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# NUMERICAL MODELING OF IMPLANT SURGERY AND REHABILITATION OF HUMERUS BONE FRACTURES FOR THE ELDERLY PATIENTS

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**Background:** Implantation is becoming more widespread in such areas of modern medicine as orthopedics and traumatology. Due to the lack of an adequate substitute for natural bone, combined approaches are used. For older patients, the problem is exacerbated by a decrease in bone mineral density. When choosing a scheme for the surgical treatment of long bone fractures, preference is given to simple and maximally sparing approaches. In this regard, the main task of osteosynthesis is to provide optimal mechanical channels not only for the fracture healing process, but also to restore full functional capabilities in the future. The paper considers the urgent task of optimizing and increasing the efficiency of planning rehabilitation measures, including taking into account the individual characteristics of a particular patient, and the results are of fundamental and applied importance.
**Objectives:** development of physical and mathematical models for modeling the stress-strain state of the elements of the musculoskeletal system to optimize the planning of bone surgeries when installing implants.
**Materials and methods**. For the analysis, both specific clinical results and modern methods of computer modeling and processing of results were used. The advantage of physical and mathematical models based on the used finite element method is the possibility of optimizing the design of prostheses and reducing the problems caused by osteopenia.
**Results:** To illustrate the proposed approach, a specific example of the treatment of a comminuted fracture of the humerus in an elderly patient is considered. To describe the physicomechanical properties of bone tissue, sets of standard data on the main characteristics of tissues and materials of implants such as elastic modulus and Poisson's ratio were used. As the bone grows together, simultaneously with a decrease in stresses, the difference between the stress on the entire structure and the stress on the bone decreases. This indicates that the bone begins to take on an increasingly significant relative part of the load, which should have a positive effect on its bone mineral density.
**Conclusions:** The advantages of modeling using the finite element method and by non-invasive modeling of the work of the patient's musculoskeletal system with various variants of prostheses (implants) and the choice of the most optimal one are shown. It was found that the use of the Von Mises stress-strain state as a criterion for assessing the stress-strain state of the system gives effective assessments of the reliability of the structure and its elements.
**KEY WORDS:** implants; fracture of the humerus; postoperative rehabilitation; von Mises stress; numerical modeling.

**ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ПРИ ХІРУРГІЇ ТА РЕАБІЛІТАЦІЇ ПЕРЕЛОМІВ ПЛЕЧОВОЇ КІСТКИ У ПОХИЛИХ ПАЦІЄНТІВ ЗА ДОПОМОГОЮ ІМПЛАНТАТІВ**

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**Актуальність**. Імплантація набуває все більшого поширення в таких областях сучасної медицини, як ортопедія і травматологія. Зважаючи на відсутність адекватного замінника натуральної кістки, використовують комбіновані підходи. Для літніх пацієнтів проблема посилюється зниженням мінеральної щільності кісткової тканини. При виборі схеми оперативного лікування переломів довгих кісток перевагу віддають простим і максимально щадним підходам. У зв'язку з цим основне завдання остеосинтеза полягає в забезпеченні оптимальних механічних умов не тільки для процесу зрощування перелому, але й для відновлення в подальшому повноцінних функціональних можливостей. В роботі розглянута актуальна задача оптимізації і підвищення ефективності планування реабілітаційних заходів, в тому числі і з урахуванням індивідуальних особливостей конкретного пацієнта. Отримані результати мають фундаментальне й прикладне значення.
**Мета роботи**: створення фізико-математичних моделей для моделювання напружено-деформованого стану елементів опорно-рухового апарату для оптимізації планування операцій на кістках при установці імплантатів.
**Матеріали та методи**. Для аналізу в роботі використовувалися як конкретні клінічні результати, так і сучасні методи комп'ютерного моделювання та обробки результатів. Перевагою фізико-математичних моделей на основі використаного методу скінченних елементів є можливість оптимізації конструкції протезів і зниження проблем, викликаних остеопенією.
**Результати**. Для ілюстрації пропонованого підходу розглянуто конкретний приклад лікування осколкового перелому плечової кістки у літньої пацієнтки. Для опису фізико-механічних властивостей кісткової тканини були використані набори стандартних даних про основні характеристики тканин і матеріалів імплантатів — модуля пружності і коефіцієнта Пуассона. По мірі зрощування кістки одночасно зі зниженням напружень відбувається зменшення різниці між напругою на всій конструкції і напругою на кістці. Це свідчить про те, що кістка починає приймати на себе дедалі більшу відносну частину навантаження, що має позитивно впливати на її мінеральну щільність.
**Висновки**. Показано переваги моделювання із залученням методу кінцевих елементів і шляхом неінвазивного моделювання роботи опорно-рухової системи пацієнта з різними варіантами протезів (імплантатів) і вибір найбільш оптимального з них. Встановлено, що використання в якості критерію оцінки напружено-деформованого стану системи імплантат-кістка напруги по Мізесу дає ефективні оцінки надійності роботи конструкції і її елементів.
**КЛЮЧОВІ СЛОВА**: імплантати; перелом плечової кістки; післяопераційна реабілітація; напруги по Мізесу; чисельне моделювання.

## ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПРИ ХИРУРГИИ И РЕАБИЛИТАЦИИ ПЕРЕЛОМОВ ПЛЕЧЕВОЙ КОСТИ У ПОЖИЛЫХ ПАЦИЕНТОВ С ПОМОЩЬЮ ИМПЛАНТАТОВ

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**Актуальность.** Имплантация получает все большее распространение в таких областях современной медицины, как ортопедия и травматология. Ввиду отсутствия адекватного заменителя натуральной кости, используют комбинированные подходы. Для пожилых пациентов проблема усугубляется снижением минеральной плотности костной ткани. При выборе схемы оперативного лечения переломов длинных костей предпочтение отдают простым и максимально щадящим подходам. В этой связи основная задача остеосинтеза состоит в обеспечении оптимальных механических условий не только для процесса сращивания перелома, но и для восстановления в дальнейшем полноценных функциональных возможностей. В работе рассмотрена актуальная задача оптимизации и повышения эффективности планирования реабилитационных мероприятий, в том числе и с учетом индивидуальных особенностей конкретного пациента. Полученные результаты имеют фундаментальное и прикладное значение.

