Research of Parameters of the Stress-Strain State of a Bone Tissue in Norm and at Pathology by Means of the Developed Automated System

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Abstract

In this article stage by stage performance of the methodology of studying the stress-strain state of bone tissue in norm and at pathology, allowing to obtain a model of bone and soft tissue on computer tomography, and to perform a biomechanical analysis of the models based on finite element method. In article also it is told about the mathematical model, appreciating the anisotropy and heterogeneity of the biomechanical properties of firm biological tissues, as well as the impact of elements of human musculoskeletal device.

Keywords: parameters of the stress-strain state of bone tissue, computer-aided design, biomechanical rationale of the bone treatment method

1 Introduction

Treatment of injuries and pathologies is often reduced to installation of implants, devices of external and internal fixing, endoprotheses. Introduction in a body of the person of various designs leads to redistribution of loading in bone tissue and changes its internal structure.

Now in the solution of questions such as dynamic loading of biological tissue and admissible deformations of a bone tissue when merging fractures of bones

apply methods of computer modeling. Development in the field has narrowly targeted, problem-oriented character, demands from the operator of knowledge program soft. There are no debugged techniques. Besides, considerable temporary resources, computing capacities and studying of various software products are required.

It is necessary to develop an unconventional approach to make the biomechanical rationale of choosing the most effective method in diagnostic and treatment of musculoskeletal human, that allows to construct the biology object models, appreciating the peculiarities of their anatomical structure based on computer tomography, purpose of the anisotropy and heterogeneity of the biomechanical properties, values influences of different elements of the musculoskeletal system in static and dynamic, to conduct a comparative analysis of the stress-strain state of the received models on the selected criteria.

The purpose of creating a system - modeling of the individual osteosynthesis, researching and controlling parameters of the stress-strain state of biological object of a human musculoskeletal device in different physical areas: electromagnetic, thermal, strength analysis. The package of applied programs represents the individual program for each patient.

Therefore working out architecture of the program and realisation of its subroutines are actual formation of scientific bases of creation of an automated system on the set of software modals, construction of a program architecture and realisation of subprograms.

Created elements of software algorithms and information management system allow to build a solid model of multiple soft and bone tissue in the first software module, to perform various geometric operations with these models in the second program module, to obtain the estimated multivariate models of bone and soft tissue in the third module, to compute the stress-strain state of the obtained models under various external influences, save and compare these models in the database to further using for the decision of new problems.

2 Methodology and Mathematical Model

System Mimics is chosen as the first software modal quickly to transform in 3D objects from tomography, and to prepare these objects for the further analysis. The package includes SurgiCase Orthopaedics - base of the designed models of systems of fixing and information base of properties of materials for them.

System Catia is taken as the second software modal to reconstruct the objects of a musculoskeletal device. Further export of model needs to be executed in the sterelitografichesky .stl format or in the neutral .iges (.igs) format (Fig. 1). They are supported by the most popular CAD and CAE system. Then, it is necessary to receive solid-state model. There are two options. The model in the .iges (.igs) format is presented in the form of a cloud of points. The qualitative finite-element network is under construction, the surface on a network "stretches", its

geometrical defects improve and the surface for receiving solid-state model is closed.

In the .stl format the model is presented in the form of triangles, it is only necessary to correct defects of geometry and to execute closing of a surface.

The first option is more exact, the received model is most approached to original object, but there is a probability of receiving model with difficult geometry. Therefore when exporting model to one of formats of data it is necessary to define a priority between quality of geometrical model and complexity of the solution of a task. Function of this module allow to cut out the volume of biological tissue for osteotomy or resection planning.

Fig.1 Solid-state model of a femur

As the third software modal ANSYS Multiphysics is chosen – universal finite-element complex to carry out calculation of the stress-strain state of objects of a human musculoskeletal device.

Work in the Ansys takes place in several modules: Design Modeler, Static Structural, Transient Structural, Modal, Engineering Data, Fluent, Steady-State Thermal, Transient Thermal. Advantage of such construction that one calculation model is used for a wide range of problems of interdisciplinary interaction.

The purpose of this stage is receiving calculation models. First of all, it is necessary to set properties of materials, namely elastic and strength properties of firm biological tissue, endoprotheses.

