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Biomechanical justification of the Ilizarov external fixation osteosynthesis for gunshot fractures of the proximal femur

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Abstract

Introduction The search for the optimal method of external osteosynthesis for proximal femoral fractures without pelvic fixation has once again become relevant. This is due to casualties with gunshot fractures of this location, accompanied by extensive soft tissue defects, referred to military medical organizations.

Purpose To develop a method for stabilizing bone fragments using the Ilizarov apparatus through biomechanical modeling of various external osteosynthesis options for proximal femoral gunshot fractures, ensuring gradual hip joint movement and weight-bearing on the involved limb.

Materials and Methods Based on computer tomography data, a biomechanical model of a proximal femoral fracture and its osteosynthesis methods using various fixation devices were constructed. Stresses and strains arising from typical loads experienced by the injured during controlled weight-bearing on the operated lower limb were studied. In bench tests on specially prepared models, the elastic strength of the Ilizarov apparatus models was investigated, and the maximum mechanical loads that the studied fixators can withstand were identified and analyzed.

Results The use of the Ilizarov apparatus, ensurig stabilization of the proximal fragment with a bundle of polyaxially inserted tensioned 3-mm wires and its additional fixation with support rods, provides the most favorable stress-strain parameters in the "bone-fixator" system compared to an unreinforced Ilizarov apparatus configuration. The results of the finite element modeling were confirmed with bench tests. Comparison of the results of biomechanical modeling of external osteosynthesis variants with the Ilizarov apparatus and internal osteosynthesis with a proximal femoral nail indicates the advantages of internal fixation.

Discussion The obtained data are in full agreement with the results of biomechanical studies that presented the results of biomechanical modeling of osteosynthesis options for tibial fractures. According to these authors, in the "bone–locked nail" system, the mechanical stress in the fixator is lower than in the "bone–external fixator" system. Moreover, prolonged stress concentration on the elements of the fixation device can cause their weakness. However, the inability to use internal osteosynthesis techniques in proximal femoral gunshot fractures justifies the development and clinical application of the proposed Ilizarov apparatus configuration, which stress-strain parameters are the closest to the proximal femoral nail.

Conclusion The data obtained substantiate the possibility of using the developed external osteosynthesis method with the Ilizarov apparatus in clinical practice for treating gunshot fractures. The results of the experimental study prove the prospect of using the proposed Ilizarov apparatus configuration for long-term stabilization of this type of fracture under the conditions of graded weight-bearing on the involved limb and hip joint movement throughout the entire consolidation period.

Keywords: biomechanics, biomechanical modeling, finite element method, external osteosynthesis, femoral gunshot fracture, equivalent stresses

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INTRODUCTION

Surgical treatment of the injured with gunshot fractures of the proximal femur that are accompanied by soft tissue and bone defects remains one of the unsolved problems in current military traumatology. The greatest challenges in treating such patients arise when the gunshot wound to the soft tissues presents an extensive defect, and the wound healing process is complicated by the development of suppuration or wound infection. In such cases, fracture stabilization by sequential osteosynthesis (conversion of a half-pin-based fixator to an internal fixator) is impossible, and the method of choice is external osteosynthesis with the Ilizarov apparatus [1, 2].

The extensiveness and infection of soft tissue defects, as well as the comminuted nature of the fracture in such patients, often preclude the use of the Ilizarov apparatus that includes half-pins for osteosynthesis in the proximal module [2]. This forces traumatologists to use the Ilizarov apparatus with hip joint fixation for external osteosynthesis. One solution to this problem may be to modify the configuration of the external fixator. Thereby, the following requirements should be followed: relative stability of bone fragments maintained throughout the fracture healing; early patient mobilization, and the ability to apply graded weight-bearing on the involved lower limb.

Those data are confirmed by the research of Kryukov [3] on the possibility of a dosed weight-bearing load to ensure earlier differentiation of cell structures in the fracture area and stimulate reparative osteogenesis. Also, according to Kolchanov et al., proper tensometric ontrol of the axial load on the limb during rehabilitation significantly activates the recovery processes [4].

Advances in the development of new surgical treatment methods for patients with long bone fractures have been achieved through the symbiosis of clinical and biomechanical research [5, 6]. Current methods of mathematical modeling and applied information technologies have significantly increased the capabilities of researchers, including in the development of treatment technologies for patients with bone fractures. The most effective and universal method of computer modeling is the finite element method [7]. It has found wide application in the modeling of various engineering designs and biomechanical systems [4, 8, 9]. At the same time, to confirm the results of computer modeling and prepare for clinical testing, it is advisable to conduct load bench tests.

The combination of the need to develop a method for osteosynthesis of gunshot fractures of the proximal femur using the Ilizarov apparatus that meets the above requirements, and the availability of specially developed approaches to the use of biomechanics for this method [10, 11] determined the feasibility of carrying out this experimental study.

Purpose To substantiate, through biomechanical modeling, the possibility of using the developed method of external osteosynthesis with the Ilizarov apparatus which ensures hip joint movements and a dosed weight-bearing on the limbs in gunshot fractures of the proximal femur.

MATERIAL AND METHODS

Based on X-rays and a CT scan of a definite patient, processed using the Mimics software package, a solid-state 3D geometric model of the femur and pelvis was constructed. Using the 3Matic software package, virtual solid-state models of the wire/half-pin-based Ilizarov fixator and the proximal femoral nail (PFN) were constructed that corresponded to the configurations planned to be used clinically.