**Цель работы:** создание физико-математических моделей для моделирования напряженно-деформированного состояния элементов опорно-двигательного аппарата для оптимизации планирования операций на кости при установке имплантатов.
**Материалы и методы.** Для анализа в работе использовались как конкретные клинические результаты, так и современные методы компьютерного моделирования и обработки результатов. Преимуществом физико-математических моделей на основе использованного метода конечных элементов является возможность оптимизации конструкции протезов и снижение проблем, вызванных остеопенией.
**Результаты.** Для иллюстрации предлагаемого подхода рассмотрен конкретный пример лечения оскольчатого перелома плечевой кости у пожилой пациентки. Для описания физико-механических свойств костной ткани были использованы наборы стандартных данных об основных характеристиках тканей и материалов имплантатов — модуля упругости и коэффициента Пуассона. По мере сращивания кости одновременно со снижением напряжений происходит уменьшение разницы между напряжением на всей конструкции и напряжением на кости. Это свидетельствует о том, что кость начинает принимать на себя все более значительную относительную часть нагрузки, что должно позитивно влиять на ее минеральную плотность.
**Выводы.** Показаны преимущества моделирования с привлечением метода конечных элементов и путем неинвазивного моделирования работы опорно-двигательной системы пациента с различными вариантами протезов (имплантатов) и выбор наиболее оптимального из них. Установлено, что использование в качестве критерия оценки напряженно-деформированного состояния системы имплантат-кость напряжения по Мизесу дает эффективные оценки надежности работы конструкции и ее элементов.
**КЛЮЧЕВЫЕ СЛОВА:** имплантаты; перелом плечевой кости; послеоперационная реабилитация; напряжения по Мизесу; численное моделирование.

One of the features of the modern stage of scientific progress is the development of new methods that are located at the junction of various fields of knowledge. Despite the fact that biophysics itself is at the intersection of biology and physics, new directions are also emerging within this area of knowledge. They rely on the one hand on existing treatment technologies related to the placement of implants, and on the other hand on the widely used Computer Aided Engineering (CAE) systems. Significant advances in the implementation of existing technologies have been achieved in such areas as dentistry [1], as well as traumatology and orthopedics [2, 3]. At the same time, works related to orthopedics and traumatology can be conditionally divided into two main areas. The first area includes [2], where the authors analyze “the experience of treating 140 victims in the trauma department of the Kharkiv Regional Clinical Trauma Hospital. Treatment of patients with fractures of the tibia, humerus and femur was carried out by the method of blocking intramedullary osteosynthesis (BIOS), various rods and navigation systems from different manufacturers. The errors and complications characteristic of this technique are analyzed, the reasons and the ways of their prevention are indicated”.

However, with this approach, in fact, only fait accompli facts are stated, and only a probabilistic assessment of possible consequences is given. But each individual patient, first of all, is interested in the result in his case. Therefore, for successful prediction, methods of data analysis and the results of calculations of the operation of the entire implant-bone system are required. The problem in this formulation of the problem belongs to the second direction. The main task is to calculate the strength of the "implant-bone" system. The task itself depends on the specifics of the means used. For example, when using a lockable Bliskunov fixator, it is necessary to study the stress-strain state of the osteosynthesis system, which was done in [3]. The authors note that to study the stress-strain state (SSS) of mechanical orthopedic structures, both analytical or numerical calculations and full-scale or model experiments can be used. The term "analytical calculations" in mathematical physics usually combines methods and algorithms that allow one to obtain a solution in a closed form with any predetermined accuracy. In practice, the application of these methods is usually limited to problems with a fairly simple geometry, boundary conditions, and loads (sources). In a clinical setting, carrying out field experiments using metal osteosynthesis, which requires the use of special load and deformation sensors, is an extremely difficult and expensive task. But the main thing is that carrying out such model experiments requires additional substantiation of the adequacy of the results obtained to the basic models [3]. Unlike analytical methods, numerically oriented methods for studying the stress-strain state of mechanical systems do not have such severe restrictions. They make it possible to vary the geometric parameters of structural elements and the physical and mechanical properties of materials over a wide range. Continuous progress in the field of computing also contributes to the increasing application of mathematical modeling methods in various fields of science. The most popular for solving problems of mathematical modeling (including problems of biomechanics, orthopedics and traumatology) is the finite element method [4–10]. This method was used to study the behavior of the humerus [3] and hip joints (Femoral Stems) [4], the problems of bone strength [5], simulate the augmentation of the hip bone (femoral bone augmentation) [6], study the features of treatment of Bennett's fractures [7], mechanical properties of the vertebrae [8] and the proximal femur [9]. A more detailed review of the features of the use of finite element method — FEM in solving problems of biomechanics and orthopedic surgery is given in [10].

