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Biomechanical study of a combined fixation system for gunshot femoral fractures

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Gunshot injuries of the femur in combat settings are associated with high-energy trauma and unstable diaphyseal fractures (81.4 %), which require fixation methods with increased demands for mechanical rigidity. Objective. To investigate the stress-strain state of a computer model of the femur with a comminuted fracture fixed with an intramedullary spacer and an external fixation device using pins of 5 mm and 6 mm in diameter. Methods. A three-dimensional model of a diaphyseal comminuted femoral fracture and two models of combined fixation («external fixator + intramedullary spacer») with four pins of 5 mm and 6 mm diameter were created. Biomechanical analysis was performed using the finite element method. The evaluated parameters included displacement, stress, and strain under a static load of 400 N. Results. Numerical analysis of the stress-strain state demonstrated that both studied constructs with 5-mm and 6-mm pins provide sufficient fixation stiffness. Increasing the pin diameter to 6 mm resulted in reduced maximal displacements and peak stresses, indicating a biomechanical advantage of the «bone – intramedullary spacer + external fixator with 6-mm pins» system. Conclusions. The conducted numerical stress-strain analysis showed that despite adequate stability provided by both fixation systems, the «bone + intramedullary spacer + external fixator with 6-mm pins» construct has a biomechanical advantage over the construct with 5-mm pins in terms of maximal displacement, stress, and strain values.

Вогнепальні ушкодження стегнової кістки в умовах бойових дій характеризуються високоенергетичними травмами та нестабільними діафізарними переломами (81,4 %), які потребують методів фіксації з підвищеними вимогами до механічної жорсткості. Мета. Дослідити напружено-деформований стан комп'ютерної моделі стегнової кістки з багатоуламковим переломом, фіксованої інтрамедулярним спейсером і апаратом зовнішньої фіксації зі стрижнями діаметрами 5 та 6 мм. Методи. Створено тривимірну модель діафізарного багатоуламкового перелому стегнової кістки та дві моделі комбінованої фіксації «АЗФ + інтрамедулярний спейсер» із використанням чотирьох стрижнів діаметрами 5 та 6 мм. Біомеханічний аналіз виконано методом скінченних елементів. Оцінювали показники напружено-деформованого стану — переміщення, напруження та деформація — за умов прикладання статичної сили 400 Н. Результати. Чисельний аналіз напружено-деформованого стану показав, що обидві досліджувані конструкції зі стрижнями параметрами 5 і 6 мм забезпечують достатню жорсткість фіксації. Збільшення діаметрів стрижнів до 6 мм супроводжується зниженням максимальних переміщень і пікових напружень, що свідчить про біомеханічну перевагу системи «кістка + інтрамедулярний спейсер + АЗФ зі стрижнями діаметром 6 мм». Висновки. Проведений чисельний аналіз напружено-деформованого стану продемонстрував, що попри достатню стабільність обох систем фіксації стегнової кістки, «кістка + інтрамедулярний спейсер + АЗФ зі стрижнями діаметром 6 мм» має біомеханічну перевагу над системою «кістка + інтрамедулярний спейсер + АЗФ зі стрижнями 5 мм» за показниками максимальних переміщень, напружень і деформацій. Ключові слова. Вогнепальний перелом, стегнова кістка, апарат зовнішньої фіксації, інтрамедулярний спейсер, метод скінченних елементів, біомеханічне моделювання.

Keywords. Gunshot fracture, femur, external fixation device, intramedullary spacer, finite element method, biomechanical modeling

Introduction

Gunshot wounds to the limbs account for 62.6–70.0 % of the structure of modern combat surgical trauma, with a significant portion affecting the lower limbs [1, 2]. The share of gunshot injuries to the thigh reaches 13.6–28.3 %, and femoral fractures make up 7.0–22.3 % of all injuries [2, 3]. Their severe nature, caused by the high kinetic energy of the projectile, leads to the formation of large bone defects, numerous fragments, and significant soft tissue destruction [3, 4]. Diaphyseal lesions account for 81.4 % of injuries [5]. In 79.5 % of patients, bone tissue defects are detected [1, 6], and in 84.5 %, traumatic shock develops, which further complicates treatment tactics and increases the risk of early complications [2, 7].

