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THE DESIGN AND STRUCTURAL ANALYSIS OF THE ENDOPROSTHESIS OF THE HIP JOINT

Abstract

The paper presents results of the preliminary structural analysis of model of the endoprosthesis of the hip joint. Basics of anatomy and biomechanical analysis of the hip joint were introduced. Based on data from atlas of human anatomy and medical imaging, the prototype of endoprosthesis was modelled using Solid Edge ST8 software. After determining physical properties of structural materials, the Finite Elements Analysis of the model was conducted using in SolidWorks software under various load conditions. Finally the results of analysis are presented.

1. INTRODUCTION

For many years a phenomenon called population ageing, linked with continuing low or negative population growth rate, is being observed. The most tangible repercussion is growing demand for medical services dedicated for elder. From orthopedics' point of view one of the most frequently performed procedures is hip replacement, or in other words an implantation of specially designed and manufactured endoprosthesis of hip joint to replace structures damaged or destroyed as a result of medical conditions or accidents.

Due to complicated structure and biomechanical properties of the hip joint it is necessary to maintain the best fitting possible to preserve functionality of the joint and assure comfort of the patient. Thanks to major breakthroughs

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and constant development in the field of medical imaging (mostly computed tomography and magnetic resonance imaging)it is possible to obtain more and more precise data on the anatomical structure of the hip joint. The analysis of that data is crucial in the process of building biomechanical models of the joint. All of the above mentioned information along with data on the structure of the human skeleton become the basis for the process of endoprosthesisdesigning. During the implantation they also have a huge influence on planning and performing a surgery.

2. HIP JOINT BIOMECHANICS

A hip joint is an example of a ball-and-socket joint, which is distinguished by a wide range of possible moves. In the human locomotor system it is one of the most exploited synovial joints, hence it is at greater risk of degenerative changes. The hip joint contains following structures: the pelvic bone, whose unate surface of acetabulum (or a cotycoloid cavity) creates an articular surface, the femur (or thighbone)with the head located on the articular surface and the joint capsule surrounding mentioned structures, filled with synovial fluid to reduce friction. Additional elements are very strong ligaments that suppress excessive movement around the joint [1,2].

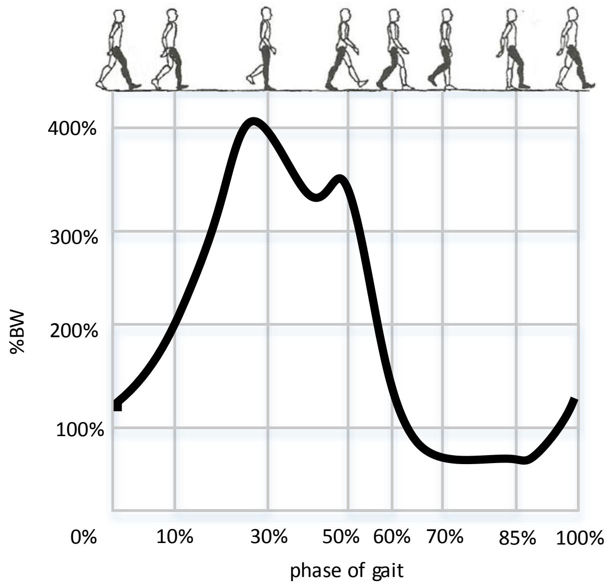

Fig. 1. Percentile contribution of body weight (%BW) in loads carried by the hip joint [1]

The hip joint carries static and dynamic loads, results of the body weight, forces from muscles in fluencing the joint and the gravity force. To maintain effective way of defining the load, the %BW unit (percent of body weight [N]) is used to describe forces of before mentioned reactions. Maximal forces influencing the hip joint are measured using instrumented hip implants with telemetric data transmission. Depending on used methods and a specificity of study forces values are between 369%BW and 400%BW [5,6]. Angles, directions and values of vectors representing forces that influence the joint are changing depending on a function and a phase of a gait (Fig. 1) or an activity currently performed (bend/snap, abduction/adduction, rotational moves).

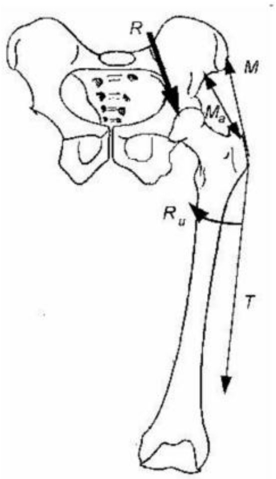

Fig. 2. The active model of loads in the hip joint [1]

During studies on properties of forces influencing the joint assumption is made, that while standing on both legs, the body weight is distributed equally on both limbs. In case of standing on a single leg, the force of reaction in fluencing the articular surface depends also (among other things) on the force generated by abductor muscles, which are required to maintain balance of the body (Fig. 2). However, the exact assessment of directions and values of all important forces is almost impossible, so while creating biomechanical models of hip joint it is essential to apply major simplifications [1,2,3,4].