Firm biological tissue is the anisotropic environment, for definition of its characteristics the local system of coordinates is entered ($i, j=1, 2, 3$). The example of their arrangement for a tibial bone is shown in Fig. 2. Orientation of axes of coordinate system gets out proceeding from symmetry in structure of bone fabric [1, 4-7]. For example, for a compact layer the x_1 axis is combined with the prevailing direction osteon, i.e. with the direction of a longitudinal axis of a bone. The direction of the x_2 axis gets out along a tangent to a section circle as

compact bone fabric has cylindrical structure of lamellyarny bezosteonny bone fabric. The x_3 axis gets out orthogonal to the x_2 and x_3 axis. For a spongiozny layer the x_1 axis has the same direction, as well as for compact, the x_2 axis has the transversal direction, the x_3 axis – przedniezadny.

Fig 2. Orientation of samples in a diaphysis of a tibial bone

Communication between a tensor of stain σ_{kl} and a tensor of deformation e_{ij} in the course of loading is presented in the form of a tensor row linearly - elastic deformation: $e_{ij} = a_{ijkl}\sigma_{kl}$; $i, j, k, l = 1, 2, 3$, where a_{ijkl} – tensors of a pliability of the 4th rank.

This polynom can be written down in a matrix look at deformation of stretching (compression) and torsion:

$$\begin{Bmatrix} e_{11} \\ e_{22} \\ e_{33} \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} = \begin{Bmatrix} a_{1111} & a_{1122} & a_{1133} & 0 & 0 & 0 \\ a_{2211} & a_{2222} & a_{2233} & 0 & 0 & 0 \\ a_{3311} & a_{3322} & a_{3333} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{2323} & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{1313} & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{1212} \end{Bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix},$$

where e_{ij} ($i, j = 1, 2, 3; i = j$) – deformation at stretching (compression), γ_{ij} ($i, j = 1, 2, 3; i \neq j$) – deformation at shift.

Under the symmetry terms of a matrix pliability: $a_{1122} \approx a_{2211}$, $a_{1133} \approx a_{3311}$, $a_{2233} \approx a_{3322}$. Then material constants $E_i = (a_{iiii})^{-1}$ ($i = 1, 2, 3$) and

coefficients of cross deformation $\mu_{ij} = -a_{jii} \div a_{iiii}$ $i, j = 1, 2, 3; i \neq j$ are calculated, the characterizing elastic properties of a bone tissue.

The important parameter of the stress-strain state of biological object of a human musculoskeletal device is specific energy of deformation which shows quantity of the energy spent for deformation of unit volume of a studied bone site at a set stress. At monoaxial stretching along the x_1 axis it is calculated as $U_i = 0,5a_{iiii}\sigma_{ii}^2$, in case of deformation at shift in the $x_i - x_j$ planes $- U_{ij} = 2a_{ijij}\sigma_{ij}^2$ ($i, j = 1, 2, 3; i \neq j$).

The data anisotropic biomechanical characteristic of bone and soft tissue undertake from the knowledge base prepared from references and scientific pilot studies. Further, there is a creation of a finite element network. It is required to achieve a quality network, carrying out each time the analysis of quality of splitting by the built-in Ansys Structural tool. Then contact conditions which depend on properties of model materials are set. Boundary conditions which have to be sufficient [2] are appointed.

The following stage, task of pressure value for the bone tissue, caused by action of muscles, gravity, environment influence (Fig.3).

Fig.3 Areas of external forces influence

On pictures of the computer tomogram 3D modeling of soft tissue, measurement of their area of sections, orientation in space is carried out. Values of the distributed force on some platform, i.e. values of pressure, are represented through vector decomposition on coordinate axes of local or global coordinates systems.

The last stage, parameters of the stress-strain state of firm biological tissues for calculation get out. The calculated data can be seen in visual graphical representation or in the form of tables, schedules and charts.

3 Results and Discussion

We will review an calculation example of the stress-strain state of a femur by means of system. Pressure values upon bone tissue are presented in Table 1.

Table 1 Values of pressure sizes from muscles on a femur

Name of muscle group	Pressure P_x , MPa	Pressure P_y , MPa	Pressure P_z , MPa
Long sgibatel	0,10966	2,1932	4,3864e-002
Musculus iliopsoas	0	3,4375	0
gluteus maximus	0,43119	1,1642	-0,73302
Long razgibatel	0,53887	1,7064	-0,12574
Abductor	0,16996	1,3153	2,6147e-002
Adductor magnus	6,5399e-002	1,4878	-1,0036
Top part of a person body	1,3134	0,64617	-1,1925
Top part of an endoprosthesis	1,3134	0,64617	-1,1925
Lower part of an endoprosthesis	0	0	1,99

Then parameters of the stress-strain state were calculated. On the basis of the carried-out calculations it is visible that the greatest data of deformation are observed in middle and top part of a head and the top half of a neck of a femur. The maximum stress arises in the lower part of a neck of a bone, and small stress – in top. In the lower part of a bone it is less than cut stress, than in the top part.

