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Structural Analysis of the Pelvic Girdle before and after Hip Replacement Procedure

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Abstract. The paper presents results of a preliminary study on a structural analysis of the pelvic girdle, comparing results for the analysis performed before and after the hip replacement procedure with taking into account changes in the mechanical properties of the articular cartilage of the joint. Basic anatomy and biomechanics of the hip joint is introduced. The mechanical analysis of the hip joint model is conducted in each case. Final results of the analysis are presented. The numerical model of the tested objects has been made on the basis of CT and CAD modeling. Hip bone models have been made using specialist software such as Materialise Mimics. The model made in the program has been exported to a data exchange file in order to obtain the editable CAD files. Thus the obtained models have become a starting point for implementation of the numerical model of personalized hip replacement. Numerical models of bone and implant have been performed in Solidworks environment. Mechanical analysis has been carried out while using a finite element analysis. During performing calculations with the help of the finite element analysis other physical quantities such as loads, tensions, restraints or other examples representted in the system while using continuous function have also been discretized. While performing the process of discretization software has been aimed at maximally approximation of discreet and continuous form using approximation methods.

Keywords: hip joint, pelvic, femur, endoprosthesis, finite element analysis

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Структурный анализ таза до и после процедуры замены тазобедренного сустава

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Реферат. В статье представлены результаты предварительного исследования структурного анализа тазового пояса, сравниваются результаты анализа, проведенного до и после процедуры замены тазобедренного сустава, с учетом

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изменений механических свойств суставного хряща. Вводится базовая анатомия и биомеханика тазобедренного сустава. В каждом случае проводится механический анализ модели тазобедренного сустава. Приводятся окончательные результаты анализа. Численная модель испытуемых объектов сделана на основе компьютерной томографии и CAD-моделирования, модели костного мозга выполнены с использованием специализированного программного обеспечения Materialise Mimics. Модель, сделанная в программе, затем экспортировалась в файл обмена данными, чтобы получить редактируемые файлы CAD. Таким образом, полученные модели стали отправной точкой для внедрения численной модели персонализированной замены тазобедренного сустава. Численные модели кости и имплантата были выполнены в среде SolidWorks. Механический анализ проводился с использованием метода конечных элементов. Во время выполнения расчетов с использованием МКЭ-анализа также дискретируются другие физические величины – нагрузки, напряжения, ограничения, представленные в системе с использованием непрерывной функции. При выполнении процесса дискретизации программное обеспечение нацелено на максимальное сближение дискретной и континуальной моделей с использованием методов аппроксимации.

Ключевые слова: тазобедренный сустав, таз, бедро, эндопротез, МКЭ-анализ

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Introduction

For many years a phenomenon called population ageing, linked with continuing low or negateve population growth rate, is being observed. The most tangible repercussion is growing demand for medical services dedicated for elder people. From orthopedics' point of view one of the most frequently performed operations is total hip replacement – the implantation of purposely designed and manufactured prosthesis of the hip joint, replacing structures damaged or destroyed as a result of various accidents or medical conditions.

Anatomy of the hip joint

A joint (or articulation) is a location of contact and movement of bones. A hip joint is a connection between femur and pelvis, with three degrees of freedom in three planes – coronal, median and axial [1]. Its articular surfaces have got the most regular shape compared to other joints in human body [1, 2].

The pelvic skeleton is formed by a pair of hip bones and the sacrum, connecting the pelvis with the spine. Right side of the pelvic skeleton is shown on fig. 1. The hip bone consists of the ilium, ischium, and the pubis, which combined form the cotyloid cavity of the hip joint (or the acetabulum) [2–7].