3. THE DESIGN OF THE ENDOPROSTHESIS OF THE HIP JOINT

For the purposes of studies the design and virtual prototype of the bipolar endoprosthesis of the hip joint was created. The model consists of prosthetic shaft inserted into properly prepared thigh bone of a patient, removable head, prosthetic socket and socket inlay, both spherically-shaped (Fig. 3).Elements of the prototype were designed and assembled in Solid Edge ST8, using sequence modeling tools. Implementation of two highly-efficient graphic modelers – Parasolid and D-Cubed allows combining direct modeling 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.

Fig. 3. The model of the endoprosthesis of the hip joint (extruded view) [source: own study]

The structure of the shaft is based on the thigh bone, maintaining the value of an 125°angle measured between the body and the neck of the bone. It is shaped as a 122,5 mm nog (measured from the top of before mentioned angle to the shaft end)tapering in distal direction. The total length of the neck is 46 mm. The head in the shape of 30 mm diameter orb is mounted on octangular profile of the shaft's head, that fixes the head and prevents its rotation around the neck. Internal diameter of the socket in lay equals the diameter of the head, meanwhile external diameter is 40 mm. To stop slipping out the socket inlay out of the prosthetic socket, protrusions are designed on its external surface that match indentations on internal surface of prosthetic socket. The 50 mm internal diameter matches the diameter of the external diameter of the socket inlay [7,8].
The prosthetic socket and socket in lay are placed on the properly prepared (drilling) cotycoloid cavityof the pelvic bone, which is the articular surface for the hip joint (Fig. 4). In choosing a place of mounting and determining above mentioned dimensions, data obtained from the atlas of the human anatomy [9] and X-ray images of the structure available in Webdatabase[10] were used.

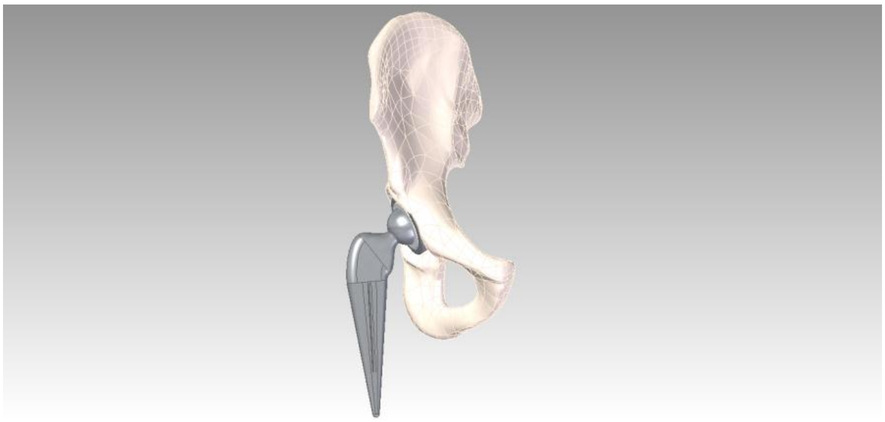

Fig. 4. The pelvic bone with mounted endoprosthesis of the hip joint (front view) [source: own study]

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 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. FEA method

Finite Element Analysis is one of basic methods of conducting a computer aided engineering calculations. It is one of the techniques of discretization of geometric systems, i.e. dividing a continuum into a finite amount of subareas.

Main principle of FEA is to divide geometric model into finite elements uniting in nodes, what creates the discrete geometric model, split in simply shaped subareas, called the finite elements. During FEM calculations other physical quantities are also being discretized: loads, tensions, restraints or other examples represented in the system with the use of continuous function. While performing the process of discretization software aims at maximally approximation of discreet and continuous form using approximation methods. After converting the data analysis follows, consisting in uniting individual elements as a whole using equilibrium conditions and displacement compatibilities. It results in receiving a set of algebraic, simultaneous equations – the mathematical description of analyzed problem. The equations are solved using the equilibrium conditions and their outcome used to compute sought quantities, i.e. tensions[11,12,13].

4.2. Methodology of studies

Studies were performer in SolidWorks Simulation software. The tool is often used as for conducting analysis for design teams. Its main advantage is the cost, much lower in comparison to any other FEA software. SolidWorks allows user to check a product for faults before manufacturing, which helps avoiding mistakes in early phase of designing process. In order to achieve credible results, materials (of which the element will be manufactured) were assigned to each element. Properties of materials are presented in Table 1.