Model 1 of the Ilizarov apparatus (Fig. 1 a) was a half-pin/wire based assembly consisting of a 180 mm diameter distal ring on two olive wires and a ring of the same diameter on two half-pins. Attached to the ring was a 140 mm long bar which holds six 2-mm diameter tensioned wires inserted into the proximal femur.

Model 2 (Fig. 1 b) was alike but had additional parallel and oblique rods that strengthened the long bar and 3-mm diameter wires for fixing the proximal fragment (Patent for Invention No. 2821665).

Model 3 (Fig. 1 c) was a known wire/half-pin assembly previously developed at the Department of Military Traumatology and Orthopedics, which involved immobilization of the hip joint [12].

Model 4 (Fig. 1 g) represented a fracture of the proximal femur fixed with a proximal femoral nail (PFN).

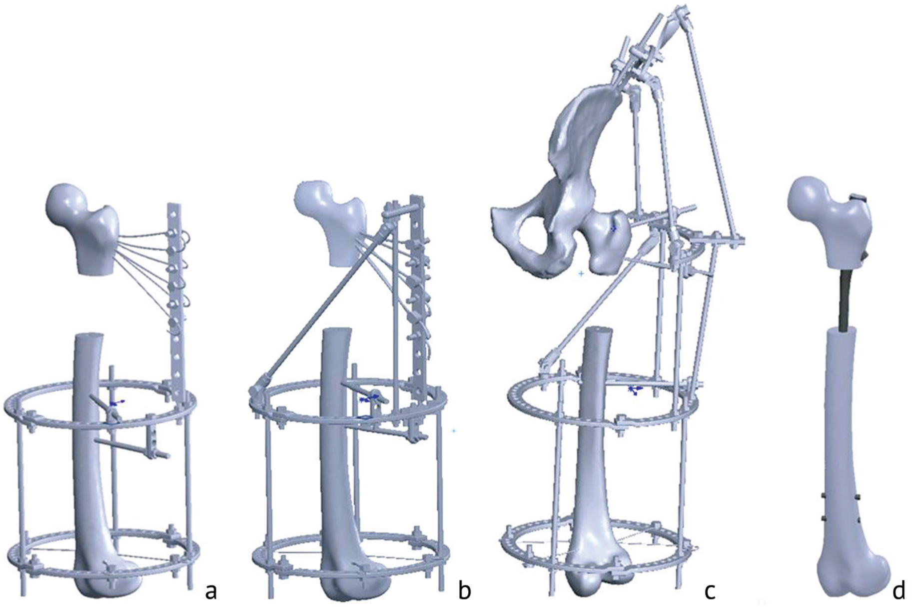


Fig. 1 Solid models of the Ilizarov half-pin/wire based apparatus (a, b, c) and the proximal femoral nail (d)

External and internal fixators, created using the SolidWorks computer-aided design system, were placed on the femur model according to their clinical use. A type 3.1.A3 fracture was then simulated. This yielded four solid 3D femur fracture–fixator models. Model 4 (PFN) was considered the reference (control) model in terms of achieved stability.

Finite element modeling of the stress-strain state of the constructed models was performed in Ansys 19.2. A static elasticity problem was solved for each model. As boundary conditions, an axial load corresponding to 25 % of the average human body weight (200 N) was applied to the femoral head of the constructed models, simulating the graduated weight-bearing walking on crutches. The distal femur was rigidly fixed (Fig. 2). In Model 3, the axial load was applied to the iliac crest. The junction of the femoral head and the acetabulum was considered immobile [13, 14].

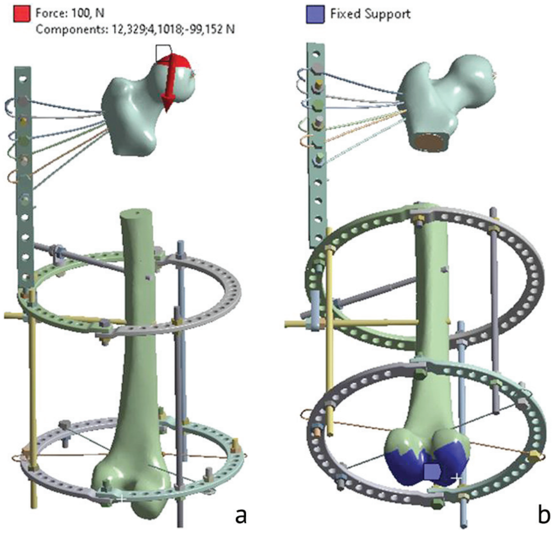


Fig. 2 Boundary conditions: (a) applied force (shown by the red arrow); (b) rigid fixation (shown in blue)

All materials were considered homogeneous, linearly elastic, and isotropic. The properties of the materials are presented in Table 1. Young's modulus of cancellous bone tissue was calculated based on CT data for a specific patient using a developed technique [11]. The properties of the remaining materials presented in Table 1 were taken from literary sources [10, 15].

