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COMPUTER AIDED DESIGN AND STRUCTURAL ANALYSIS OF THE ENDOPROSTHESIS OF THE KNEE JOINT

Abstract

The paper presents results of the preliminary structural analysis of model of the endoprosthesis of the knee joint. Basics of anatomy and biomechanics of the knee joint were introduced. Based on data from computed tomography, the model of knee joint was constructed. The prototype of the endoprosthesis of the knee joint was designed. After determining physical properties of structural materials, the Finite Elements Analysis of the model was conducted under various load conditions. Finally the results of analysis are presented.

1. INTRODUCTION

The aging population will increase the demand for medical services. From orthopaedics' point of view one of the most frequently performed procedures is knee replacement, or in other words an implantation of specially designed and manufactured endoprosthesis of knee joint to replace structures damaged or destroyed as a result of medical conditions or accidents. The growing demand for this type of treatment leads to the continuous expansion of the queues. The solution to this problem could be the use of modern technology and rapid prototyping in the design process of implants tailored to the individual patient. This could potentially allow to reduce the manufacturing cost of prostheses, shorten the time of surgery and hospitalization and in consequence, allow to carry out more operations.

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2. ELEMENTS OF ANATOMY AND BIOMECHANICS OF HUMAN KNEE

Mechanical function of each joint in the human skeletal system is to enable movement of the bones in the conditions of carrying loads. The knee joint is the largest joint in human body characterized by a complex structure. This joint is a combination of three bones: the femur, tibia and fibula. The joint includes a patella. The knee is the joint that transmits the loads that occur when moving between these elements. Schematic structure of the knee joint is presented in Fig. 1. It consists of femoral-tibial joint, patellofemoral joint and ligament complex [1, 2].

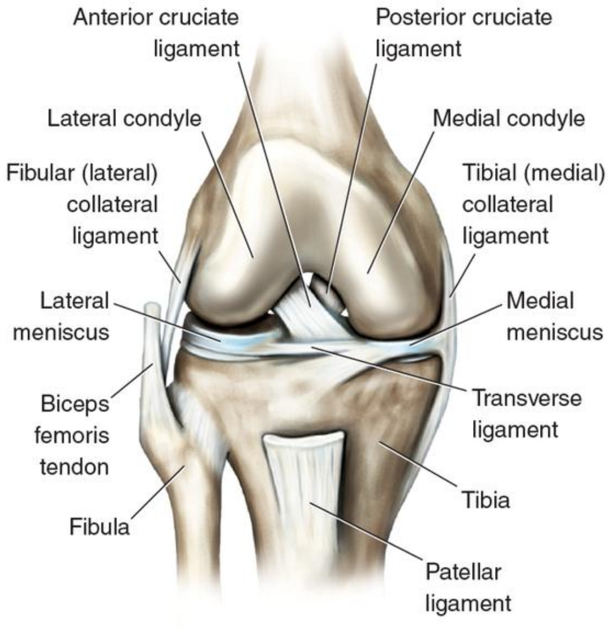

Fig. 1. Human knee in extension [18]

The main element of the knee is the femoral-tibial joint. Acetabulum is formed by two condyles of the tibia (medial and lateral), and further deepened by the meniscus (medial and lateral) [2, 3]. The menisci have very good elastic properties. Their function is mainly shock absorption occurring during the movement and distribution of the pressure over a larger area. The condyles of the femur create the joint heads. Articular cartilage that covers the condyles of the femur and tibia, is to provide lossless sliding motion, and protect the knee against overloads. All the joint surfaces are covered with hyaline cartilage [1, 3].

The movement of bending and straightening the knee joint is held in the sagittal plane. The configuration of the articular surfaces and the range of motion depends on the number of degrees of freedom, as well as loads that occur in the joint. Anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) combine closely the femur and tibia. During the rotation of the bent knee ligaments they wrap around each other. The rotation of the knee joint is possible only when the knee isflexed, this movement is blocked at both the full knee extension and at maximum flexion. The maximum internal rotation is 40° while the external rotation is about 52°. Knee in flexion shown in Figure 2. The maximum possible to obtain range of movement in the knee joint can vary between healthy individuals [2, 3, 4, 5].