Summarizing the results obtained, it should be noted that, despite a significant number of works devoted to the problems of biomechanics and traumatology, many important problems have not yet been studied in detail. In particular, as noted in [11–13], a decrease in bone mineral density (BMD) after 70 years leads to profound changes in the mechanical properties of bone tissue. There is a direct relationship between the modulus of elasticity, which characterizes the stiffness of a material, and the ultimate strength with age. It is assumed that the change in the biomechanical properties of bone with age is associated not only with a decrease in BMD, but also with a qualitative change in collagen, bone binder - mucopolysaccharides, and structural changes in the bone. This requires, in particular, additional study of the effect of changes in the characteristics of materials (primarily the modulus of elasticity) on the operation of the bone-implant structure. Another important issue is the criteria for assessing the stress-strain state and limit states of a structure with an implant. Currently, there are four criteria (hypotheses) of strength in mechanics. When using them, to obtain reliable simulation results, an appropriate experimental or theoretical justification is required. For example, in [3], when analyzing the operation of the osteosynthesis system of the humerus, a criterion for maximum tensile or compressive stresses was adopted, corresponding to the so-called first hypothesis of strength [13]. On the other hand, as is known [15], the first hypothesis (criterion) reflects the engineering ideas of strength calculations, proposed by G. Galileo and used for simple systems until the end of the 19th century. At present, the so-called fourth (energy) hypothesis of strength has received the widest application [16]. However, its use requires, first of all, an appropriate analysis.

Therefore, the purpose of this work is to create computer aided engineering (CAE) models for analyzing the operation of implants and subsequent prediction of the results of surgical treatment of limb fractures, as well as optimization of rehabilitation activities.

The main objectives of the article:

– to show the fundamental possibility of using the relatively simple CAE models for calculating loads at different stages of rehabilitation, especially for elderly patients;

– to demonstrate the change in the distribution of stresses in the bones at different values of the parameters and to identify the most characteristic patterns;

– to carry out a comparative analysis of various criteria (hypotheses) of strength and substantiate the choice of the most adequate and universal of them;

– outline the ways for further research in this area to reduce trauma during surgery and shorten the rehabilitation period by optimizing the shape of the implants.

## PROBLEM STATEMENT AND METHOD OF SOLUTION

### *General remarks*

Research in various fields of orthopedic surgery and traumatology requires a methodology that makes it possible to reproduce (simulate) different situations [4–7]. This methodology can be used to study the biomechanics of the musculoskeletal system both in healthy people and in patients with pathological abnormalities, as well as for modeling various prostheses and implants. The main task of modeling is to predict changes in the distribution of stresses around the zones of implantation, which should prevent incorrect placement of implants and accelerate rehabilitation. An important advantage of physical and mathematical models based on FEM is also the possibility of optimizing the design of prostheses and implants to minimize problems caused by such phenomena as stress-shielding or osteopenia.

To clarify the essence of the work, first of all, we note that modern biomechanics, when solving specific problems, relies on the corresponding models - physical and mathematical. Physical models, i.e. sets of corresponding simplifications (when insignificant characteristics, for example, the color of a sample when calculating the strength) are discarded, and only the most important ones remain. Mathematical models based on physical models are, generally speaking, a set of equations and additional conditions — initial and boundary. Then the problem is solved using computational methods, algorithms based on them, and appropriate software. Such the most modern and versatile software is modern computer aided engineering (CAE) systems, which were mentioned above. They consist of two main components - the actual computing part intended for calculations and the interface for displaying data. Recently, for the input of initial data (geometry), software has been connected to process the data of diagnostic equipment (3D tomograph, ultrasound). Therefore, in accordance with the logic of research, let us first consider a mathematical model.

### *Basic equations and additional conditions*

Within the framework of CAE systems, the FEM Finite element method is most often used for strength calculations [15–21]. This method is based on the equations of the theory of elasticity. In the simplest one-dimensional case, this is Hooke's law, which relates strain $\varepsilon$ to stress $\sigma$ by a linear relationship of the form:

$$\sigma = E \cdot \varepsilon, \tag{1}$$

where: $E$ — coefficient of proportion, called the longitudinal modulus of elasticity (Young's modulus). We emphasize that in various literary sources devoted to the problems of mechanics, not only different systems of units are often used, but also different designations for quantities identical from a physical point of view. Therefore, in order to achieve clarity in the presentation of further material, we first give some specific definitions regarding the main quantities used. In the most general case, the body under consideration is divided into a set of elementary volumes (most often cubic) and the values of normal ($\sigma_x, \sigma_y, \sigma_z$) and tangential ($\tau_{yx}, \tau_{zy}, \tau_{zx}, \tau_{xy}, \tau_{yz}, \tau_{xz}$) stresses are written on their faces — only 9 values. However, by virtue of the law of pairing of tangential stresses, which is formulated as:

$$\tau_{yx} = \tau_{xy}, \;\; \tau_{zy} = \tau_{yz}, \; \tau_{zx} = \tau_{xz} \tag{2}$$

only six quantities are independent — $\sigma_x, \sigma_y, \sigma_z$ and $\tau_{yx}, \tau_{zy}, \tau_{zx}$. Since tension/compression along one of the axes (even in the case of a homogeneous isotropic material) changes the dimensions along the other two axes, one more parameter must be introduced to describe the properties of the material — the lateral compression ratio $\nu$ or Poisson's ratio. In addition to tensile / compressive deformations and (corresponding stresses), there are deformations and, accordingly, shear stresses. Tangential strains and the corresponding stresses are also related by a constant G called the shear modulus or shear modulus. However, there is a relationship between the shear modulus G and Young's modulus $E$ and Poisson's ratio $\nu$, defined by the relationship:

$$G = \frac{E}{2\cdot(1+\nu)} \tag{3}$$

Thus, for a complete description of the elastic properties of homogeneous isotropic materials, two constants are sufficient — Young's modulus $E$ and Poisson's ratio $\nu$. Then the general relations can be written in the form:

$$\begin{aligned}
\sigma_x &= \frac{E}{(1+\nu)}\varepsilon_x + 3\cdot\frac{\nu}{(1+\nu)}\sigma_0; \quad \tau_{zy} = \frac{E}{2\cdot(1+\nu)}\gamma_{zy};\\
\sigma_y &= \frac{E}{(1+\nu)}\varepsilon_y + 3\cdot\frac{\nu}{(1+\nu)}\sigma_0; \quad \tau_{zx} = \frac{E}{2\cdot(1+\nu)}\gamma_{zx};\\
\sigma_z &= \frac{E}{(1+\nu)}\varepsilon_z + 3\cdot\frac{\nu}{(1+\nu)}\sigma_0; \quad \tau_{yx} = \frac{E}{2\cdot(1+\nu)}\gamma_{yx};
\end{aligned} \tag{4}$$

where: $\sigma_0$ — average stress [14, 22].

