Modeling knee joint endoprosthesis mode of deformation

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Abstract. The purpose of the work was to define the efficient design of the endoprosthesis, working in a multiple-cycle loading environment. Methodology and methods: triangulated surfaces of the base contact surfaces of endoprosthesis butt elements have been created using the PowerShape and SolidWorks software functional environment, and the assemblies of the possible combinations of the knee joint prosthetic designs have been prepared. The mode of deformation modeling took place in the multipurpose program complex ANSYS. Results and discussion: as a result of the numerical modeling, the following data were obtained for each of the developed knee joint versions: the distribution fields of absolute (total) and relative deformations; equivalent stress distribution fields; fatigue strength coefficient distribution fields. In the course of the studies, the following efficient design assembly has been established: 1) Ti-Al-V alloy composite femoral component with polymer inserts; 2) ceramic liners of the compound separator; 3) a Ti-Al-V alloy composite tibial component. The fatigue strength coefficient for the femoral component is 4.2; for the femoral component polymer inserts is 1.2; for the ceramic liners of the compound separator is 3.1; for the tibial component is 2.7. This promising endoprosthesis structure is recommended for further design and technological development.

1. Introduction

The most important task in developing various options for the design of the knee joints is to define the distribution of stress and deformation fields in the context of multiple-cycle fatigue effects. Physical modeling of biomechanical behavior of biological objects with actual active loads measurements is not feasible. However, it is possible to solve this problem by applying numerical finite elements modeling using the multipurpose program complex ANSYS.

Motion analysis in any joint requires the use of kinematic data. Kinematics defines the motion range of the structural components and describes the joint surface motion in three planes: frontal (coronary or longitudinal), sagittal and transverse (horizontal). Figure 1 presents the knee joint calculation scheme which employs the following terms and definitions: 1) the anterior-posterior translation (PZ translation): axis translation of the axial force from the flexion/extension axis measured in the direction perpendicular to both axes; 2) anterior-posterior force $F_{PZ}$ is applied to the tibial component along the line of action perpendicular to the tibial axis and to the flexion/extension axis which passes through the axial force axis; (3) axial force $F_{OS}$ is applied to the femoral component of the knee joint endoprosthesis in the direction parallel to the tibia axis. The axial force line of action is shifted so as to pass through a point on the tibial component of a knee joint prosthesis which is offset by 0.07 w $\pm$ 0.01w in medial direction from the tibia axis, where w is the full width of the tibial
component; 4) flexion/extension axis is the nominal rotation axis of the femoral component relative to the tibial component; 5) tibial axis is the nominal longitudinal axis of the tibia corresponding to the central axis of medullary cavity of proximal tibia; (6) tibial rotation is the rotation of the knee-joint prosthesis tibial component around the axial force axis; (7) the moment of tibial rotation $M_t$. This moment is applied to the femoral component of the knee-joint endoprosthesis and operates around the axial force axis.

![Figure 1](image1.png)

**Figure 1.** The knee joint endoprosthesis load pattern: 1 - femoral component flexion 2 - the axis of axial force; 3 - tibial axis

The results of the research of [1-7] and the data presented in [8, 9] provided the basis for defining the functional dependencies of the force characteristics whose graphs are presented in Figure 2.

![Figure 2](image2.png)

**Figure 2.** The moment of action of knee joint maximum load

The purpose of this study is to develop a finite element model for the research of the endoprostheses mode of deformation under the specified loading conditions to determine the efficient design of the knee joint. The following tasks must be sequentially accomplished in mathematical modeling of the knee joint biomechanical behavior: 1. create three-dimensional knee joint elements models and build the assemblies of the investigated options of knee joint design; 2. describe and present the physical and mechanical characteristics of the components of knee joint materials in appropriate form; 3. specify the initial and boundary conditions of the mathematical model.
2. Materials and methods
According to the research plan, a triangulation model of a human skeleton was created on the basis of a patient's computer tomography scans. At the same time a 3D scanning of polyethylene separators (liners) of femoral and tibial components of a foreign analogue of the knee joint prosthesis was performed. Combined with the data of a 3D point cloud obtained from the axial sectioning (tomograms) by reverse engineering methods using the functional environment of PowerShape, the triangulated (faceted, grid) surfaces were created and solid models of the possible designs of knee joint prostheses were prepared. The SolidWorks CAD system software produced assemblies of knee joint of possible combinations of endoprosthesis design. The geometric data conversion was performed and the solid models were refined to the format of the finite element ANSYS complex in the graphics module DesignModeler. Based on the analysis of the work [10-13], the following modes of structure behavior were selected for the finite element simulation: Transient Structural, Static Structural and Explicit Dynamics.

The ANSYS element system provides the possibility of investigating the destruction caused by the multiple cycle fatigue. In general, the endurance calculation was performed by a combined calculation of deformations and stresses. The appropriate models (Alternating Stress Mean Stress and Strain-Life Parameters) were selected in the Life section of the Material Properties window and the fatigue characteristics of the material were set.

The assemblies were imported into ANSYS format after the solid model of the knee joint design had been reprocessed in the graphics module DesignModeler. In the mathematical model tree, each knee joint component (femoral, tibial, or separator) is assigned the corresponding material from the database.

In the Connections section of the knee joint calculation model, the following contact surfaces are normally selected and identified:
1. Stationary Contact (Bonded) - the area of the tibial component and the separator conjugation;
2. Friction/Sliding Contact (Frictional) - the surface of the femoral component and the liner conjugation.