On the basis of the analysis of the received result it is possible to draw a conclusion that high stress in the 3rd and 4th segments of a bone at compression is explained by the smaller thickness of a layer in comparison with other segments (Fig. 4). But at a bone bend the maximum stress is observed in the 1st segment where the compact layer is rather thicker [3]. Thus, distribution of stress and strain is explained by an anatomic structure of bone tissue.

Fig.4 Distribution of normal stress in the direction of an axis z of global coordinates system

There are two options of reduction of the equivalent stress and strain arising in a bone at prosthetics: a choice of suitable material of an endoprosthesis and its location in a bone. As a result of comparison of calculations with different endo-

prostheses: steel corrosion-resistant 30×13 and the titan VT1-00, was is noticed that in endoprosthesis model from steel more maximum normal stress σ_1 , σ_2 , σ_3 , than in model from the titan is observed slightly (Table 2).

Table 2 Distribution of normal stress

Endoprosthesis material: steel corrosion-resistant 30×13	Endoprosthesis material: titan VT1-00
Minimum stress σ_1 is equal (-1,5228e+007) Pa (endoprosthesis) Maximum stress σ_1 is equal: (7,8968e+007) Pa (endoprosthesis)	Minimum stress σ_1 is equal: (-1,4962e+007) Pa (4th segment) Maximum stress σ_1 is equal: (4,5584e+007) Pa (endoprosthesis)

Minimum stress σ_2 is equal (-1,1737e+007) Pa (4th segment) Maximum stress σ_2 is equal: (2,8339e+007) Pa (endoprosthesis)	Minimum stress σ_2 is equal (-1,1595e+007) Pa (4th segment) Maximum stress σ_2 is equal: (2,023e+007) Pa (endoprosthesis)

Minimum stress σ_3 is equal (-8,9719e+006) Pa (endoprosthesis) Maximum stress σ_3 is equal: (2,7605e+007) Pa (endoprosthesis)	Minimum stress σ_3 is equal (-9,1395e+006) Pa (5th segment) Maximum stress σ_3 is equal: (2,0685e+007) Pa (endoprosthesis)

It should be considered at an endoprosthesis material choice. At this arrangement of an endoprosthesis the smallest normal stress arises in the 4th and 5th segments of a compact bone tissue, and the smallest values of these parameters for the titan. Also it is necessary to pay attention that the maximum full stains happen in the 4th segment of a femur. The greatest values of tangent stress in the YZ plane τ_1 , τ_2 arise in the 5th segment (Table 3), and they are similar for both cases of an endoprosthesis installation. Having carried out the comparative analysis of the stress-strain state parameters of models, it is possible to draw a conclusion that use of an endoprosthesis from the titan for this patient more rationally.

Table 3 Distribution of tangent stress (YZ plane) τ_2

Endoprosthesis material: steel corrosion-resistant 30×13	Endoprosthesis material: titan VT1-00
Minimum stress is equal (-4,0038e+007) Pa (endoprosthesis) Maximum stress is equal: (6,0294e+006) Pa (5th segment)	Minimum stress is equal: (-2,3265e+007) Pa (endoprosthesis) Maximum stress is equal: (6,1037e+006) Pa (5th segment)

Thus the maximum operating stress arises at an angle 45° to the direction of the applied force, forming a wedge-shaped form (Fig. 5). At an angle 45° at perpendicular loading in relation to a longitudinal axis of a bone the maximum shift stress works.

Fig.5 Distribution of equivalent stress values in the 3rd segment of a compact bone layer at compression along an axis x

The squeezing force on some area, equal $1,7E + 10^7$ Pa, at first perpendicularly, and then in parallel concerning the direction of a longitudinal axis of a femur was attached to a surface of the 3rd segment of a compact bone tissue. Therefore, the endoprosthesis arrangement thus can lead to a change of bone tissue at some kinds of activity of the person.

4 Conclusion

In this way, using calculation systems, there was a possibility to restore anatomically correct structure of the damaged parts of musculoskeletal device and to make functionally stable. The system allows to make changes to geometrical, settlement models of the best results without loss yielded for receiving. Thereby it is possible to fulfill a rational complex of medical actions of diseases of firm biological tissue that will reduce time of patient rehabilitation and will reduce risk of repeated operating.

Acknowledgements. This work was supported by the Tver state medical academy, the Institute of prosthetics and means of rehabilitation of Federal State Budgetary Institution SPb NTSEPR of G. A. Albrecht.

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Received: September 11, 2014; Published: November 3, 2014