Influence of the fixation region of a hip stem on the behaviour of the "bone–implant" system

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Abstract: In this paper, the stress state of the femoral bone and stem prosthesis is studied using the finite element method, and considering different types of prosthesis fixation in the medullary canal of the femur under action of functional loads. To obtain reliable results of the performed finite element analysis, model generation of both the femur and the endoprosthesis of real size and shape, physico–mechanical properties of the material and the values of the functional load, is employed. The finite element analysis of the stress-strain state shows that for diaphyseal fixation the area of contact between the surface of the stem and the bone is too small. As a result, this type of fixation causes large stresses in the stem what further leads to fatigue fracture of the implant. In the case of diaphyseal fixation type, stress concentration arises in the distal femur and leads to a risk of stress–shielding effect or bone fracture. An increase in the area of contact between the implant and the bone raises the stiffness of the "bone–implant" system, and the values of tensile and compressive stresses in the implant are reduced. For metaphyseal fixation, stress is evenly distributed in bone and no excessive concentrations are observed. In this case, values of stresses in implants do not exceed the endurance limit of the metal of which the implants are made, what ensures a margin of safety. Finally, the presented numerical method can be used to consider the influence of structural changes and clinical technique of installing endoprostheses in the femoral canal on the durability of implants.

1. Introduction

Total hip replacement (THR) is now one of the most effective methods of treatment for patients with severe diseases of the hip joint [1]. It restoring hip function and relieving patients of pain by replacing pathological hip joints with artificial ones. There are about 500,000 THR surgeries in Europe each year, with growing numbers throughout the world [2]. However, despite the wide range of designs in hip arthroplasty, major problems are associated with instability and loosening of the endoprosthesis and development of proximal femur stress–shielding syndrome [3-4]. The fixation may be unstable and leads to loosening of the implant when the relative micromotion between stem and bone interfaces exceed threshold value. A magnitude of micromotion under 50 μm can be defined for bone ingrowth, from 50 μm to 150 μm as probable bone ingrowth, and larger than 150 μm leads to formation of fibrous tissue that can prevent bone ingrowth [5-6]. At the same time, if in certain areas of the implant the functional load causes stress which exceeds fatigue limit then destruction occurs [7]. Also after the installation, the implant may greatly influence the transmission of the load to the host tissue, what can cause proximal stress-shielding due lack of load or cortical hypertrophy in distal part, due overload, respectively [8-9].

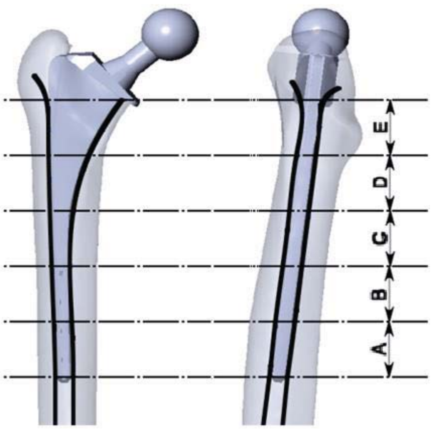
Therefore, in the process of designing implants, efforts should be aimed at solving the aforementioned problems. Even during the most objective physical experiments, it is very difficult to account for differences in mineral density of different specimens. Furthermore, it is impossible to repeat experiments on the same specimen due to total or partial destruction caused by stress and overloading. Currently one of the most effective and informative methods of studying problems of biomechanics is the method of mathematical modeling, and in particular the finite element method (FEM). Using FEM has obvious advantages, such as highly accurate results and the low cost of numerical experiments with the ability to change basic parameters, such as geometry, material properties, forces magnitudes, and it allows us to gain a large range of results that are difficult to measure non-invasively with equipment, including, stress–strain, relative micromotion and contact pressure.

There are many studies that apply finite element analysis to bones or to joints [10-12]. Those studies have reported the stress or strain distributions in various situations. However, to the best of our knowledge, there is small amount of studies aimed on using FEM to analyze the influence of region stem fixation on the behaviour of the “bone–implant” system.

Therefore, in order to improve treatment outcomes and quality of life of patients, the goal of this study was the biomechanical oriented analysis for the choice of optimal implant fixation in case of hip replacement using the finite element modeling of stress-strain state "bone - implant" systems. We hypothesise that proximal fixation would provide the best physiological loading of femur and evenly distribution strain over lateral and medial sides of a bone.