Table 1

Mechanical properties of pelvic tissues and implant materials according to literary sources [9, 14]

Tiisue, material	Young's modulus, GPa	Poisson's ratio	Tensile strength, MPa
Cortical bone	16.8 [15]	0.3 [18]	170 [12, 18, 19]
Cancellous bone	0.84 [15]	0.3 [18]	10 [18, 20, 21]
Titanium alloy	110 [12, 16]	0.3 [16]	900 [12]
Stainless steel	200 [12, 17]	0.3 [17]	600 [18]

Due to the complexity of the femoral fracture model's geometry, an irregular tetrahedral computational net was created to calculate its stress-strain parameters. A denser hexahedral computational net was created for the Ilizarov apparatus and proximal femoral nail models, allowing for simulation results that were less dependent on their dimensions.

The results of biomechanical modeling of the stress-strain state in the constructed Ilizarov apparatus models were compared with each other and with the PFN fixation of the proximal femur. The experimental data were validated by comparing them with the results of bench tests aimed at determining the displacement of fragments in a proximal femur fracture model fixed with the developed apparatus (Model 2).

To verify the obtained finite element modeling data, a special femur model was created, closely matching the characteristics of natural bone and fixed with the Ilizarov apparatus in the developed configuration (Model 2). Bench testing of the developed apparatus was conducted at the Belelyubsky Mechanical Laboratory of the Emperor Alexander I St. Petersburg State Transport University to determine its elastic strength properties. The experiment was performed on a Shimadzu AG-X Test 50 kN testing machine (Shimadzu, Japan). Graduated load was applied to the femoral head (Fig. 3).

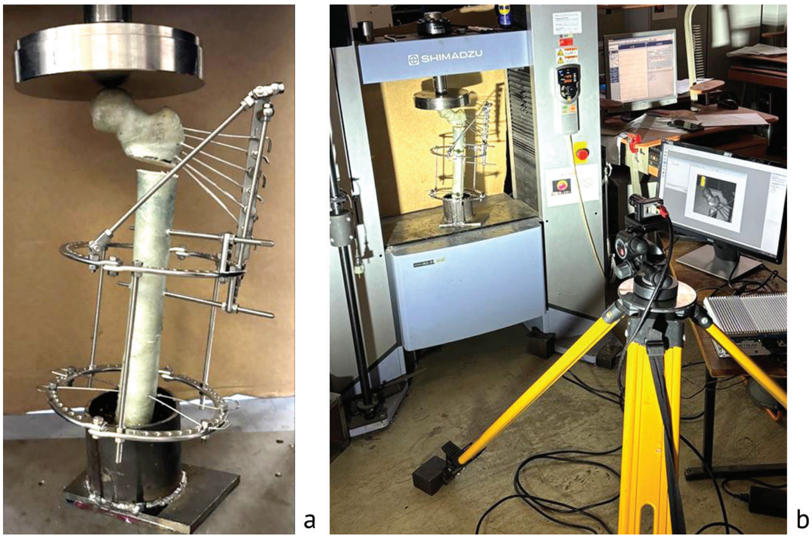
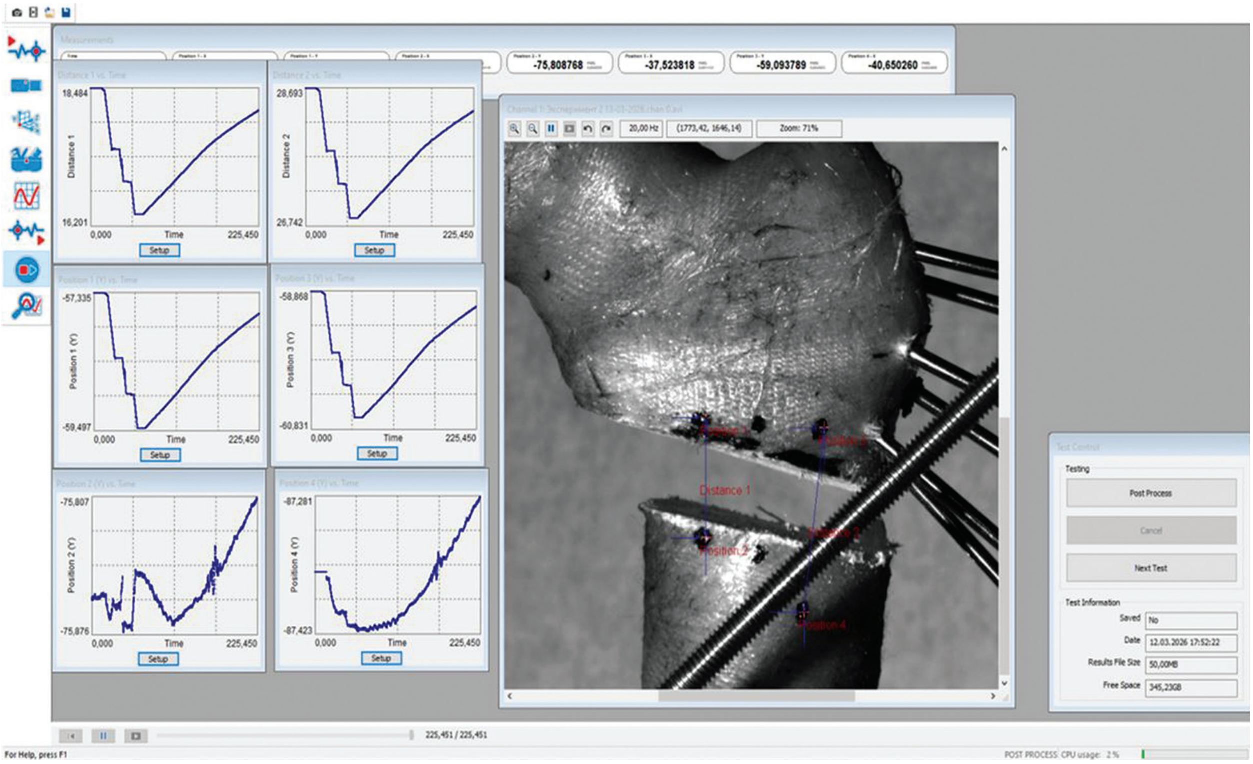