The finite element grid formation (Figure 3) was performed for the following parameters: Finite Element (FE) Method, i.e. combining tetragonal (Tetrahedrons) and hexagonal (Hex Dominant) grids; the size of the finite elements (Element Size) of the model's main volume is 1.4 mm; the size of FE potentially located in the friction contact zone is 0.2 mm; mesh refinement options for the contact area (Inflation): the maximum number of refinement layers is 5, the growth increment (Growth Rate) is 1.2.

![Figure 3. Finite element model of the knee joint endoprosthesis](image)

When assigning restrictions on translation, the Fixed Support option on the Environment panel's subsection Supports was selected and the bottom bearing face of the tibial component was defined (in
calculations without tibia). The bottom bearing face of tibia top element was fixed in case of including the geometric and physical characteristics of the tibia in the calculation model of the knee joint.

Based on the calculation scheme (Figure 1), and taking into account the functional constraints of the rotation angle of the knee joint femoral component as well as the forces and moments of the cycle duration percentage (Figure 2), the anterior-posterior force $F_{PZ}$, the axial force $F_{OS}$ and the moment of tibial rotation $M_{t}$ were sequentially implemented in the Load Description module.

The integral analysis of all functional constraints showed that the maximum force at the knee joint is at the time equal to $\tau = 13$. Figure 2 shows the given point in time with the indicated numerical values of the physical parameters. At this point in time when the femoral component is rotated to 15.310, the axial force $F_{OS} = 2600$ N, the anterior-posterior force $F_{PZ} = 109.62$ N, and the moment of tibia rotation $M_{t} = -0.9033$ Nm.

Since, on average, an adult performs $0.5 \times 10^{6}$ load cycles while walking for one year and the lifetime of modern endoprostheses is 10 years, the knee joint prosthesis must therefore withstand the required load for $10 \times 0.5 \times 10^{6} = 5 \times 10^{6}$ load cycles. Additionally, according to the requirements of the stated project, the life of the product under development must be at least 20 years, and therefore the specified law of change loads within $10^{7}$ load cycles must be applied while modeling fatigue deformation of the knee joint endoprosthesis.

3. Results and discussion
Two schemes for fixing the knee joint have been considered: 1) at the bottom bearing face of the tibial component (Figure 4, a); 2) at the lower bearing face of the solid tibia model section (Figure 4, b). The degree of freedom constraints of the second design model of the knee-joint prosthesis are closer to the real conditions of knee joint functioning. The tibial component of the endoprosthesis must be installed into the pre-prepared cavity of the tibia and fixed with medical cement. The prosthetic component contacts the cortical bone and the spongy bone tissue on virtually the whole plane of the stem. Thus, only this method of knee joint endoprosthesis installment will be used in further modeling scenarios.

![Figure 4](image-url)

Figure 4. Degrees of freedom constraints in the design model of the knee joint endoprosthesis: a - without tibia; b - with tibia.

The proposed change to the base material for the femoral component (replacing the CoCr28Mo6 alloy for Ti-Al-V) does not degrade the strength properties of both the component itself and the endoprosthesis as a whole. Since the research [14-17] stated that the Ti-Al-V alloy has better biocompatibility with the human organism than the CoCr28Mo6 alloy, the change is considered to be justified. Further mathematical models for the metallic matrices of the femoral component will consider and assign only the Ti-Al-V alloy.
The efficient design of the knee joint endoprosthesis (Figure 5) has been defined as a result of the mode of deformation modeling, and the following results have been obtained:

Figure 5. 3D models of the knee joint endoprosthesis (assembly with tibia)

1. Total deformation of the structure: 1.749 mm (Figure 6, a).
2. Equivalent stresses (Figure 6, b) operating
   - in the femoral component: 280 MPa;
   - in the polymer inserts of the femoral component: 24.6 MPa;
   - in the ceramic liners of the compound separator: 152 MPa;
   - in the tibial component: 203 MPa;
3. Fatigue strength coefficient (Figure 6, c):
   - for the femoral component: 4.2;
   - for the femoral component polymer inserts: 1.2;
   - for the ceramic liners of the compound separator: 3.1;
   - tibial component: 2.7.

Figure 6. Numerical simulation results: a - absolute (total) deformation of knee joint endoprosthesis with tibia (deformation of the ceramic liners of a compound separator); b - equivalent stresses for knee joint endoprosthesis with tibia (stress for the knee joint femoral component); c - Coefficient of fatigue strength for the knee joint endoprosthesis with tibia (coefficient values for polymer inserts).
Thus, it follows from the modeling results that the knee joint endoprosthesis shall withstand the load during the required resource of the prosthesis.

4. Conclusion

1. On the basis of an analytical survey of literary sources and theoretical studies, the joint and its components ranges of motion were defined in three planes: frontal (coronal or longitudinal), sagittal and transverse (horizontal). Kinematic and power schemes of knee joint endoprosthesis were received.

2. The mathematical model formation of the knee joint biomechanical behavior was carried out on the basis of a finite element ANSYS complex using a simulation of the material isotropic properties. The preparation of solid models took place in the CAD-complexes of PowerShape and SolidWorks based on triangulation models of human skeleton and the faceted surfaces of polyethylene separator (liner) as well as femoral and tibial components of the joint received in 3D scans.

4. As a result of the numerical modeling, the following data were obtained for each of the developed knee joint versions: the distribution fields of absolute (total) and relative deformations; equivalent stress distribution fields; fatigue strength coefficient distribution fields. The research yielded a promising knee joint design consisting of: 1) a composite femoral component of the Ti-Al-V alloy with polymer inserts; 2) the ceramic liners of the compound separator; 3) a composite tibial component of the Ti-Al-V alloy. In this case, the coefficient of the fatigue strength for the femoral component is 4.2; for the femoral component polymer inserts is 1.2; for the ceramic liners of the compound separator is 3.1; for the tibial component is 2.7.

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