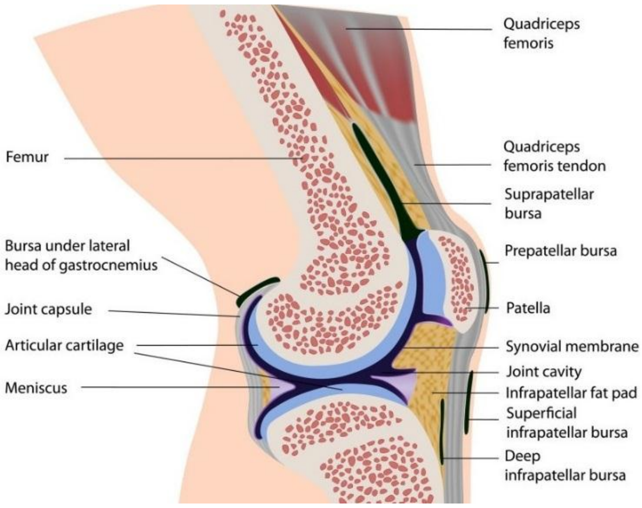

Fig. 2. Human knee in flexion [19]

During full extension the stabilisation of the knee joint is provided primarily by the geometry of the distal femur and the proximal end of the tibia. Stabilisation of the joint in the transverse direction is provided by medial and lateral collateral ligaments.

The knee joint is surrounded by a strong joint capsule, isolating it from the environment and ensuring stabilization. With the provided therein to synovial fluid responsible for the damping and lubricating the entire connection. Synovial bursa is responsible for the production of synovial fluid. The structure of articular cartilage, and synovial fluid properties make the coefficient of friction of the joint at a typical load is 0.0026, and the maximum load value is 0.0038. For comparison, the coefficient of friction two-oiled metal surface is from 0.3 to 0.5 [3, 6].

In the proper functioning of the knee joint an important role plays heterotopic bone – patella. The patella is connected with a joint with a patellar tendon and quadriceps tendon. This bone has a role in stabilising the anterior aspect of the knee joint, and protecting it from the excessive overload. Patella moves during flexion and extension along the surface of the articular patellofemoral joint on the femur. During this movement, only about 25% of the articular surface of the patella is adjacent to the femur [3, 7].

Shape of the articular surface and the structure of ligaments fundamentally define the scope of the characteristics of motion of the joint. The connection between the femur and the tibia is a kinematic pair of Class IV. There is a possibility for the rotational movements in relation to two axis (flexion and rotation), however the rotational movement is blocked in third axis (abduction and adduction) and the translational movement (mainly anteroposterior). The knee joint is mainly adapted to transmit the vertical compressive load [1, 3].

The knee joint is transferred highest stress in comparison to other joints of the human body. The values of these loads are dependent on activity. The internal forces of muscles and external forces have an effect on the knee. An example of an external force may be the force of gravity. Also the important factors include: the weight of the human body, the force occurs in the muscle, and the various angles between the axes of the parts of the body [1, 7].

The dominant scheme of the knee loads is Maqueta model. While standing on both legs knees are loaded about 85% by whole body weight. This is due to the fact that the load does not include the legs below the knees. On the other hand, in the case of standing on one leg joint will be load about 93% of body weight.

Andriacchi said, that he axial load carried by the knee joint during stair climbing or the level walking can be 1,3, while during the run can be twice the weight [8]. According to O. Schipplein, loading of the joint may be five times the value of the weight of a human during a run. In turn, the results of experiment as presented by S. Scott D. Winter show that the knee can be loaded with a force exceeding eleven times the body weight. These are extreme cases and leading to injury, although it illustrates the amount of load that the knee must withstand [9].

3. PROJECT OF THE ENDOPROSTHESIS OF THE KNEE JOINT

To complete the project the advanced engineering software – CAD was used, which led to the creation of three-dimensional elements of the bones of the knee joint on the basis of images obtained from CT and the individual elements of the prosthesis. It also uses software CAE to calculate the strength of the endoprosthesis. The following programs were used during production: Materialise Mimics, Solid Edge and Solidworks.

The first step in creating models of the bone is to generate the mask by selecting the tissue using the Hounsfield scale, within the lower 120 and upper 3.071. Then, the mask created would be trimmed using the Crop tool Mask to cover the bones comprising the knee joint. This process is carried out in several stages in order to generate the most accurate model of the bones. This step consisted of generating a three-dimensional model resulting from the trimmed mask, with the help of tool – Generate 3D model. The models obtained in this manner require considerable refinement by supplementing the missing parts of the surface. The final effect of this process is presented in Fig. 3.