A set of additional conditions must be added to the basic equations and sources (load) must be specified. Additional conditions include boundary conditions that restrict displacements on specified surfaces or lines and, in the presence of internal boundaries, boundary conditions (contact conditions). To go from the microscopic level (equations for one finite element) to the macroscopic level (the entire body or structure under consideration) it is necessary to take into account the connections at the nodes of various elements. One also needs to take the form of an approximating function to describe the distribution of the solution in the area of the element itself or on its face, edge. These operations within the framework of modern CAE systems are performed in a semi-automatic mode or by software using an appropriate program — a grid generator [23]. As a result, from a mathematical point of view, the problem is reduced to the formation of a system of linear algebraic equations (SLAE) and its solution. The number of equations is equal to the number of unknowns and is determined by the number of elements. In a compact operator form, the resulting SLAE can be written as follows:

$$\hat{A}X = B, \tag{5}$$

where: $\hat{A}$ — matrix operator (square matrix of known coefficients), $B$ column vector of the right-hand sides (with known elements, usually corresponding to sources/load), $X$ — vector column of unknown (to be determined) coefficients. After solving the SLAE, using certain numerical values of the coefficients, displacements and other required quantities are found: normal and tangential stresses on specified surfaces or lines, relative deformations and other quantities. If necessary, the received data is displayed in graphical mode using the program interface. The results of SSS calculations obtained in this way are the initial data for subsequent processing and interpretation within the framework of the main theoretical problem posed — to demonstrate the change in the stress distribution in the bones at different values of the parameters and to identify the most characteristic patterns. To solve practical problems related to the optimization of operational and rehabilitation measures, it is necessary to make a reasonable choice of criteria.

***Strength criteria*** *(hypotheses)* [14, 15].

The point of introducing strength hypotheses is that they eliminate the need for a huge number of experiments [14, 15]. One or another criterion of equivalence serves as the basis for practical strength calculations only under the condition that for a number of special cases the results of its experimental verification turned out to be sufficiently close to theoretical calculations or numerical simulation [26]. The reasons for the destruction of materials are complex physical processes, both at the macroscopic and microscopic levels. This does not allow until now to develop a universal and simple hypothesis of strength and therefore there are used several basic hypotheses. It is important that all of them are based on the concept of a dimensionless (having no physical dimension) safety factor $k$ as a ratio of the actual value of a certain parameter, for example, tensile stress, which we will supply with the index (1) to emphasize its relation to the first hypothesis — $\sigma_s^{(1)}$ to the maximum possible value of the same parameter $\sigma_{s,\lim}$ . The limit value $\sigma_{s,\lim}$ must be preset.

To make an informed decision on the choice of the strength hypothesis, it is necessary to carry out a physical analysis of their features. The first hypothesis of strength, proposed by Galileo, which was already mentioned above, is based on the assumption that the cause of material failure is the highest normal stresses in absolute value. The condition for the strength of the material (structure) in this case is the requirement that the safety factor be less than one:

$$k = \frac{\sigma_s^{(1)}}{\sigma_{s,\lim}} < 1. \tag{6}$$

The main disadvantage of this hypothesis is that the determination of the equivalent stress does not take into account the other two principal stresses. For example, under all-round compression, the material can withstand significantly higher stresses than under uniaxial compression.

The second hypothesis of strength or the hypothesis of the greatest linear deformations proposed by Mariotte and then developed by Saint-Venant proceeds from the assumption that the greatest linear deformations are the cause of failure. Within the framework of this approach, the equivalent stresses are first calculated by the formula:

$$\sigma_{eq}^{(2)} = \sigma_1 - \nu \cdot \left(\sigma_2 + \sigma_3\right) \le \left|\sigma_{\lim}\right|, \tag{7}$$

where: $\sigma_1, \sigma_2, \sigma_3, \sigma_{\lim}$ — three main and maximum permissible stress, respectively. Or, which is equivalent (taking into account the above notation):

$$\varepsilon_1 = \frac{1}{E} \cdot \left(\sigma_1 - \nu \cdot \left(\sigma_2 + \sigma_3\right)\right) \le \left|\varepsilon_{\lim}\right|. \tag{8}$$

The second hypothesis, as follows from (8), takes into account all three main stresses. Nevertheless, it is not sufficiently confirmed by experience and is rarely used.

The third hypothesis, or the hypothesis of the greatest shear stresses, was proposed by Coulomb and developed by Saint-Venant. In accordance with this hypothesis, the greatest shear stresses are the cause of material failure. The third strength hypothesis is based on the condition:

$$\sigma_{eq}^{(3)} = \sigma_1 - \sigma_3 \le \left|\sigma_{\lim}\right|. \tag{9}$$

The main disadvantage of the third hypothesis is that it does not take into account the second principal stress and gives an acceptable accuracy (10–15%) only for plastic materials.