Traditional fixation methods do not always provide the necessary stability in cases of large bone defects and multi-fragment injuries. In such situations, there is a need for combined consolidation techniques, including the use of external fixation devices (EFD) combined with intramedullary constructs and antibiotic cement spacers [8, 9]. The optimal configurations of these systems, their rigidity, load resistance, and ability to maintain controlled fracture alignment remain undefined, and existing clinical data are fragmented and limited.

For this reason, biomechanical studies are becoming increasingly important, as they allow the creation of models of severe gunshot injuries, evaluation of various combined fixation options, and analysis of their behavior under load. The results of such experiments are crucial for practical medicine, as they help reduce the risks of secondary displacements, instability of the constructs, local overloading, and the development of infectious complications, as well as contribute to optimizing surgical tactics in the case of gunshot fractures.

In the publication [8], the authors demonstrated the biomechanical superiority of an EFD system with six 5-mm diameter rods and an intramedullary spacer (IMS) over a construct with exclusive EFD fixation for gunshot fractures of the femur (GSFF). However, the question of determining the optimal number and diameter of the rods in the EFD system combined with IMS to ensure sufficient fracture stability remains relevant.

One way to enhance the stability of bone fragment fixation is by increasing the diameter of the EFD rods. Biomechanical studies suggest that this approach helps reduce fragment displacement and increases the rigidity of the fixation system. In works [10, 11], it was shown that the optimal fixation for GSFF is an EFD system consisting of a beam and four 6-mm diameter rods placed in different planes. However, the use of larger diameter rods is associated with greater trauma to bone and soft tissues, is technically more complex, and may prolong the duration of the surgical procedure.

Currently, the number of publications studying the biomechanical properties of the femur in combined fixation options remains limited, emphasizing the need for further research to develop individualized approaches to choosing surgical treatment tactics for patients with GSFF.

Thus, the scientific problem of optimizing combined fixation in GSFF is highly relevant both for fundamental biomechanical research and for modern traumatology and military surgery. This study is a continuation of the authors' own research aimed at investigating the behavior of the "bone + EFD + IMS" system in this category of injured patients.

Objective: to investigate the stress–strain state of a computer model of the femur with a comminuted fracture fixed with an intramedullary spacer and an external fixation device using rods with diameters of 5 and 6 mm.

Material and Methods

In collaboration with specialists from the Biomedical Engineering Laboratory of the State Institution "Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine", a finite element model of the femur with a gunshot comminuted fracture in the middle third was constructed (7 intermediate fragments with partial contact between them). In the diaphyseal region, the minimum bone diameter was 33.0 mm, and the width of the medullary canal was 15.0 mm. In the transition zones from the diaphysis to the metaphysis, the diameters increased in accordance with the anatomical features of the femur. Soft tissue structures of the thigh were not considered in the created model.

Fixation of the femur using a combination of an IMS and a rod-based EFD was analyzed. The following models were studied: 1 — two 5.0-mm diameter rods proximally and two distally, fixed to a single bar; 2 — an analogous configuration with 6.0-mm diameter rods. The distance from the femur to the supporting EFD bar with a diameter of 10 mm was 100 mm.

The IMS consists of a 5-mm-thick frame made of surgical steel (AISI 316) and coated with bone cement (polymethyl methacrylate). The total thickness of the spacer was 10 mm. A metal loop is located at the proximal end, allowing implantation and removal of the fixator [8, 9].

The proximal end of the spacer was positioned in the region of the greater trochanter of the femur, and the distal end was located 20 mm above the articular surface. EFD rods with diameters of 5.0 and 6.0 mm were inserted bicortically in the areas of medullary canal widening, alongside the trajectory of the spacer.

During modeling, the material was considered homogeneous and isotropic. The mechanical properties of the materials were selected according to data from the technical literature [12–15]. The following physical and mechanical parameters were used for the analysis: E — Young's modulus, v — Poisson's ratio (Table 1).