2. Materials and methods

One of the most important stages in the development of endoprostheses is biomechanical rationale of performance and reliability of implants. In this case, the carried out FEM analysis allowed to estimate the stress state of the "femur – implant" system. The influence of conditions fixation of the implant at various levels of the medullary canal of the femur to the stresses occurring in the bone structures and the implant under the action of functional loads have been investigated (Fig. 1). Parameters and dimensions of geometric models of the femoral components corresponded to their real size and shape. In this work, the size and the shape of the ORTAN® (Ukraine) femoral component is used. From the literature data [13], the value of the components of load (in the case of a human body weight of 700 N) was equal to: Fx=520 N; Fy=177N; Fz=1854N, where: X stands for the front axis; Y–axis is sagittal; and Z is the vertical axis. Also we have taken into account influence forces acting on the surface of the bone during walking. For the numerical calculations was chosen isotropic model of the material for all bodies, with the relevant physical and mechanical parameters. Titanium alloy (Ti6Al4V), having a modulus E = 110 GPa and Poisson ratio ν = 0.3, has been selected as the material for the physical properties of the femoral component of the hip endoprosthesis. The described type of femoral component with collar can be used with distal and proximal fixation types. Distal fixation contributes to jamming the stem in the area of narrowing of the femur medullary canal while proximal fixation supposes fixed in diaphyseal and metaphyseal parts of the femur at the same time. In this work, the distal and proximal fixations of stem are considered (Fig. 1).



Area of fixation	Types of fixation
DE	by collar
CDE	metaphyseal
BCDE	metaphyseal– diaphyseal
ABCDE	full
ABCD	diaphyseal–metaphyseal
ABC	diaphyseal
AB	diaphyseal
A	diaphyseal

Figure 1. Types of fixation of cemented femoral stem of the prosthesis in different zones of the medullary canal of the femur

Three-dimensional model of the femur has been developed based on the results of computer tomography (CT) scans. The heterogeneous material properties of the femur have been calculated based on the bone density values. The following relationship between the Hounsfield units (HU) of the CT scanner and apparent density (ρ) have been taken: $\rho = 1 + 7.185 \times 10^{-4} \times \mathrm{HU}$, Young's modulus is: $E = -388.8 + 5925 \times \rho$ [14]. A total of 20 different bone materials have been assigned for the heterogeneous models. Poisson's ratio ν = 0.3 has been selected for the physical properties of the femur. In this study primary stability of prosthesis is based on pressure between bone tissue and metal and continues during loading with coefficient of friction μ=0.3. For each type of stem fixation, maximum micromotion of the stem in the bone was evaluated using the relative tangential node displacements in the contact surface under maximum loads during gait by equation (1):

$$Micromotion = \sqrt{[CSLIP(x_1, n)]^2 + [CSLIP(x_2, n)]^2} \quad (1)$$

Finally, for finite element analysis in the present study, the three-dimensional geometric model of femur with impant was imported and meshed using ABAQUS software (version 6.14, Dassault Systems, 2015). The FE bone-implant system models used in this study consist of 1100123 tetrahedral elements with maximum length of the edge equals 2 mm.

3. Results and discussion

The purpose of this study is to develop a FEM model for a human femur with stem and to investigate the effects different stem fixations on stress state of system “bone-cement-implant”. The strain distribution obtained from the models are compared with each other for evaluating the load-transmit efficiency. Furthermore, the stem micromotion and stress distribution which cause stem loosening and fracture are analysed.

The results showed that the stress state of the stem prosthesis occurs due to the bending moment in the frontal plane and compression forces in the axial direction (Fig. 2). For both bone and implant compressive stress arising on the medial side while tensile stresses arising on the lateral side.

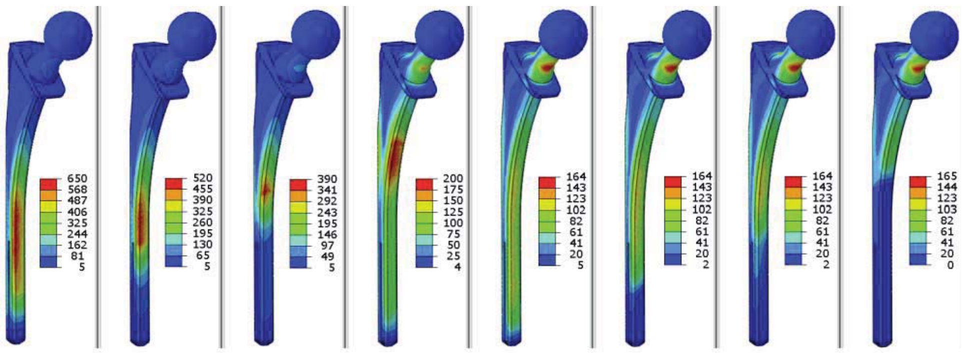


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Figure 2. Distribution of equivalent stress on the medial side of the prosthesis in the case of different types of fixation