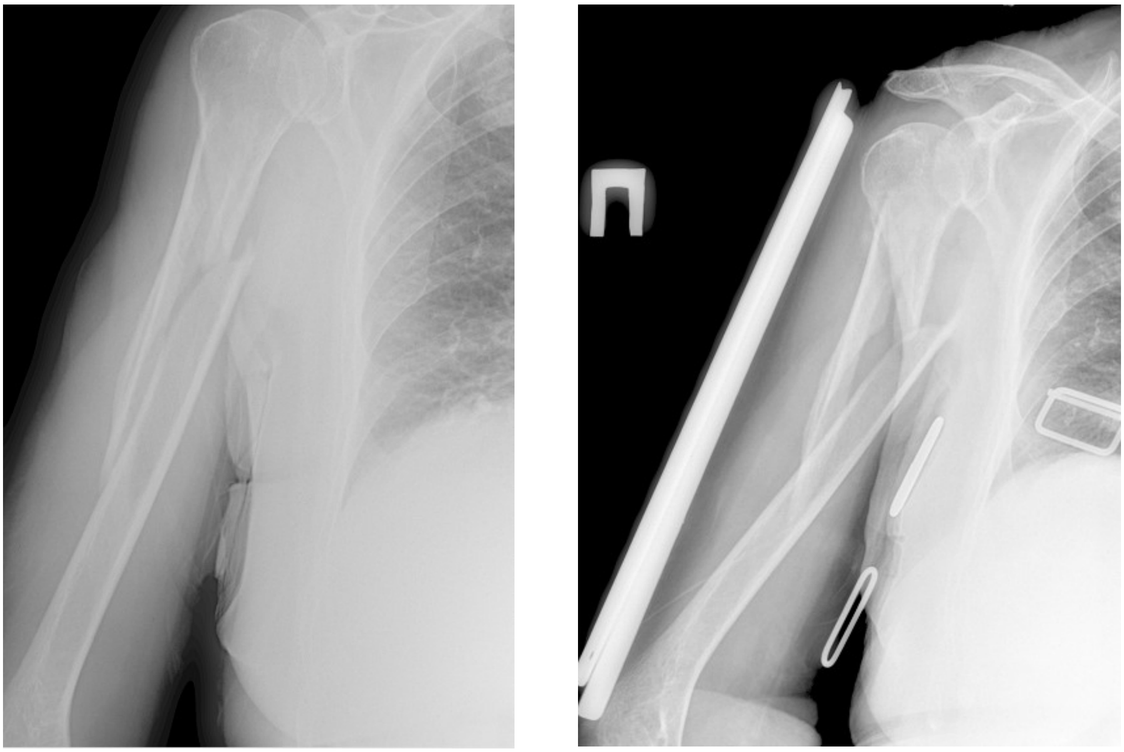
The fourth hypothesis of strength or energy is based on the amount of specific potential energy spent on changing the shape before the onset of the limiting state. In the most general case, the total specific potential energy of deformation of a unit cube can be represented as the sum of the energy spent on changing the volume (tension / compression) and changing its shape. In this case, the corresponding limiting state condition looks like this:

$$\sigma_{eq}^{(4)} = \sqrt{\frac{1}{2}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_2\right)^2\right]} \le \left|\sigma_{\lim}\right| \tag{10}$$

It goes without saying that for each material it is necessary to preliminarily determine the numerical value of the stress limit — $\sigma_{\lim}$. However, the main applied advantage of this hypothesis is the possibility of its application for the tasks of comparative analysis of various structures and modes of their operation on the basis of an energy assessment in the absence of accurate data on the values of limiting stresses or strains. This is due to the fact that it is the potential energy in static problems that is the source of destruction of a material or structure. Therefore, as a criterion for assessing the stress-strain state of the implant — bone structure, we will choose the fourth hypothesis of strength and the quantitative criterion of the stress value according to von Mises (10).

## RESULTS AND DISCUSSION

To illustrate the proposed approach, let us consider an example of treatment of a comminuted fracture of the humerus in an elderly patient, which occurred on December 31, 2013 as a result of a fall (Fig. 1, a). An attempt to use an orthosis for setting the fragments and fixing them for 7 weeks did not give any result (Fig. 1, b).



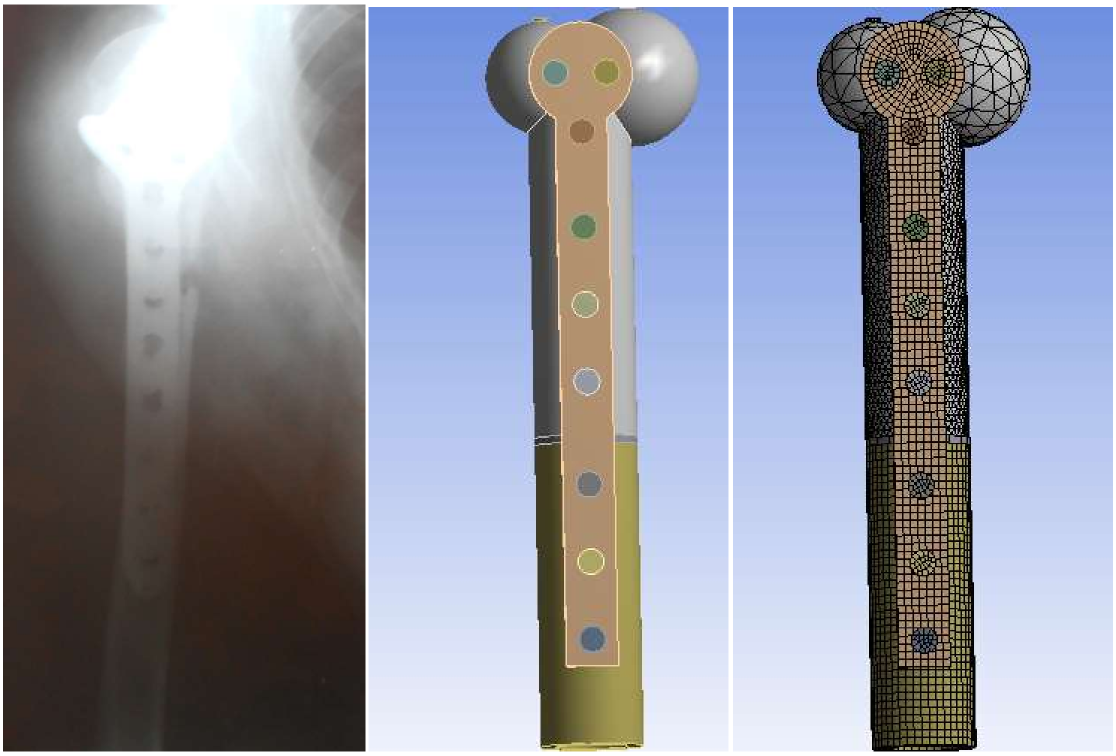
a b

Fig. 1. X-Ray picture of the right humerus.