Tab. 1. Table of materials [3,14,15]

Material	Element	Young's modulus [MPa]	Poisson's ratio
Titanium alloy ProtasulTi	Prosthetic socket	110000	0.3
Titanium alloy Protasul 100	Shaft, head	100000	0.3
Cortical bone	Pelvic bone	17000	0.3
Polyethylene	Socket inlay	1000	0.4

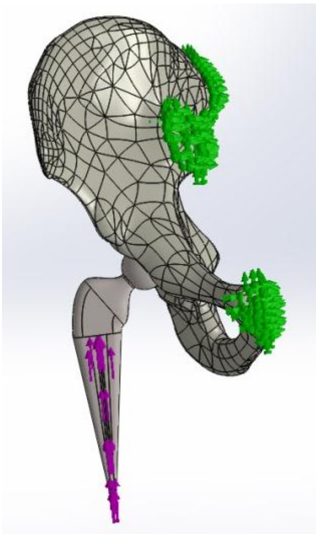

Fig. 5. Places offixing of the pelvic bone (green)and application of force (violet)

In order to receive correct results it was crucial to properly fix the model. For maintaining the best coherence with anatomical structure, the pelvic bone was fixed in the pubic symphisis and the sacroiliac (fig. 5).

In next step, the force was applied to the shaft of the endoprosthesis with value matching the value of the body weight (in N)during performing different activities [1]. In performed studies the value of the human body weight was set on 980 N, which was then assumed as 100% of body weight(%BW). Examination was conducted for reaction forces: 100 to 500%BW.Results of the analysis are presented in Table 2 and Figure6.

Tab. 2. Maximal calculated stress for tested %BW [source: own study]

%BW	Maximal stress [MPa]
100	940
150	1464
200	2031
250	2646
300	3318
350	4056
400	4876
450	5799
500	6863

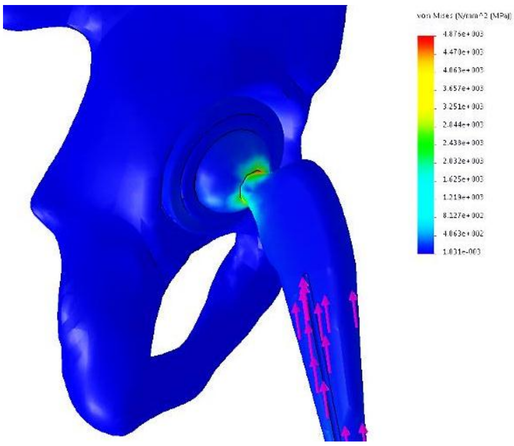

Fig. 6. Stress distribution for 400%BW [source: own study]

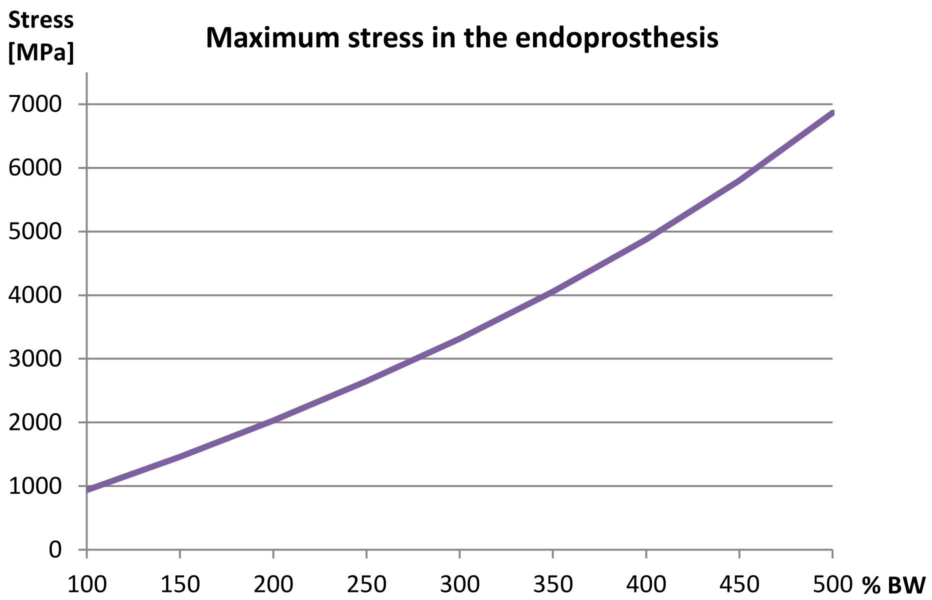

Fig. 7. The relation between stress in the endoprosthesis and%BW used as load in FEA [source: own study]

5. CONCLUSIONS

The unique structure of the hip endoprosthesis results in maximum stress accumulation in the neck of the endoprosthesis' shaft. Values of mentioned stress increase approximately linearly in relations to increasing force affecting the endoprosthesis. Observed phenomenon may pose as a starting point for a thesis, that the neck of the endoprosthesis' shaft is most probable location fora mechanical damage in situation of extremal load.

Modern IT technology, designing and development of biomaterial engineering can support the work of physicians (especially surgeons), because of the opportunity they create in carefully planning the course of procedures, reducing time of given procedure. Another advantage of mentioned techniques is the possibility of determining mechanical properties and a durability of implants already in designing phase.

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