The results showed that the most unfavorable for the bone is diaphyseal fixation. Since a contact between stem and bone too small, a large level of stress was detected in the distal part of the bone. The latter behavior increases the risk of bone fracture and leads to a proximal stress-shielding effect due loading lack (Fig. 2). Depending on the type of fixation of the implant, the maximum equivalent von Mises stress in the implants varies in the range from 650 to 90 MPa. During calculation, it has been found that for the design of stem endoprosthesis of the hip joint, the most dangerous diaphyseal fixation types are: A, AB, ABC. In these cases, micromotion leads to failure of bone ingrowth (>150 μm) and can lead implant loosening (Fig. 3). In the latter case, the stresses vary from 650 MPa to 390 MPa. These type of implants and fixations are unacceptable, since stresses occurred in the body stem exceed the limit of durability of the metal, and such loads may imply fatigue fracture of the stem. An increase in the area of contact between the stem reduces bending and the maximum equivalent stresses in the implant. For these types of fixation, our results have shown that the maximum stresses in the elements of the assembly have not exceeded the durability limit of the material, and all elements of the system have been in a state of elastic deformation. Therefore, metaphyseal, metaphyseal–diaphyseal, diaphyseal–metaphyseal types of fixation and fixation using collar guarantee the required safety margin. Also in these cases, except pure collar fixation, micromotion is below the threshold for osseointegration (<150 μm). This indicates that a collar may have importance in preventing implant instability, if close contact between collar and bone is taken. Calculations showed that the metaphyseal-diaphyseal and collar type of fixation of the stem is most acceptable for the femur. In these cases, the tensile stresses and compressing stresses are evenly distributed with the lateral and medial side, beginning from the metaphyseal and ending at the diaphyseal part of the bone (Fig. 3). In these types of fixation an important role plays collar of stem, which helps to normalize the load transfer to the proximal part of femur that eliminates excessive stress concentration in the distal.

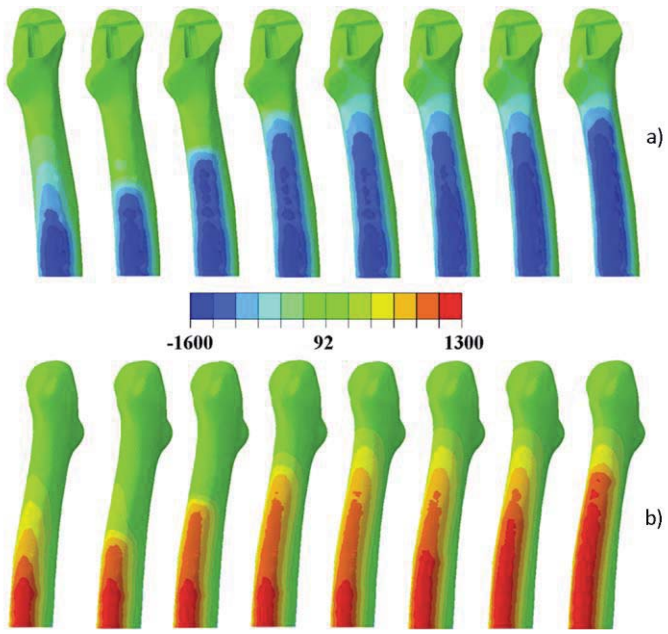

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Figure 3. Distribution of compressive (top) and tensile (bottom) strains (in microstain) on the medial and lateral sides of the femur, depending on the type of fixation of the endoprosthesis stem under the action of functional loads.

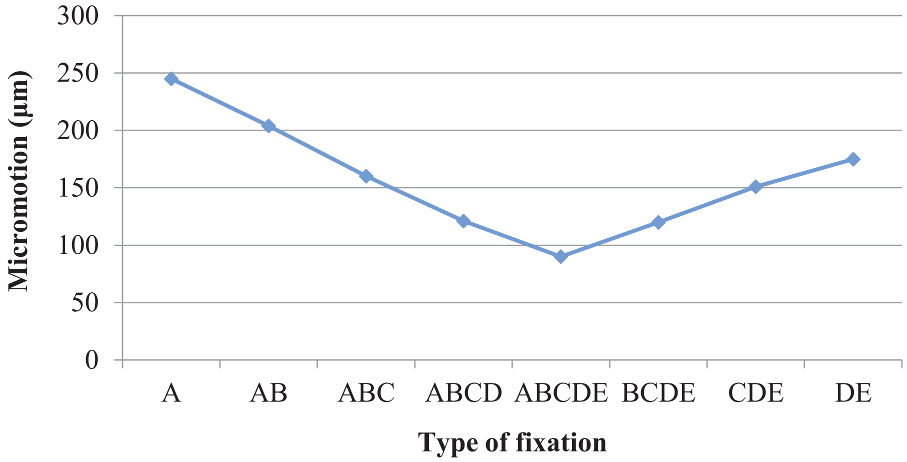

Figure 4. Changes in the maximum micromotion of the implant surface for different variants of implant fixation.

It should be mentioned, however, that in this study had a number of limitations. The material properties in the FE-models were inhomogeneous but isotropic and linear. Nonlinearity and anisotropy might be able to improve predictions. Only the effect of one loading modeled using FE analysis. In reality femur is exposed to numerous other forces in activities of daily living. Here we consider only maximum values of stem micromotions, however, area of these micromotions can also have influence on implant stability.

4. Conclusion

In this research, the biomechanical effect of different stem fixation is analyzed using computational results. The following biomechanical characteristics of the system have been studied: distribution of stresses and micromotions in implants and strain distribution in femur. From the obtained results, it is found that proximal fixation can prevent resorption of the medial femoral neck, decreases the proximal stress shielding and the risk of fracture. Proximal fixation has advantage even in comparison with full fixation of endoprosthesis where there is still a concentration of strains in distal part of femur. However, full fixation can provide better mechanical stability for implants.

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