An anatomical femur model was obtained by converting a computed tomography scan into a solid model using the IntelliSpace Portal software environment and imported into SolidWorks 23. Calculations of the stress–strain state of the models were performed using the SimSolid software environment.

To analyze the stress–strain state of the biomechanical models, the finite element method was used. The following boundary conditions were defined: the distal articular surface of the femur was rigidly fixed; a static force of 400 N, corresponding to 40 kg (half the body weight of a male serviceman), was applied to the femoral head; and a triangular mesh with Gauss points was created. The investigated effects included displacement, stress, and strain. In the SimSolid software, a system of linear equilibrium equations of the finite element model was solved, with determination of displacement at each node.

Stress values were compared at control points, namely: the upper third of the femur, the gunshot fracture zone, the lower third, the areas where the EFD rods entered the bone, three points on the IMS, and the middle of the bar for both variants of femoral fixation (Fig. 1). The maximum stress values in these anatomical regions and structural elements were analyzed.

Results

At the first stage of the study, the stress–strain state of the femoral model with a gunshot fracture fixed using an IMS and an EFD with 5.0-mm diameter rods was examined. Analysis of the "displacement" parameter showed that the maximum displacement reached 4.5 mm in the region of the proximal epimetaphysis of the femur, where displacement of the proximal fragment was observed, while the distal fragment remained stable. In the gunshot fracture zone, the maximum displacement was 1.9 mm. The distal fragment demonstrated rigid fixation with displacement values up to 0.3 mm. In the area of the upper part of the bar and on the proximal EFD rod, the corresponding displacement value was 3.7 mm (Fig. 2a).

Examination of the "deformation" parameter showed that the peak value reached 0.052 % in the gunshot fracture zone. In the upper and lower thirds of the femur, the deformation ranged from 0.011 % to 0.052 %. The highest values were localized in the middle third of the IMS, at 0.117 %. On the EFD rods, the deformation was 0.032 % at the bone entry sites (Fig. 3a).

Assessment of the "stress" parameter showed that the highest value occurred in the middle section of the IMS in the gunshot fracture zone, amounting to 50.3 MPa. On the lower rod and the two upper rods at the bone entry points, the stress ranged from 44.6–48.7 MPa. In the femur, the maximum stress level in the fracture zone was up to 22.6 MPa (Fig. 4a, c).

In the second stage, the stress–strain state of the femoral model fixed with an IMS and EFD using 6.0-mm diameter rods was investigated.

The "displacement" parameter was analyzed, and it was found that the maximum displacement reached 3.0 mm in the upper part of the model. In the gunshot fracture zone, the displacement of the fragments was up to 1.5 mm. The displacement of the bar and upper rod in the upper part of the EFD structure was 2.5 mm (Fig. 2b).

In the "deformation" analysis, it was determined that the maximum values reached 0.018 % and were

Table 1

Physical and mechanical properties of the materials used

Material	Young's Modulus, E, MPa	Poisson's ratio, v	Yield strength, RHa, MPa
Cortical bone layer	183 50	0.30	170
Trabecular bone layer	500	0.28	10
Surgical steel AISI 316	200 000	0.30	505
Bone cement	1.82	0.18	70

observed in the middle parts of the three lower EFD rods, the bar, and the upper part of the IMS frame. In the gunshot fracture zone and at the bone entry points, the deformation was 0.014 %, with no peak values detected (Fig. 3b).

The "stress" values were then analyzed. On the three lower EFD rods, the maximum stress was 44.2 MPa, at 43.4 MPa in the upper part of the IMS, and 35.4 MPa in the central section of the bar (Fig. 4b, d). No critical peak values were detected. The stress in the femur at the gunshot fracture zone, as well as in the upper and lower fragments, was up to 4.4 MPa.

Based on the obtained data, a comparative analysis of the stress values at control points for the two femoral fixation options — IMS and EFD with four rods of diameters 5.0 and 6.0 mm — was conducted (Fig. 5).