As a result, a decision was made on the need for surgical treatment, open reduction of fragments and extramedullary osteosynthesis of the right humerus, which was carried out on 06.03.2014 (Fig. 2, a).

### *CAE model and parameter selection*

When carrying out calculations, we used the ANSYS Mechanical Software Suite. As mentioned above, the concept of a CAE model implies a set of geometric elements together with a set of physical and mechanical properties of materials and connections (contact conditions) between individual elements. At the subsequent stages, a mesh of nodes (vertices) of elements is formed, and displacements, deformations and stresses are calculated. In this case, the modeling task is to analyze the distribution of stresses in order, on the one hand, to ensure reliable bone fusion at the fracture site, and on the other hand, to optimize the further load on the bone in order to reduce the immobilization time as much as possible and, as a consequence, prevent a decrease in bone mineral density (BMD) tissue (osteopenia). In the case of intramedullary osteosynthesis, posttraumatic osteopenia of tubular bones was studied in [17]. However, extramedullary osteosynthesis (external fixation) differs from intramedullary both in the duration of immobilization and in the distribution of loads due to the asymmetry of the structure. When carrying out calculations, it is natural to strive to use the most adequate model. However, the approximation of a model to reality often leads to its complication and, in many cases, even to a loss of accuracy due to the accumulation of round-off errors when performing arithmetic operations on a computer. Therefore, a relatively simple model from the point of view of geometry was created for modeling (Fig. 2, b, c).



a b c

Fig. 2. X-ray picture of the right humerus after surgery (a), diagrams of the bone with an implant (b, c).

The next task is to assign numeric values to parameters. To describe the physical and mechanical properties of bone tissue, standard data on the main characteristics of tissues and materials of implants - elastic modulus (Young's modulus) — $E$ and Poisson's ratio — $\nu$ are used. Papers [24, 25] are devoted to the determination of these parameters and the analysis of the results obtained. Naturally, the values of these parameters can vary depending on many factors — age, energy intensity of the injury, individual characteristics, diet, etc. Therefore, Table 1 presents not the exact values of the parameters, but their averaged values according to [16, 18–20, 24, 25] or the boundaries of the change in characteristics.

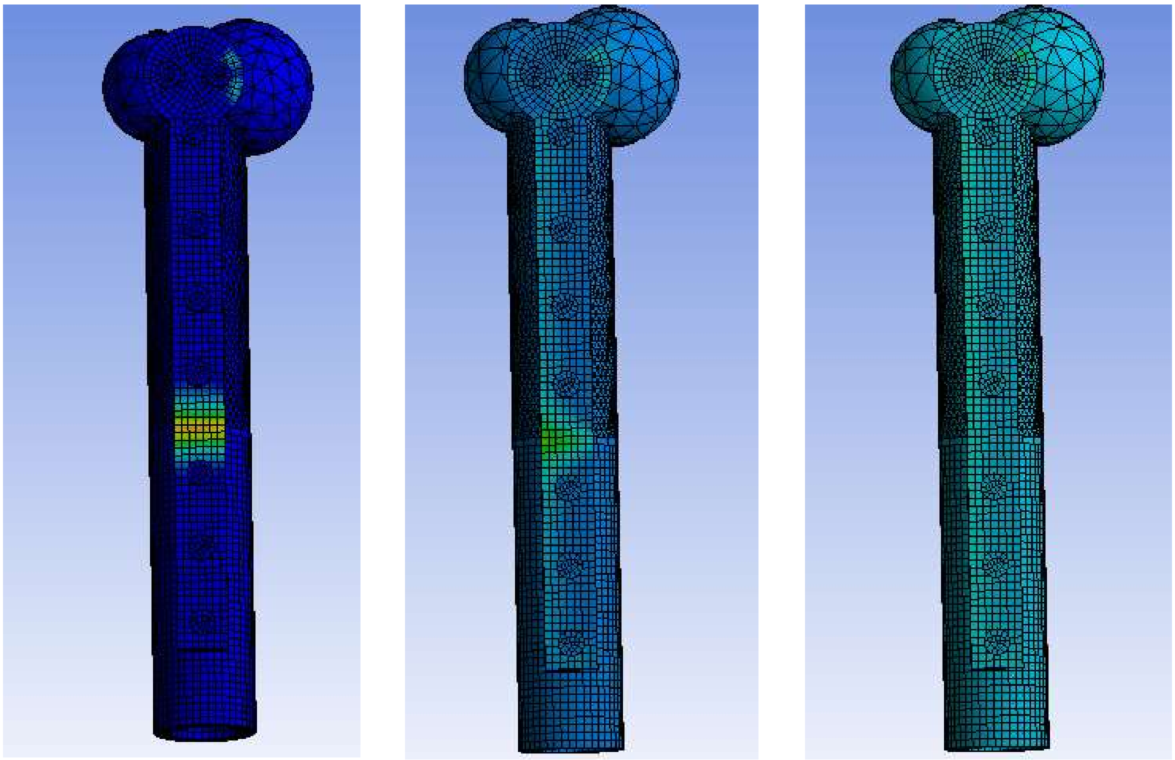
The values from Table 1 were used as a basis for modeling bone stress with an implant. To carry out numerical calculations, it is necessary to specify the boundary conditions and the load. In this case, the boundary conditions (fixation) were set in the lower section (by area), and the load (compressive 0.6 MPa is standard for some technical applications, on two circular sections with a diameter of 0.6 cm. each. It is equivalent to a force of 3.4 kg) is applied to the articular head (caput humeri) and to the larger apophysis (tuberculum majus). The main goal of computational experiments is to simulate the distribution of loads during rehabilitation at various values of the parameters (first of all, Young's modulus). Some calculation results are shown in Fig. 3–6.