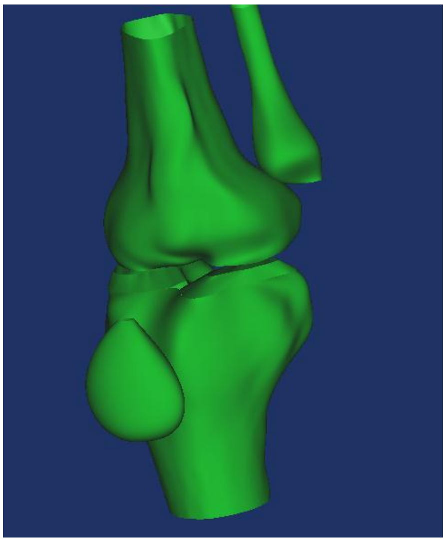

Fig. 3. Surface models of all the bones of the knee [source: own study]

Created three-dimensional model was then exported to the .igs file. This file format allows to open it in a program such as Solidworks and to perform the stress analysis.

Prepared in this way models were used to design the knee endoprosthesis used for knee replacement. It is important that all the dimensions of the bones and the distance between them have been preserved. This has a major impact on the process of designing the prosthesis closely matched to the patient. Motion of the prosthesis is based on literature data contained in U.S. Patent [10, 11, 12, 13, 14]. The model was created in SolidWorks.

As a final product the model consisting of four elements was created: base metal placed on the tibia, femoral component attached to the femur, the polyethylene liner attached to a metal base and in contact with the femoral component and a part on the kneecap, which is also made of polyethylene to protect it.

After designing the individual elements knee endoprosthesis and the preparation of models of bones respectively, full product was created and is presented in Fig. 4.

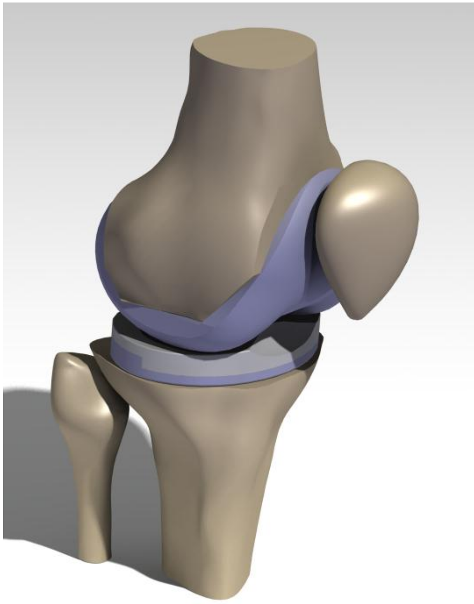

Fig.4. Assembly including bones of the knee joint merged with the endoprosthesis [source: own study]

The final stage of the design was to make the material strength of numerical simulations designed implant components.Below are presented the analysis of the strength of components of prosthesis used in study. In this paper, the polyethylene component uses high density polyethylene UHMWPE 1000 produced by "Zatorski" [7]. Table 1 presents selected physico-chemical properties of the material.

Tab. 1. Physico-chemical properties of the UHMWPE 1000 [7]

Properties	Unit	Value
Density	g/cm^3	0.93
Stress at break	MPa	>18
Elongation at break	%	17
Flexural strength	MPa	>700
Impact strength	kJ/m^2	Does not crack
SHORE hardness	–	63
Friction coefficient	μ	0.19
Grindability	μ/km	0.45

Biomaterial selected for strength calculations of base metal placed on the tibia and femoral component was cobalt alloy Co/28Cr/6Mo. Table 2 presents mechanical properties of this material.

Tab. 2. Mechanical properties of the Co/28Cr/6Mo [7]

Properties	**Unit**	**Value**
Young's modulus	GPa	235–247
Poisson's ratio	–	0.293–0.308
Elastic limit	MPa	760–839
Tensile strength	MPa	1290–1420
Compressive strength	MPa	760–839
Flexural strength	MPa	683–916
Elongation	%	25–29
Vickers hardness	HV	363–402
Rockwell hardness	–	37.1–41
Fatigue strength (10^7 cycles)	MPa	342–378
Density	kg/m^3	8190–8360

4. STUDY ON STRESS DISTRIBUTIONIN THE ENDOPROSTHESIS

The designed model was used to perform a series of preliminary studies including the stress distribution in the knee endoprosthesis with the use of Finite Element Analysis method. The performed studies are foundation for defining parameters for further exploitation of the prosthesis.