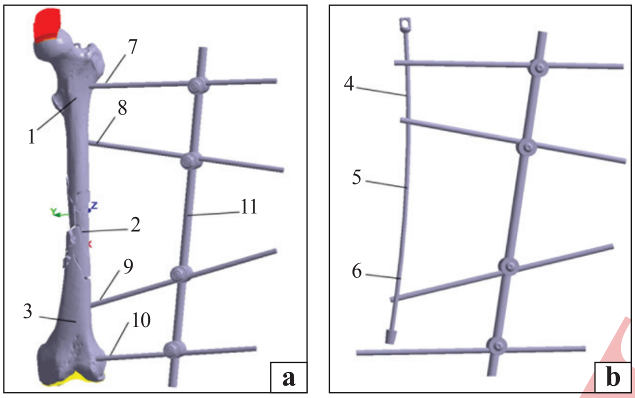

Fig. 1. Investigated models: a — femur with a fixation system, where the red zone represents the force application area, and the yellow zone represents the fixation surface; b — bone fixation systems. 1–11 — control points for measuring stresses.

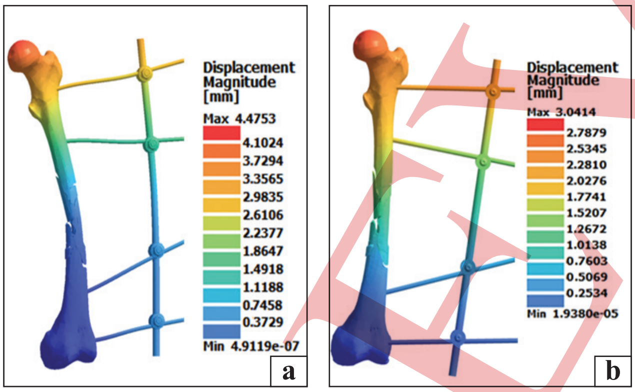

Fig. 2. Distribution of displacements in the femur model with pins of the following diameters: a — 5 mm; b — 6 mm.

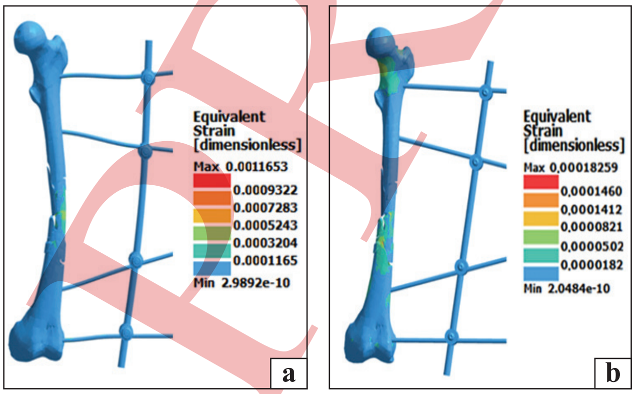

Fig. 3. Distribution of deformation in the model with pins of the following diameters: a — 5 mm; b — 6 mm.