Fig. 3 View of the femur model with a proximal fracture, fixed with the Ilizarov apparatus (Model 2), in the Shimadzu AG-X Test 50 kN testing machine (a); experimental study of the deformity using the Imetrum Dynamic Monitoring Station measuring system (b)

Displacements between the proximal and distal fragments were recorded using the Imetrum Dynamic Monitoring Station measuring system. This system utilizes a sequential video recording system, allowing for analysis using specialized software installed in the controller. Two points were marked on the anterior surfaces of the proximal and distal femur fragments, and their relative positions were monitored throughout the study (Fig. 4).



-75,808768

-37,523818

-59,093789

-40,650260

20,00 Hz

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Zoom: 71%

Test Information

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Results File Size: 50,00MB

Free Space: 345,23GB

Fig. 4 Monitored points of the Imetrum Dynamic Monitoring Station measuring system

The results of the experiment were tested in a clinical setting on a group of 46 patients and compared with the results of a clinical and additional instrumental study of wounded patients with gunshot fractures of the proximal femur, stabilized by the Ilizarov apparatus in the developed configuration.

RESULTS

The calculations yielded equivalent stress fields for the four constructed models. Typical equivalent stress fields in the fixators placed are shown in Figure 5.

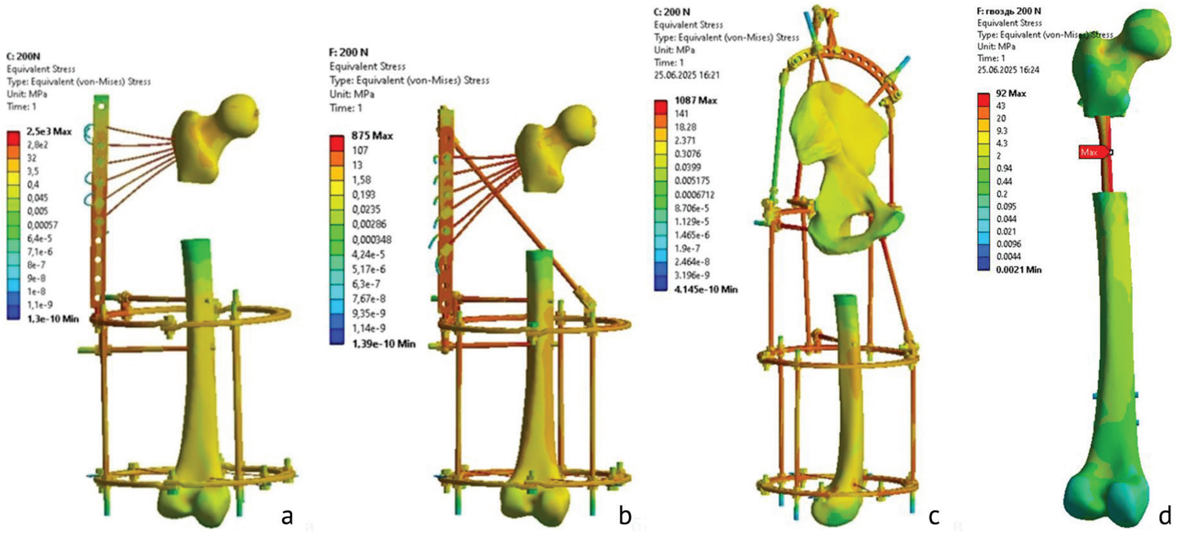

Fig. 5 Equivalent stresses with the fixators on place in the models of the femur fracture-fixator system: (a) Model 1; (b) Model 2; (c) Model 3; (d) Model 4 (control)

The equivalent stress characteristics arising in the fixator are indicative (Table 2). Thus, for the model with PFN (Model 4), its value was minimal and measured 92 MPa.

Table 2

Maximum equivalent stresses and resulting displacements of bone fragments chracteristic of the constructed models

Parameter	Model 1	Model 2	Model 3	Model 4
Maximum equivalent stress, MPa				
Entire model	2500	874	1087	92
Bar	1496	335	–	–
Cancellous bone	27	12.6	14.7	3.5
Cortical bone	1694	129	104	50
Maximum displacement of fragments, mm				
In the model	18.1	2.1	14.7	1.7

The analysis of the maximum equivalent stresses in the external fixation models shows that under a load of 200 N in Model 1 stresses in the area where the wires are attached to the bar exceed the tensile strength of stainless steel by more than twice (1200 MPa). Also, stresses exceeding the tensile strength of the cancellous and cortical bone tissue occur in the area of the proximal ends of the wires fixed to the subchondral cortex of the femoral head (Fig. 6 a, b). This is a biomechanical prerequisite for local bone destruction in this area which will inevitably lead to a loss of fracture fixation stability and displacement of bone fragments.

