red indicates the maximum.



a b c d

Fig.2 Von Mises stress in the calculation model is normal in the simulation of torsion: a) front view; b) view from the lateral side; c) rear view; d) view from the medial side.

Analysis of the fourth variant results of the study, which simulated torsion, shows that the most stressed areas are the proximal areas and the middle of the diaphysis of both forearm bones, and the least stressed are the distal parts.

Next, a study was performed of the SSS of the forearm bones in the simulation of isolated osteosynthesis of the ulna or radius fractures using TEN.

We were most interested in changes in the SSS of the forearm bones in the fracture area, which in our opinion could promote better fusion or, conversely, lead to its slowing down or the formation of a nonunion.

Graphically, the changes in SSS in the simulation of osteosynthesis using TEN diaphyseal fracture of the ulna in comparison with the norm are presented in fig. 3.

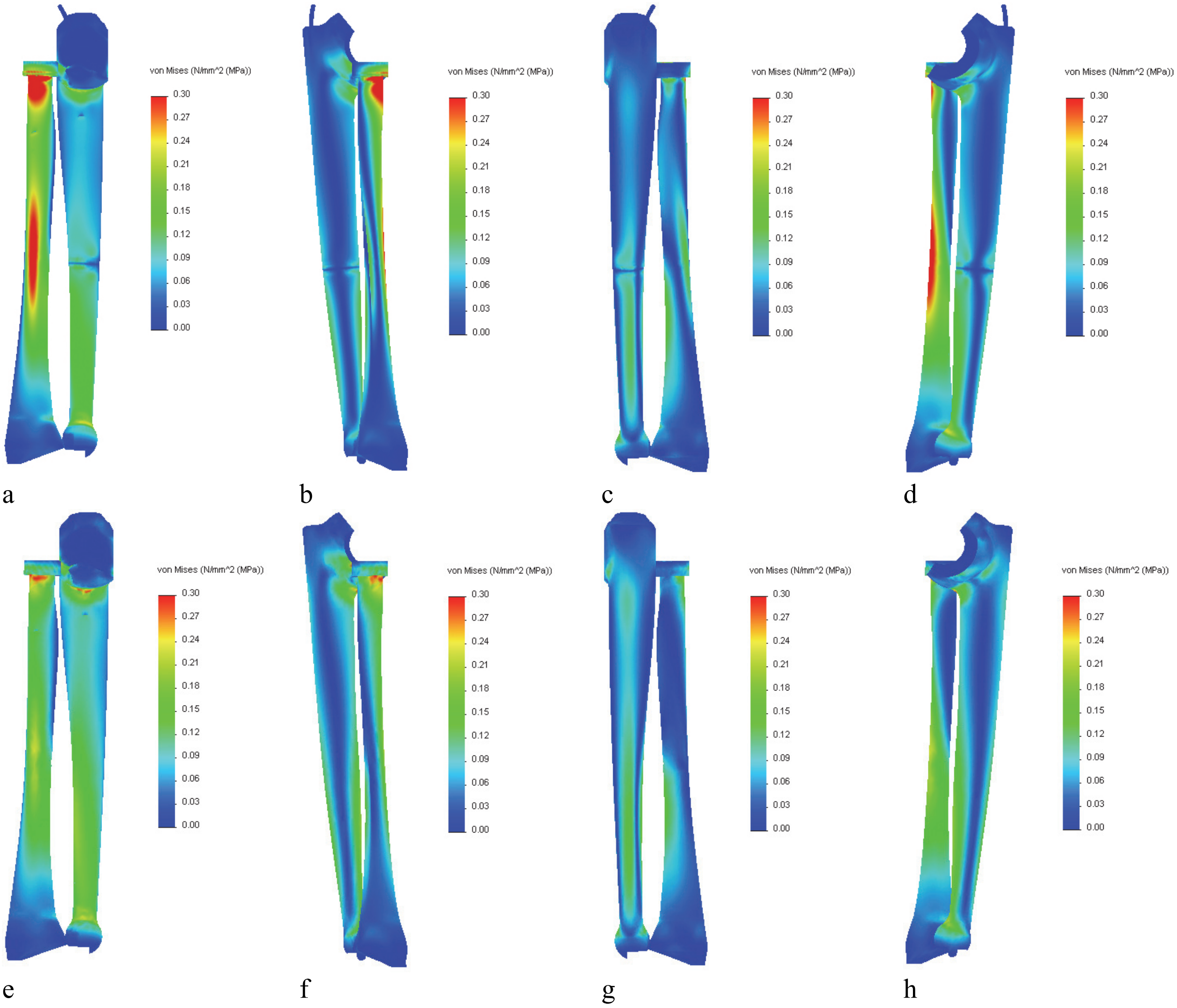


Fig.3 Von Mises stress in the calculation model with the synthesis of TEN of the ulna (a-d) and the model in the norm (d-z): a, e) front view; b, e) lateral view; in, g) rear view; d, h) medial view.