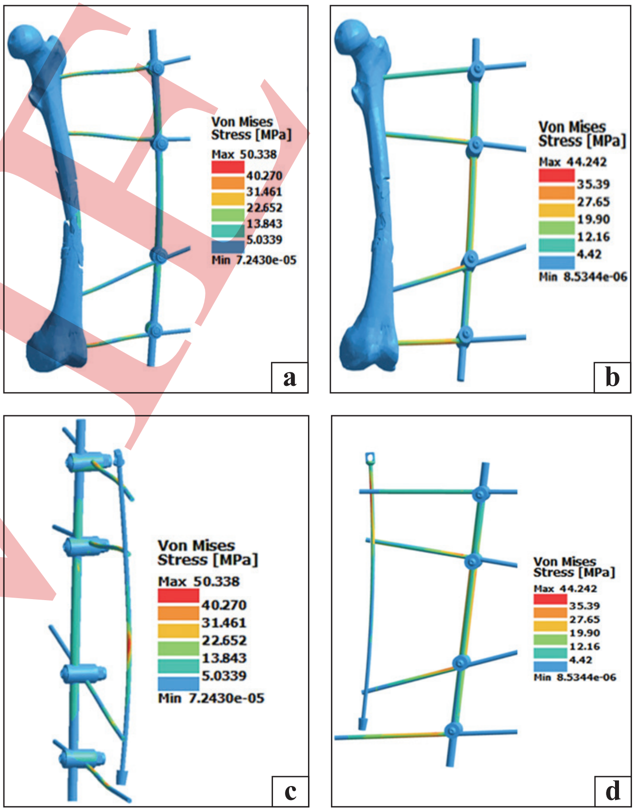

Fig. 4. Distribution of stresses in the model with pins of the following diameters: a, c — 5 mm; b, d — 6 mm (in b and d — fixation elements are placed outside the femur).

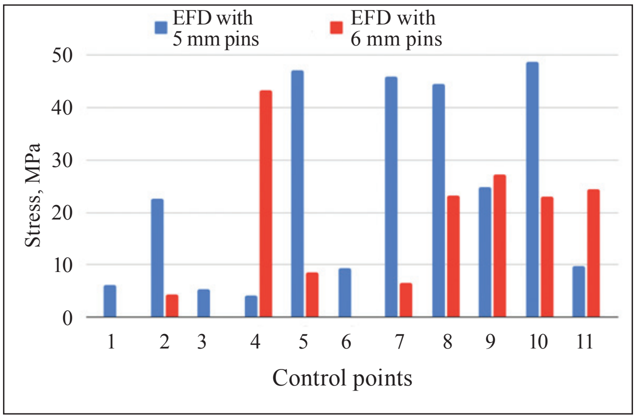

Fig. 5. Comparison of stresses in control points of the system “femur + IMS + EFD" with pins of diameters 5 and 6 mm.

The maximum values of the studied parameters for the different configurations of the combined femoral fixation system are presented in Table 3. The strength limits and the maximum allowable deformation for bone and steel are provided according to the technical literature [12–15].

Discussion

The results of the stress–strain analysis of the femur for gunshot diaphyseal fractures showed that combined fixation using IMS and EFD provides sufficient stability in both of the studied variants.

Based on the analysis conducted, it was determined that under the conditions of bone fragment fixation using both investigated designs, the stress and deformation values remain within normal ranges and do not exceed the material strength limit or the maximum allowable deformation (Table 3). The comparison of the models demonstrated that increasing the rod diameter from 5.0 to 6.0 mm resulted in a moderate decrease in peak stress at the control points and a reduction in relative deformation. However, both systems maintained sufficient overall rigidity.

In the model with 5 mm diameter rods, the displacement of the bone fragments in the fracture zone was 1.9 mm, for the EFD rods it was 3.0 mm, and for the intramedullary spacer it was 1.9 mm. In the second model (6 mm diameter rods), these values were slightly lower — 1.5, 2.3, and 1.5 mm, respectively. The difference in displacement was 0.4–0.7 mm, which, in the authors' opinion, is not clinically significant.

The stress distribution revealed a biomechanical advantage for the system "bone + IMS + EFD with 6 mm diameter rods". For the bone fragments in the fracture zone, the stress with 5 mm diameter rods was 22.6 MPa, whereas with 6 mm rods, it was 4.4 MPa. On the rods, the stresses were 45.9 MPa and 27.3 MPa, respectively. The peak stresses in the spacer were virtually the same between the models — 47.2 MPa and 43.4 MPa. These values are far from the critical limits for the materials (505 MPa for the EFD and 170 MPa for bone), indicating no risk of further deformation or failure of the structure.

A similar trend was observed during the deformation analysis. In the first model, the deformation of the bone was 0.052 %, of the rods 0.032 %, and of the IMS 0.117 %. In the second model, the respective values were 0.014 %, 0.018 %, and 0.018 %. Despite the differences in these values, the deformations for all elements remained within the elastic limits of the materials, indicating no threat of loss of stability for the construct (the maximum allowable deformation for bone tissue is 0.25 %, and for steel, it is 0.2 % —Table 3).