Besides, in Model 1, the stresses at the base of the bar, reaching approximately 1500 MPa, significantly exceeded the tensile strength of stainless steel and indicate a possible break of the fixator in that place (Fig. 6 c).

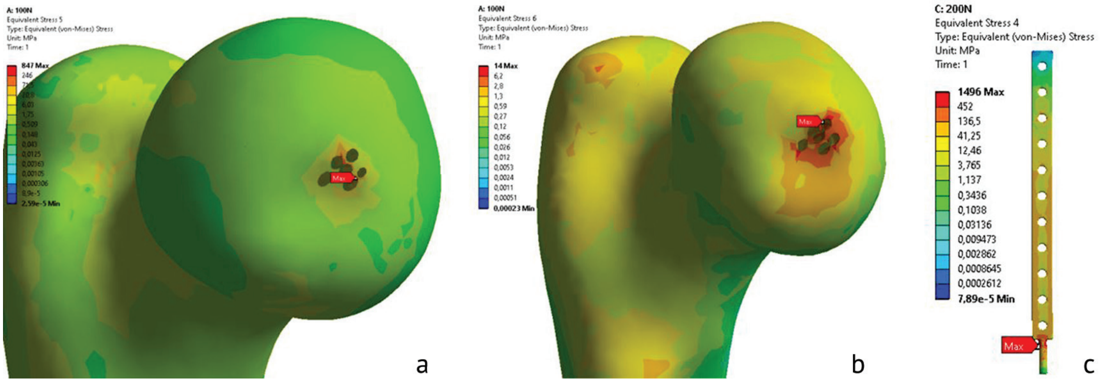

Fig. 6 Model No. 1. Areas of greatest equivalent stresses in the femur, marked in red: (a) cortical layer; (b) spongy layer; (c) equivalent stresses in the Ilizarov apparatus bar

In Model 2, the stresses in all elements of the construct, as well as in the bone tissue, were significantly lower than in Model 1. Thus, the maximum equivalent stresses in all metal components of the Ilizarov apparatus under an applied force of 100 N were 434 MPa, which is below the tensile strength of stainless steel. This value was achieved in the area where the proximal 3-mm diameter wires were attached to the Ilizarov apparatus bar (Fig. 7 a). In the bar itself, including its base, the stresses were significantly lower than the tensile strength of the material and, under a load of 200 N, were 335 MPa, what corresponded to approximately half of its tensile strength (Fig. 7 b). As for bone tissue, the tensile strength was not reached when the load increased to 200 N, with the maximum stress of 129 MPa occurring in the cortical layer of the femoral diaphysis in the area of the inferior half-pin insertion.

The characteristics obtained indicate the absence of prerequisites for breakage of the Ilizarov apparatus elements and destruction of bone tissue, that are the reasons for the loss of the achieved reduction of bone fragments and stable fixation of the fracture.

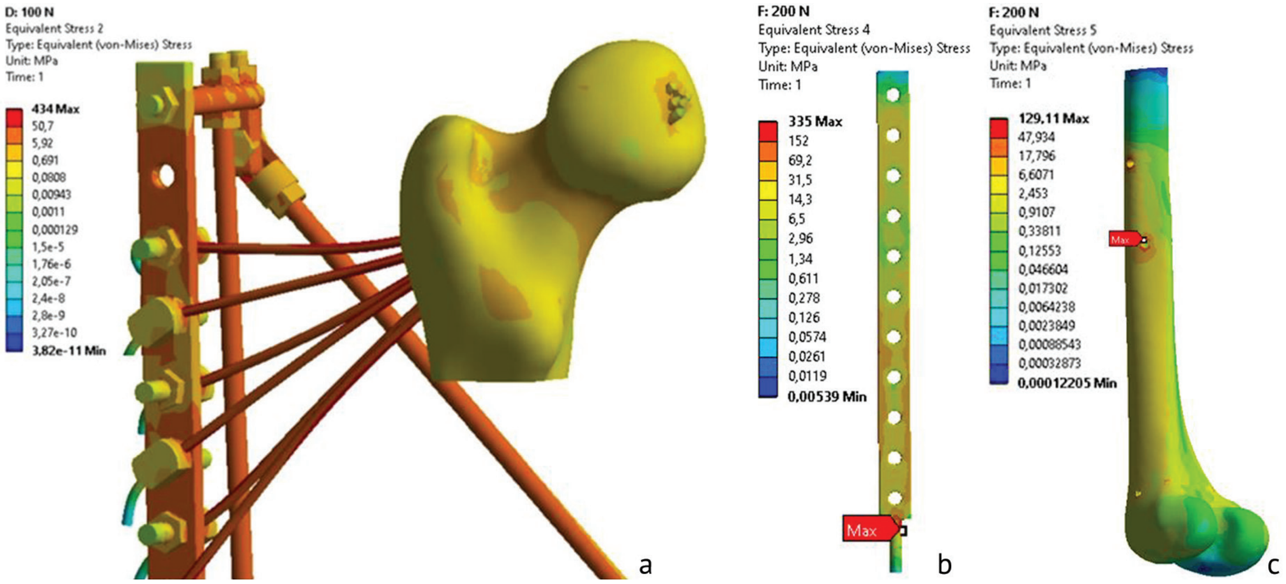

Fig. 7 Model 2. Equivalent stresses in the proximal wires (a); in the bar (b); in the area of distal half-pin insertion (c)

In Model 3, the maximum stresses were observed in the area where the upper section of the Ilizarov apparatus was attached to the anterior rod (Fig. 8 a). The supporting elements of the apparatus also experienced significant stress, including the half-pins inserted into the proximal femur fragment (Fig. 8 b). However, the stresses in those half-pins did not exceed 110 MPa and were far from the tensile strength of stainless steel.