4.1. Software used in the study

Materialise Mimics is software specifically developed for medical image processing. It is used for the segmentation of 3D medical images, resulting in highly accurate 3D models of patient’s anatomy. These patient-specific models can be implemented in a variety of engineering applications directly in Materialise Mimics or Materialise 3-matic, or exported to 3D models and anatomical landmark points to 3rd party software, like statistical, CAD, or FEA packages [15].

Solid Edge is a 3D CAD, parametric feature and synchronous technology solid modelling software. It runs on Microsoft Windows and provides solid modelling, assembly modelling and 2D orthographic view functionality for mechanical designers. Through third party applications it has links to many other Product Lifecycle Management technologies [16, 17].

Implementation of two highly-efficient graphic modellers – Parasolid and D-Cubed that allows combining direct modelling with precise control of geometry and gives engineers opportunity to conduct the designing process with speed and simplicity on a level, that has never been seen before.

Studies were performer in the environment of Abaqus software. Abaqus is the advance CAE engineering tool. Its use is mainly the analysis of systems, using the finite elements method (FEM). In the industry, this program is used to resolve issues related to the mechanics of solids and fluids, on the strength of machines and structures, taking into account many factors such as load, temperature, electrical conductivity, etc. [7]. In this work, the Abaqus was used to analyze strength designed knee prosthesis.

4.2. Methodology of studies

After preparing the data for the program are generated Abaqus finite element mesh polygons. The last step is to create a model preparation Mesh on each part. The last step is to create a model preparation Mesh on each part.

Analyses were performed for a person weighing 70 kg. To the analysis were assumed force F=3000N. After these operations have been carried out numerical calculations of deformations and displacements of investigated objects. The study included the analysis properly implanted prosthesis and the case in which there is contact in only one condyle and a acetabulum (lift-off).The second case this may, in fact, however, observed it is extremely rare.

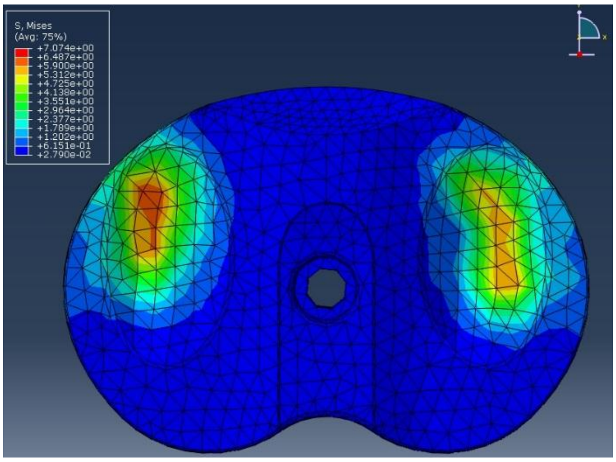

Fig. 5. Reduced stress of polyethylene pad [source: own study]

Maximum equivalent stresses occurring on the polyethylene insert amount 7MPa.While the value of contact stresses is 15MPa. Reduced stress of polyethylene pad is presented in Fig. 5.

Value of contact stresses on femoral component is 14 MPa. Equivalent stresses have not changed. Reduced stress of femoral component are presented in Fig. 6.

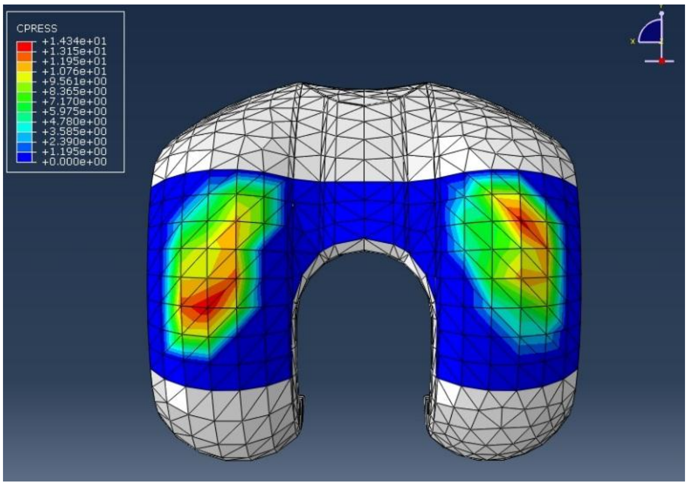

Fig. 6. Pressures established on the femur of the model [source: own study]

Reduced stress and pressure does not exceed the limit values. Therefore, this model was tested for contact in only one condyle and one of the acetabulum (lift-off). Arrangement of the elements themselves in this case is shown in Fig. 7.