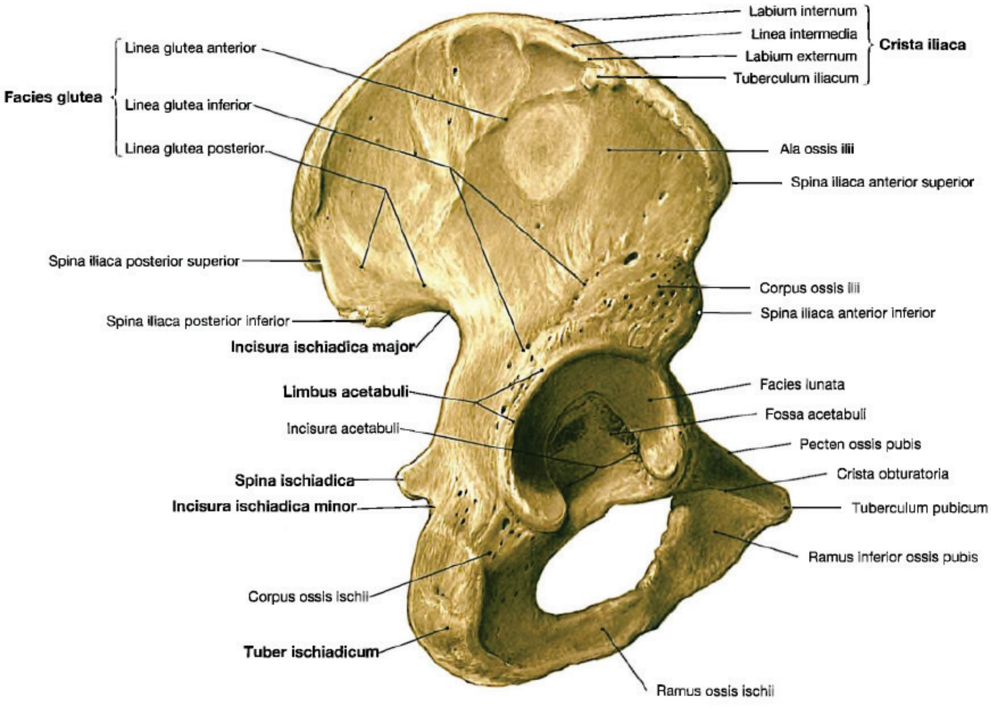

Fig. 1. The pelvic skeleton – right side [5]

The femur consists of the proximal extremity, the shaft and the distal extremity. The proximal extremity bears a large, medialward-directed head that fits into the acetabulum of the pelvic bone. Its size usually depends on gender and with an exception of the fovea capitis femoris, which gives attachment to the ligament of head of femur, is coated with cartilage. The proximal extremity of the femur is shown on fig. 2.

Articular cartilage has an important role in the human musculoskeletal system. It is located on surfaces of joints, where most of the movement of the bones is executed. Cartilage transfers and spreads loads between bones, while preserving appropriate stress distribution on a surface of the joint, reduces friction, absorbs sudden overstrains and protects bones from surface wear. Fully developed cartilage does not contain blood vessels or nerves [6–9].

The articular capsule of the hip joint is strong, dense and after the capsule of the knee joint, the biggest joint capsule in the human body. The capsule, along with the system of ligaments connecting bones and limiting the joint's mobility, is shown on fig. 3 [3, 6, 7].

The anatomy of the hip joint is further discussed by Karpiński et al. in [9].

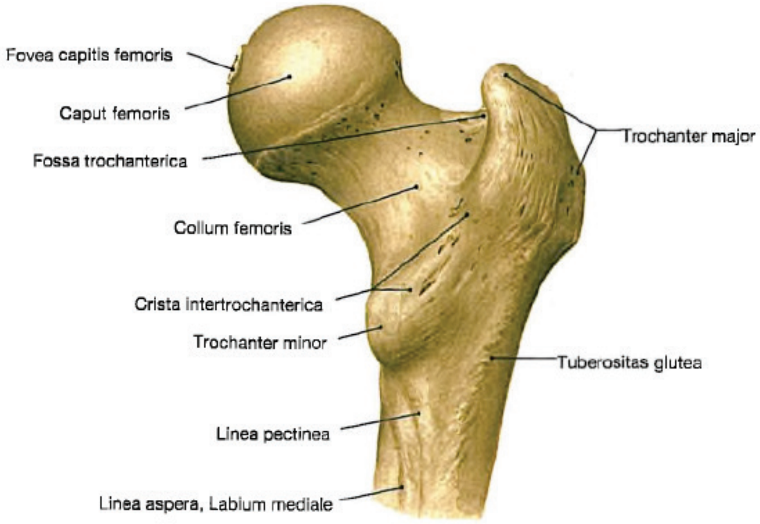

Fig. 2. The proximal extremity of right femur [5]