It was established that even under a load of 150 N, the stresses in the area where the upper half-ring is attached to the anterior rod of the Ilizarov apparatus exceeded the tensile strength of the stainless steel, potentially causing damage to the structure. In the spongy layer of the ilium, the equivalent stresses exceeded its tensile strength, reaching 14.7 MPa under a load of 200 N. In the cortical layer, the highest stresses under that load were 104 MPa, not reaching the tensile strength of the cortical bone layer.

The data obtained indicated the potential instability of the Ilizarov apparatus in Model 3 in the area of the connection of the upper sector and the anterior rod, as well as the prerequisites for loosening of the half-pins fixed in the ilium.

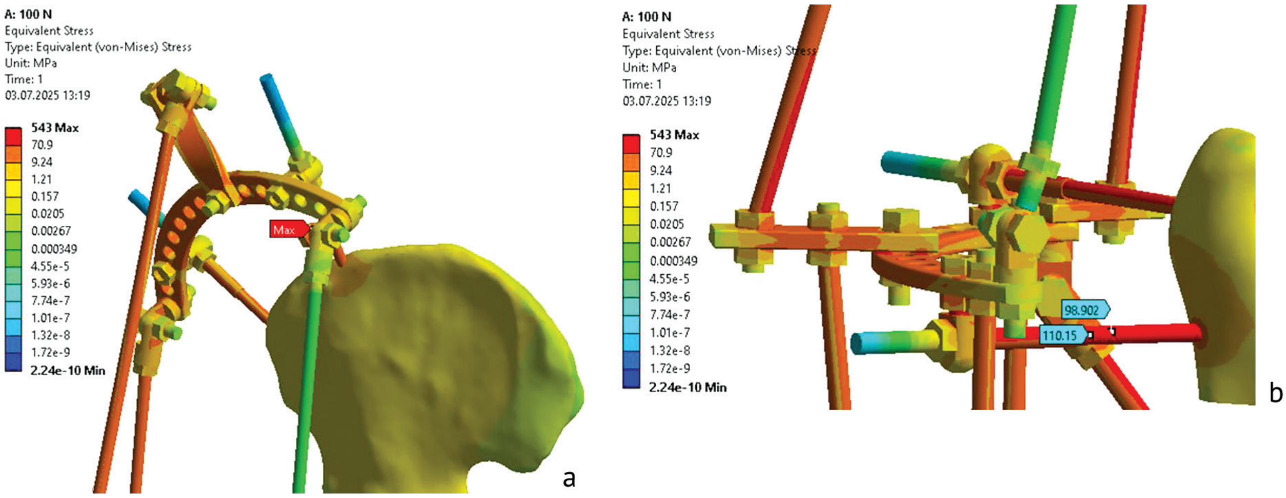

Fig. 8 Model 3. Equivalent stresses in the proximal basic half-ring of the Ilizarov apparatus (a) and in the half-pins fixing the proximal fragment of the femur (b)

The analysis of relative displacement of fragments in the constructed models shows that Models 2 and 4 exhibit the greatest stability, while Model 1 is the least stable, with a maximum fragment displacement of 9.0 mm under a load of 100 N (Fig. 9). Despite the immobilization of the hip joint, Model 3 also exhibited significant fragment displacement under a given load, reaching 7.3 mm. Models 2 and 4 exhibited minimal values of displacement, 2.1 mm and 0.86 mm, respectively.