A comparison of the obtained results with the data from previous modeling [8], during which the systems "bone + EFD with 6 rods of 5 mm diameter" and "bone + IMS + EFD with 6 rods of 5 mm diameter" were compared, was also carried out.

It was found that in the model with 6 rods, the displacement of the bone fragments and IMS was 1.4 mm, while the displacement of the rods was 0.3 mm, indicating a high stability of the construct due to the increased number of fixation points. Despite this, the stresses in the system elements remained comparable to those obtained in the models with 4 rods. In the bone and rods, the stress was 13.1 MPa, while in the spacer it reached 26.5 MPa — values lower than in the 4-rod variants. This suggests a more uniform load distribution in the EFD system with 6 rods, but it does not result in a significant reduction in displacement.

In publications [16–19], the method for placing an intramedullary implant covered with a cement mantle in case of infection in the fracture area of long bones was investigated. The metal frames most used for covering were intramedullary blocked, non-blocked, and elastic rods, as well as 2–4 Ilizarov wires.

Table 3

Comparison of physicomechanical properties in femur fixation with rod-type EFD and IMS

Configuration of EFD in combination with IMS		Displacement in the fracture zone, mm	Stress, MPa	Deformation, %
4 pins with a diameter of 5 mm	Bone	1.9	22.6	0.052
	EFD pins	3.0	45.9	0.032
	IMS	1.9	47.2	0.117
4 pins with a diameter of 6 mm	Bone	1.5	4.4	0.014
	EFD pins	2.3	27.3	0.018
	IMS	1.5	43.4	0.018
Critical values	Bone	—	170.0	0.250
	Steel (EFD pins, IMS)	—	505.0	0.200

This method ensured infection eradication and fracture stabilization. However, complications such as the destruction of the cement mantle, breakage of the metal implant, deformation and migration of the construct, and damage to the intramedullary canal of the bone were noted.

The use of an intramedullary spacer without an EFD is not recommended, as it does not provide axial or rotational stability for the fragments. The spacer material cannot maintain the length of the bone or resist twisting, so without the EFD, such a construct is mechanically unstable.

Positioning the IMS with a 10 mm diameter in the center of the bone marrow canal complicates the technique for placing EFD rods, which should be conducted in a bicortical manner, bypassing the trajectory of the spacer. Therefore, using rods with smaller diameters has advantages: it is technically simpler, reduces the duration, and minimizes the trauma of the surgical procedure.

Our study has certain limitations, considering that the finite element method models the idealized behavior of bone fragments and the fixation system elements and does not fully account for the influence of soft tissues on the parameters considered. Therefore, clinical validation of the results is important, as it lays the groundwork for using the combined fixation method with an intramedullary spacer as an effective treatment for diaphyseal fractures.

The obtained data can be used to optimize fixation schemes for gunshot fractures of the femur and improve clinical treatment protocols.

Conclusions

The numerical analysis of the stress–strain state demonstrated that the system “bone + intramedullary spacer + EFD with 6 mm diameter rods” has a biomechanical advantage over the system “bone + intramedullary spacer + EFD with 5 mm diameter rods” in terms of maximum displacement, stress, and deformation. At the same time, the obtained values of the studied parameters did not reach the critical limits for bone tissue and fixation elements, indicating sufficient stability for both combined fixation options, allowing their use depending on the specific clinical situation.

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Conflict of Interest. The authors declare no conflicts of interest.

Future Research Prospects. Future research should focus on studying the clinical effectiveness of the proposed combined fixation technique for bone fragments of the femur through prospective analysis of treatment outcomes in patients with gunshot fractures. A comparison of complication rates, consolidation times, and functional treatment outcomes using rods of different diameters is necessary.

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Authors' Contributions. Luryn I. A. — critical review of the article, final approval; Buryanov O. A. — analysis of results, final approval of the article; Yarmolyuk Yu. O. — design and modeling, statistical analysis, critical review of the article; Matviychuk B. V. — review and analysis of related works, design and modeling, drafting the article.

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BIOMECHANICAL STUDY OF A COMBINED FIXATION SYSTEM FOR GUNSHOT FEMORAL FRACTURES

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