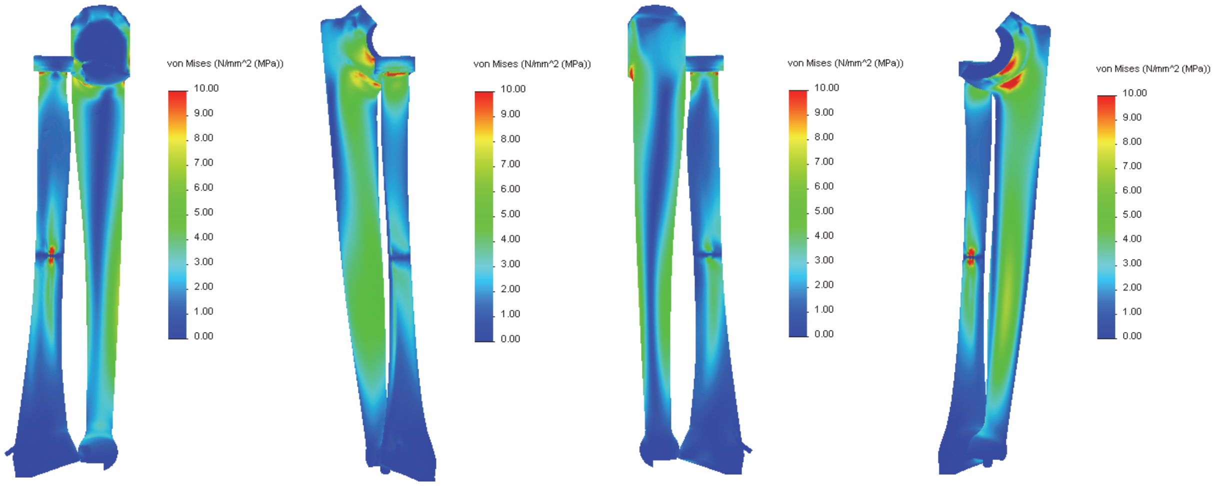
Based on this study, we can draw the following conclusions that in the modeling of osteosynthesis using TEN diaphyseal fracture of the ulna:

1. In the section of the ulna there is a decrease in stress, which is a consequence of the redistribution of forces at TEN under load located in the sagittal plane, under load located in the frontal plane and, especially, during torsion.

2. At the same time, at the point of TEN contact with the bone in the fracture site there is a zone of significant stress concentration due to the redistribution of load on the fixator, and not on the fracture site.

3. The radial bone is more stressed, especially in the proximal region.

Graphically, the changes in SSS in the modeling of osteosynthesis using TEN of diaphyseal fracture of the radial bone are presented in fig. 4.



a b c d

Fig. 4 Von Mises stress in the radial bone for the computational model with the synthesis of TEN of the radial bone: a, c) section in the frontal plane; b, d) section in the sagittal plane.

Based on this study, we can draw the following conclusions in the modeling of osteosynthesis using TEN diaphyseal fracture of the ulna:

1. In the place of contact of TEN with the bone in the fracture area there is a zone of stress concentration.
2. In the cross section of the radial bone there is a decrease in stress, which is a consequence of the redistribution of load on TEN .
3. At the same time in the ulna with TEN stress is less than in the radial one in the simulation of osteosynthesis of the ulna.

The results of SSS changes in the forearm also obtained during the study are summarized in table 2.

Table 2

Changes in SSS in the fracture area depending on the direction of the load on the forearm, MPa

Site of study	Model of load	Strain	Bending in the sagittal plane	Bending in the frontal plane	Torsion
Radial bone	Norm	0.05	1.64	0.77	2.14
	TEN	0.32	13.28	6.2	46.63
Ulnar bone	Norm	0.16	0.58	0.92	2.43
	TEN	3.0	33.74	29.35	73.96

Analyzing the data obtained, we can observe that the SSS in the bones of the forearm has changed compared to normal. When modeling the vertical load (tension) there is a stress in the middle of the shaft for the ulna – 3.0 MPa (0.16 MPa for the normal model), for radius – 0.32 MPa (0.05 MPa for the normal model).

Analysis of the results in the simulation of the load located in the sagittal plane and directed from front to back showed that the stress in the middle of the diaphysis was 13.28 MPa for the radial bone (1.64 MPa for the normal model) and 33.74 MPa for the ulna (0.58 MPa for the model is normal). Analysis of the results of the SSS study at a load located in the frontal plane and directed from the outside to the inside showed that the stress in the middle of the diaphysis is 6.2 MPa for radial bone (0.77 MPa for normal model) and, again, more intense is the ulna – 29.35 MPa (0.92 MPa for normal model). When simulating torsion in the radial wrist joint, the analysis of the results showed that in the middle of the diaphysis the stress was the highest compared to previous versions and was 46.63 MPa for the radial bone (2.14 MPa for the normal model) and 73.96 MPa for the ulna (2.43 MPa for the normal model).

Thus, according to new and previously performed [2] studies, we can observe a significant increase in SSS in the fracture site in the simulation of osteosynthesis of ulnar and radial bones using TEN in bending in the frontal plane and, especially, in torsion. The largest changes in SSS in both types of osteosynthesis compared to the norm occurred in the simulation of torsion, especially in the ulna, which in our opinion may contribute to the creation of optimal conditions for reparative osteogenesis, given that osteosynthesis by TEN provides [1] preserving the axis of forearm bones, elastic deformations in the fracture zone and cyclic loads [10, 11]. At the same time, changes in SSS in both bones of the forearm, especially in the ulna, were by several tens of times higher than normal stresses.

This, in our opinion, may mean that intramedullary fixation of a fracture of only one bone with displacement of fragments without displacement of fragments of another one (single-bone fixation) [4, 5, 15] without taking into account biomechanical features of fixation of these fractures, only to reduce operative time and radiation exposure, can lead to a number of complications, such as delayed union, nonunion and even a break of the fixator due to excessive cyclic loads on it.

Conclusion

Based on the study, we came to the following conclusion. In our opinion, a significant increase in SSS in the fracture of the ulna in its isolated osteosynthesis can lead to complications such as delayed union or a nonunion (even a break of the fixator with the wrong selection of its diameter). Thus, in the case of a fracture of both bones of the forearm, even with a stable fracture of the radial bone, it is not recommended to fix only the ulna. It is better to fix both bones according to standard methods. And in the case of a fracture of both forearm bones with a stable fracture of the ulna, you can limit by the osteosynthesis of only the radial bone.

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