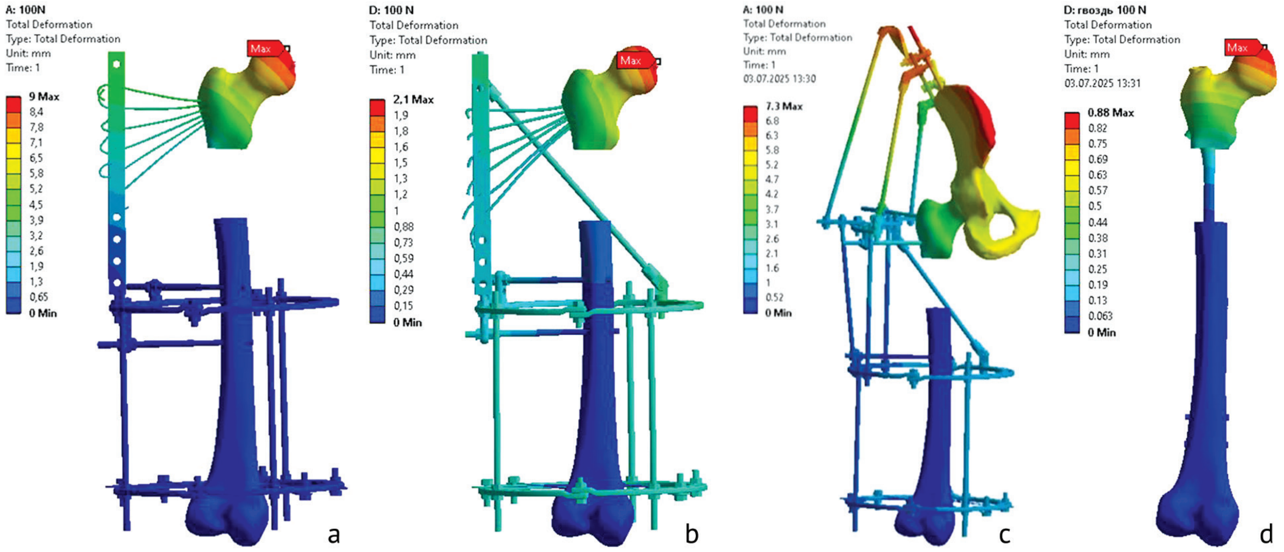

Fig. 9 Displacement of fragments in models under the load of 100 N: (a) Model 1; (b) Model 2; (c) Model 3; (d) Model 4

Thus, based on the experimental study of the stress-strain parameters of the models, significant advantages of the Ilizarov apparatus assembly Model 2 were revealed. It was achieved by the shunting the stresses arising from the weight-bearing load on the lower limb from the proximal base of the apparatus to its body through the use of vertical and oblique rods that reinforce the bar with proximal wires.

To confirm the obtained data, load bench tests were conducted. If an axial load of 200 N was applied to the femoral head, the greatest magnitude of femoral fragment displacement was recorded between positions 1 and 2 (the medial side of the fracture), while the smallest one was recorded between positions 3 and 4 (the lateral side of the fracture), amounting to 2.09 mm and 1.84 mm, respectively. The results of the bench tests confirmed the obtained finite element modeling data: under similar loads, the fragment displacement in Model 2 was 2.1 mm (Fig. 10).

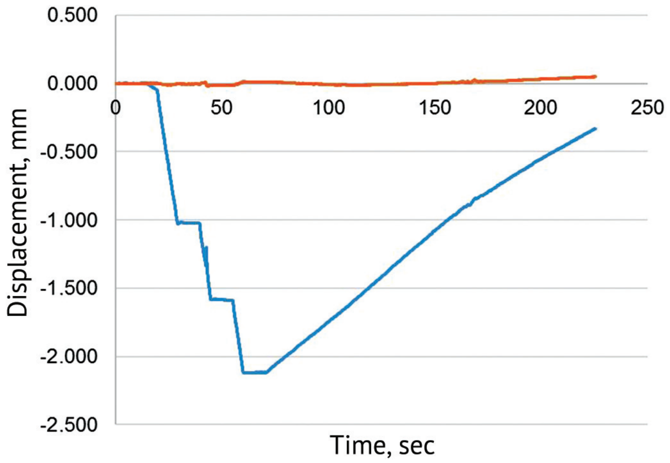

Fig. 10 Diagram of the displacement of femur fragments under vertical static axial compression under the load of 100N, 150N and 200N

DISCUSSION

The Ilizarov apparatus Model 2 for fixation of a proximal femur fracture (the bar is reinforced with vertical and oblique rods, the proximal wires have a diameter of 3 mm) causes the equivalent stresses arising in the body of the apparatus that are lower than in Model 1 and Model 3. Comparison of the maximum values of this parameter with a fracture fixed with the PFN for osteosynthesis shows that the equivalent stresses in the Ilizarov apparatus itself exceed the equivalent stresses in the proximal femoral nail for Model 1 by 27 times, for Model 2 by 9.5 times, and for Model 3 by 11.8 times. The obtained data are consistent with the results of biomechanical studies by Verkhovod et al., who conducted similar experiments for diaphyseal fractures of the tibia [22]. At the same time, the author asserts that, according to the data he obtained, fatigue stresses accumulating in the components of the Ilizarov apparatus are capable to cause breaking [22, 23, 24]. A significant difference in our study is the following: despite the high values of the parameters under consideration in the first and second configurations of the Ilizarov apparatus, it cannot be said that they can lead to fatigue fracture of the elements, since these values are far from its ultimate tensile strength. However, the data of Verkhovod et al. [22] are confirmed for Model 3.

The significant increase in equivalent stresses, characteristic of the proximal 2-mm wires of the Ilizarov apparatus in the configuration without a reinforcing bar (Model 1), may cause a loss of stability in the “bone-apparatus” system and lead to secondary displacement of bone fragments and disorders of consolidation.

According to our study, an important prerequisite for the potential instability at the fracture site with the first configuration of the external fixator is also the maximum value of the equivalent stress in the "wires-proximal fragment" contact pair, equal to 27 MPa for the spongy layer and 1694 MPa for the cortical layer. These values exceed the strength limits of bone tissue and are many times greater than the parameters achieved by the second and third configurations of the Ilizarov apparatus and the intramedullary nail. The obtained data, in our opinion, confirm and complement the results of the study described above [22], and also substantiate the advantages of the Ilizarov apparatus assembly Model 2.

The strength of a structure is its ability to withstand cyclic loads. In mechanics, there is the concept of a material's fatigue limit, which is assessed based on the fatigue test. According to literature, the fatigue limit of medical stainless steel ranges from 200 to 400 MPa [25] (Fig. 11). If stresses in the structure do not exceed the fatigue limit of the material from which it is made, then under such a load, the product is able to operate for up to 10 million cycles.