Table 1. The values of the parameters used according to the data from [16, 18–20, 24, 25].

| Tissue (material) | E (MPa) | Load direction | ν | Tensile strength (MPa) | Compressive strength (MPa) |
|---|---|---|---|---|---|
| Brachial bone | 17200 | longitudinal | 0.30 | 30 | 132 |
| Spoke-bone (radius) | 18600 | longitudinal | 0.30 | 149 | 114 |
| Elbow bone | 18000 | longitudinal | 0.30 | 148 | 117 |
| Spongy bone | 90–959 | longitudinal | 0.12 | – | 23 |
| Bone marrow | 1 | – | 0.30 | | |
| Hip | 17200 | longitudinal | 0.30 | 121 | 167 |
| Tibia | 18100 | longitudinal | 0.30 | 140 | 159 |
| Fibula | 18600 | longitudinal | 0.30 | 146 | 129 |
| Cervical vertebrae | 230 | longitudinal | н.д. | 3.1 | 10 |
| Lumbar vertebrae | 160 | longitudinal | н.д. | 3.7 | 5 |
| Cortical layer | 20000 | longitudinal | 0.30 | 90 | 150 |
| Forged titanium alloy (Ti 6Al-4V) | 110000 | – | 0.33 | – | – |
| Alloy TMZF | 74000–85000 | – | 0.33 | – | – |

When installing implants, it becomes necessary to calculate the permissible loads at different stages of rehabilitation. As can be seen from the above figures, at the early stage of rehabilitation (Fig. 3, a.)

The entire load (bright zone) is taken by the implant. as the bone fragments grow together, the load begins to be distributed more and more evenly (fig. 3, b) and at the end the stress distribution becomes almost completely uniform (fig. 3, c). Thus, (fig. 3, c) clearly demonstrates the achievement of one of the goals — minimization of maximum stresses and their almost uniform distribution throughout the structure. Concrete values of stresses should be used to determine the maximum permissible loads at each stage of rehabilitation. The illustrations of the simulation results when solving this problem are shown in fig. 4–6. Fig. 4 illustrates the dependence of the first principal stress (maximum compressive or tensile) for the entire structure and separately for bone tissue, depending on young's modulus at the fracture site, i.e. in fact, it illustrates the process of rehabilitation under various conditions (BMD values, qualitative changes in collagen and the associated young's modulus) of the entire bone. Analysis of these graphs shows that an increase in the strength (young's modulus) of bone tissue leads to a more even distribution of the load and a decrease in maximum stress. In addition, the implant takes on a significant part of the load at the initial stages of rehabilitation, and the load on the bone itself is correspondingly reduced. As the bone grows together, simultaneously with a decrease in stresses, the difference between the stress on the entire structure and the stress on the bone decreases. this indicates that the bone begins to take on an increasingly significant relative part of the load, which should positively affect its BMD (reducing the risk of osteopenia).



a b c

Fig. 3. Distribution of stresses (von Mises) at different values of young's modulus in the fracture area: a) bone 0.1 MPa max 19.5 MPa, b) bone 50 MPa max 1.48 MPa, c) 3000 MPa max 0.89 MPa.

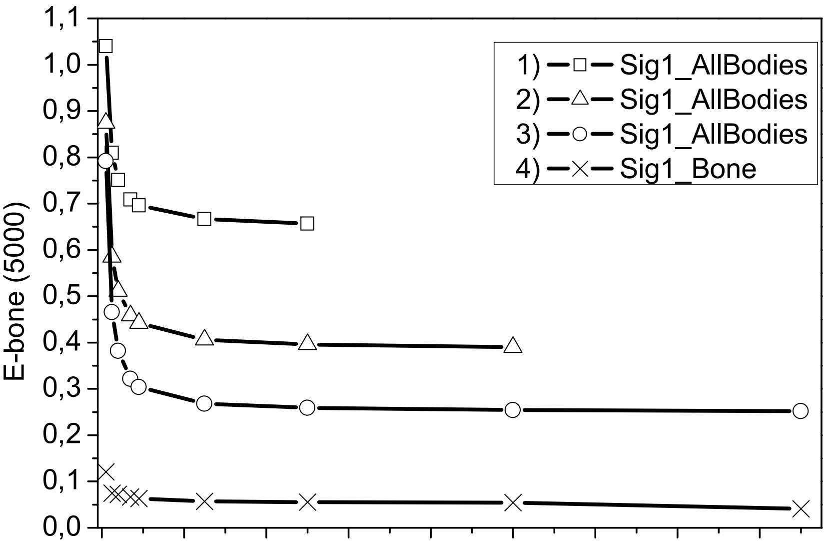



Fig. 4. Maximum values of the first principal stress for the entire structure (1–3) at different values of the Young's modulus of bone tissue and for bone tissue at the maximum value of E, depending on the Young's modulus of bone tissue at the fracture site.

Fig. 5–6 shows the maximum von Mises stresses (1), the maximum values of the first principal stress for the entire structure (2) and the same stress, but only for the bone (3), depending on the strength of the tissue at the fracture site (Young's modulus) at different BMD (values of Young's modulus) of the entire bone. The results obtained confirm the correctness of the choice of the criterion — von Mises stresses, since it is these stresses that have the maximum values. Also important is the result of significantly lower stresses in the bone compared to the maximum stresses in the entire structure. Moreover, the difference between these values is smaller for large values of strength (Young's modulus) of the bone itself. In other words, for a bone with a higher BMD (Young's modulus), a more uniform distribution of stresses occurs. From a physical point of view, this is quite natural.