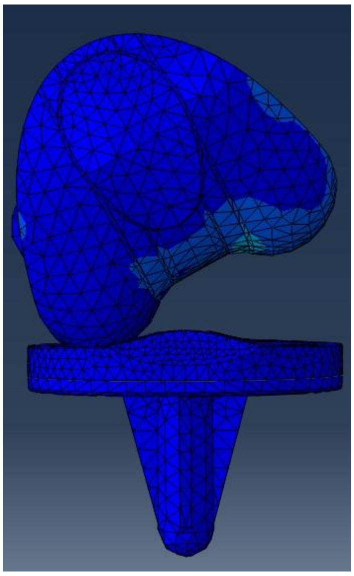

Fig. 7. The case where only one condyle in contact with the acetabulum (lift-off) [source: own study]

Reduced maximum stress occurring in a metal pad are 45MPa. Pressures up to 75 MPa while. Reduced stress of femoral component are presented in Fig.8.
In the case of the femoral pressures are 27 MPa. Reduced stress of femoral component is presented in Fig. 9.Equivalent stresses occurring on a polyethylene pad amount in this case up to 16,7 MPa. Their value is doubled compared to the model, which contacts both the knuckles. While pressures are 29 MPa.

In the case that the prosthesis are in contact only one condyle and the acetabulum, the model will be probably damaged. The reduction of the contact surface causes a significant increase of the stresses and pressures. Our case lift-off was to check whether the model created can cope with such a load with limited contact. In fact, this case exists, but the forces on the prosthesis are much smaller.

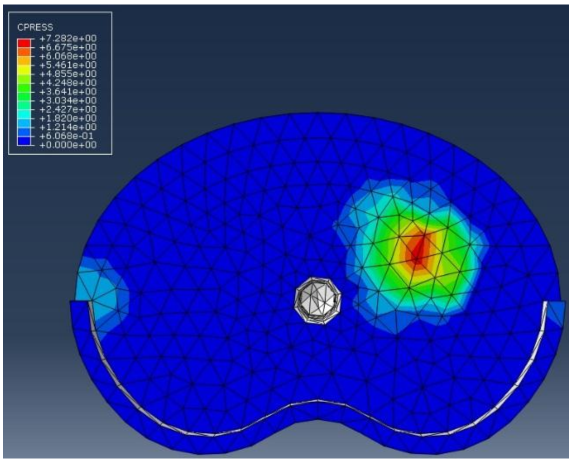

Fig. 8. The pressures occurring for lift-off on a pad metal [source: own study]

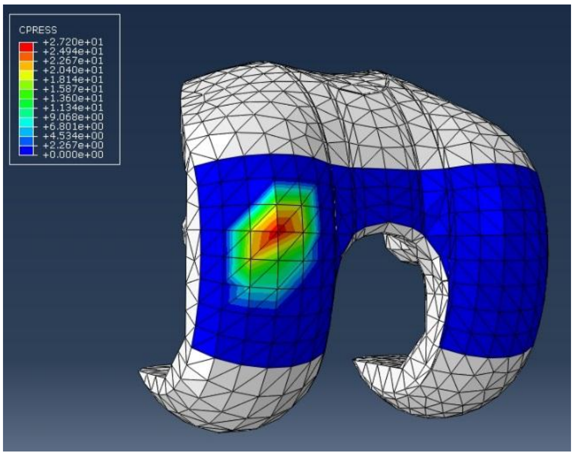

Fig. 9. Distribution of pressure on the femoral component for the case lift-off [source: own study]

5. CONCLUSIONS

Modern medicine allows the exchange of the damaged structures of the human body element artificially produced. Such procedures is due the amazing progress of science, technology and medicine.

Creating a prosthesis model for this study consisted of four main stages. The first step was to create a three-dimensional solid models of bones of the knee joint based on images from CT. For this we used Materialise MIMICS software to create surface models of the bones. Then, these models were finished and set up a full assembling of the knee using SolidWorks and Solid Edge software.

Static analysis of properly implanted prosthesis has shown that reduced stress and the pressure does not exceed the limit values. The weakest element of the model was a polyethylene liner. This is of course related to the biomaterial used in its preparation.

Analysis where only one condyle in contact with the acetabulum indicated that the reduced stress and pressure exceeds the limit values. This may be caused the fact that used considerable force, which rarely occur in properly functioning joint. In such a case it may have been damaged bone, and not part of the prosthesis.

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