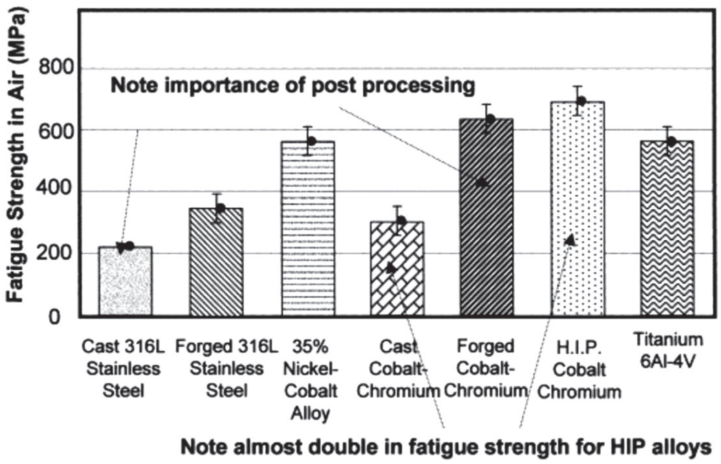

Fig. 11 Fatigue limits of implant materials [25]

Based on the obtained results, Model 4, under the loads examined, exhibits characteristics that allow us to consider it a standard. Models 1 and 3, on the other hand, are expected to fail under cyclic loading even under a force of 100 N. The developed Ilizarov apparatus Model 2 is capable of functioning without breakage under a load of 200 N. Moreover, an analysis of the experimental displacements of the fragments relative to each other indicates that they were minimal in Model 2 and comparable to Model 4.

A comparison of the data that potentially substantiate more favorable conditions for consolidation of Type A3 fractures with external osteosynthesis using the developed method (Model 2) and other clinical studies on the topic under consideration confirms the results of the biomechanical experiments performed.

The obtained experimental data on the stress-strain characteristics of the constructed models demonstrates the feasibility of clinical use of the Ilizarov apparatus with vertical and oblique reinforcement of the bar and 3-mm wire fixation. The biomechanical validation supported the clinical application of the developed Model 2 of the Ilizarov apparatus for osteosynthesis of Types 3.1.A and 3.1.B gunshot fractures accompanied by extensive soft tissue defects in the hip joint.

Some data in the specialized literature indicate high risks of using internal osteosynthesis in the treatment of wounded patients with gunshot fractures of the proximal femur. This forces traumatologists to use external osteosynthesis [16, 26]. The version of the Ilizarov apparatus (Model 3) proposed by Shapovalov et al., intended for osteosynthesis of gunshot fractures in the hip joint, involves the use of fixation with the insertion of half-pins into the iliac wing on the injured side to achieve the necessary stability between the fragments. This arrangement of the apparatus makes movement in the hip joint impossible during the entire consolidation period [27]. A similar technical solution, with the same drawback, was developed and implemented in clinical practice by Borov et al. [28]. The external fixation device they proposed consists of interconnected pelvic and femoral modules, and to achieve a certain fixation rigidity, the pelvic component includes four half-pins inserted into the supra-acetabular regions and the wings of the iliac bones on both sides.

Among the publications describing options for external osteosynthesis of Type 3.1A and 3.1B fractures without immobilization of the hip joint, it is worth highlighting the original designs of the Ilizarov wire/halfpin and half-pin assemblies [2] and the original apparatus proposed by Allahverdiev et al. [29]. An important advantage of the external fixators listed above is the possibility of movement in the hip joint and, consequently, early rehabilitation of patients, as well as their significant fracture reduction capabilities. However, the use of the described devices for the treatment of wounded with gunshot comminuted fractures of the proximal femur, especially those accompanied by extensive defects, may be limited due to the nature and severity of damage to soft tissues and bone.

It should be noted that the experimental biomechanical study presented has several limitations. They are related to the fact that we simulated loads only in a static, upright position with support on both lower limbs using crutches. We were unable to account for muscle contractions, shifts in the body's center of gravity during walking, the patient's compliance with the prescribed load, or the dynamics of changes in the mechanical properties of bone tissue.

Therefore, the use of the constructs demonstrated seems limited for treating patients with complex gunshot fractures accompanied by extensive soft tissue defects. We plan to conduct bench tests to determine the permissible static and dynamic loads of the Ilizarov apparatus constructs described above.

CONCLUSION

The results of biomechanical modeling and load-bearing bench tests indicate that the proximal femoral nail is the optimal fixation device for osteosynthesis of gunshot fractures of the proximal femur. The stress-strain parameters of the proximal femur fracture — proximal femoral nail system are unachievable with any of the proposed configurations of the Ilizarov apparatus. However, if internal osteosynthesis is not available for this category of patients, traumatologists can use external osteosynthesis methods. Given the time it takes for gunshot fractures to heal, the requirements for external fixation include ensuring early active and passive hip joint motion and graded weight-bearing, as well as maintaining the fragments in the correct position for an extended period without loss of stability at the fracture site. The construct design of the Ilizarov apparatus which involves bar reinforcement with vertical and oblique rods and proximal polyaxial tensioned 3-mm wires meets these requirements from the standpoint of the parameters studied in bench tests in regard of stress-strain deformity and displacement.

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