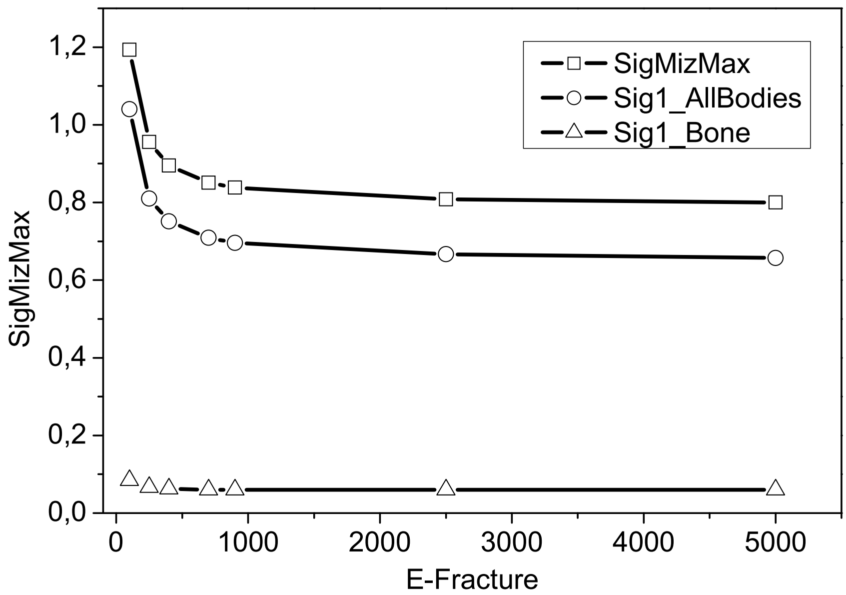



Fig. 5. Maximum values of von Mises stresses (1), the first principal stress for the entire structure (2) and the first principal stress only for the bone (3), depending on the Young's modulus of the fracture site. Young's modulus of the bone is 5000 MPa.

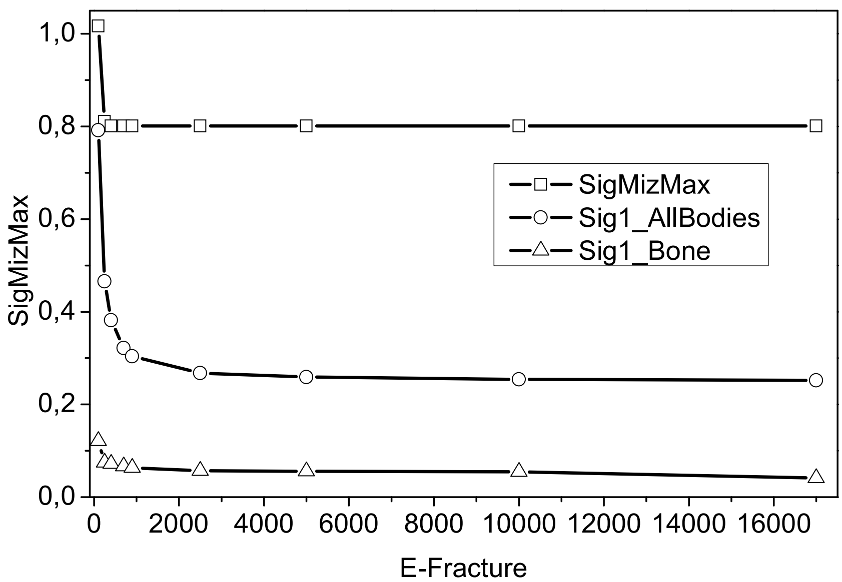



Fig. 6. Maximum values of von Mises stresses (1), the first principal stress for the entire structure (2) and the first principal stress only for the bone (3), depending on Young's modulus of the fracture site. Young's modulus of the bone is 17000 MPa.

Finally, we note that the calculations performed showed a significant increase in the safety factor after implant placement for all values of the Young's modulus of the bone after rehabilitation. In the initial stages, this is achieved due to the fact that the implant takes on the main load (Fig. 3, a), and then more and more even distribution of the load occurs, which ultimately significantly reduces the risk of recurrent fractures. In conclusion, we note that in this work only relatively simple ones are considered, both from the point of view of geometry and from the point of view of physic-mechanical characteristics of materials (homogeneous isotropic materials). The authors hope to present the results of the analysis of more complex structures and a comparative analysis of various technologies for installing implants in future works.

## CONCLUSION

The models developed by CAE for studying the stress-strain state of the elements of the musculoskeletal system using the example of the humerus with an implant have shown their efficiency and effectiveness.

The key advantage of FEM modeling is the ability to perform multiple non-invasive modeling of the patient's musculoskeletal system with various variants of prostheses (implants) and the choice of the most optimal one. This primarily relates to the problems of optimal planning of bone surgeries associated with the placement of implants.

It has been established that the use of an implant — bone stress according to Mises as a criterion for assessing the stress-strain state of the structure makes it possible to obtain, from the point of view of mechanics, effective assessments of the reliability of the work, both of the entire structure and of its elements separately.

As a result of computational experiments carried out using the developed models, the features of the operation of structures with various mechanical properties have been investigated. As a result, the possibility of effective planning of rehabilitation measures was established, both taking into account the general strength characteristics of artificial materials, and taking into account the individual characteristics of a particular patient.

As directions for further research, further improvement (complication) of both the geometric parameters of the models and the physical and mechanical characteristics of materials is proposed.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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