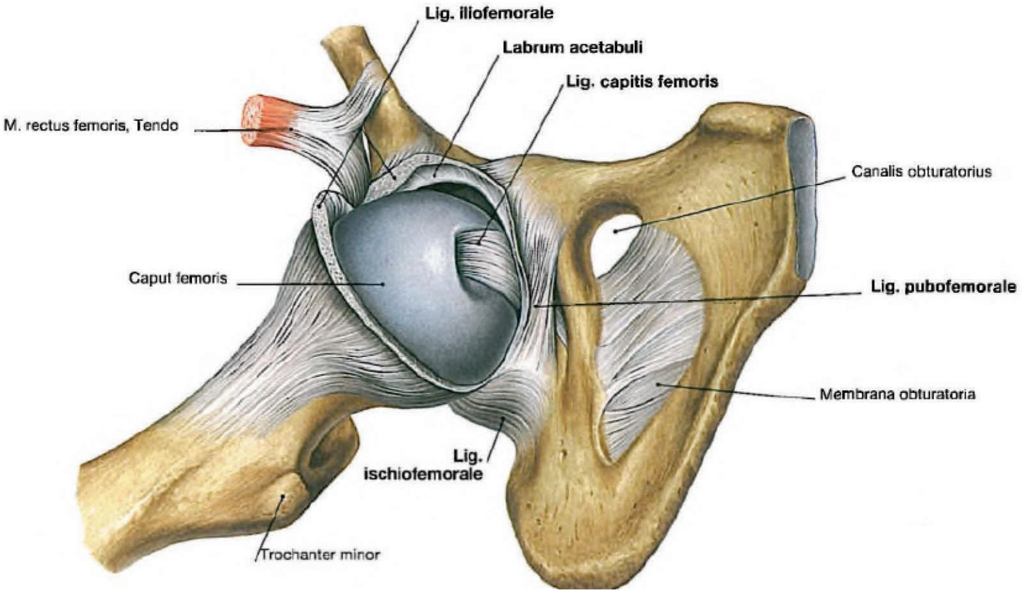

Fig. 3. The system of ligaments with dissected iliofemoral ligament [5]

Biomechanics of the hip joint

The hip joint is one of the most vulnerable to overstraining and degenerations structures in human body. It plays the crucial part in locomotion activities and carrying the loads [1, 6, 7, 10]. The range of movements in the hip joint is shown on fig. 4. These movements are limited by strong ligaments and deep articular cavity. Thanks to the structure of bone tissue and cartilage along with strong muscles and ligaments, it is exquisitely suited for the purpose of transmission of dynamic loads [6, 10].

The biomechanics of the hip joint is further discussed by Karpiński et al. in [9].

Osteoarthritis

Osteoarthritisis a group of various diseases, which despite of having different origin, lead to similar biological, morphological and clinical effects. It can affect the whole joint, mainly the cartilage (in form of chondromalacia). Osteoarthritis is one of the most frequently-occurring pathologies of the locomotion system, especially with elder people. It is often caused by biological and mechanical occurrences, which disturb the process of tissue synthesis and lead to degeneration of said tissues, both in chondrocytes and extracellular matrix as well as in subchondrial part of the bone [9, 11].

Alloplasty of the hip joint

Alloplasty of the hip joints about implantation of elements to the human organism, acting as a substitute for damaged parts of the joint, which leads to restoration of natural functions to these anatomical structures. Farther, the replacement procedure eliminates pathological changes and reduces pain, as well as recreates natural functions of the hip.

Joint replacement procedures, besides having a vast amount and range of endoprosthesis and instrumentarium, require excellent theoretical and practical background of the operating staff as well as operator's great experience. Outcome of the treatment depends on a choice of the implant, precision during operation, patient's age and cooperation in rehabilitation process, and bone tissue's capacity of distributing loads in a proximity of the prosthesis [6, 11, 12].

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 made, with such parts as prosthetic shaft inserted into properly prepared thigh bone of a patient, removable head, prosthetic socket and socket inlay, both spherically-shaped (fig. 5). Elements of the prototype designed, and then assembled in the environment of Solid Edge ST8 software, with the use of sequence modeling tools.

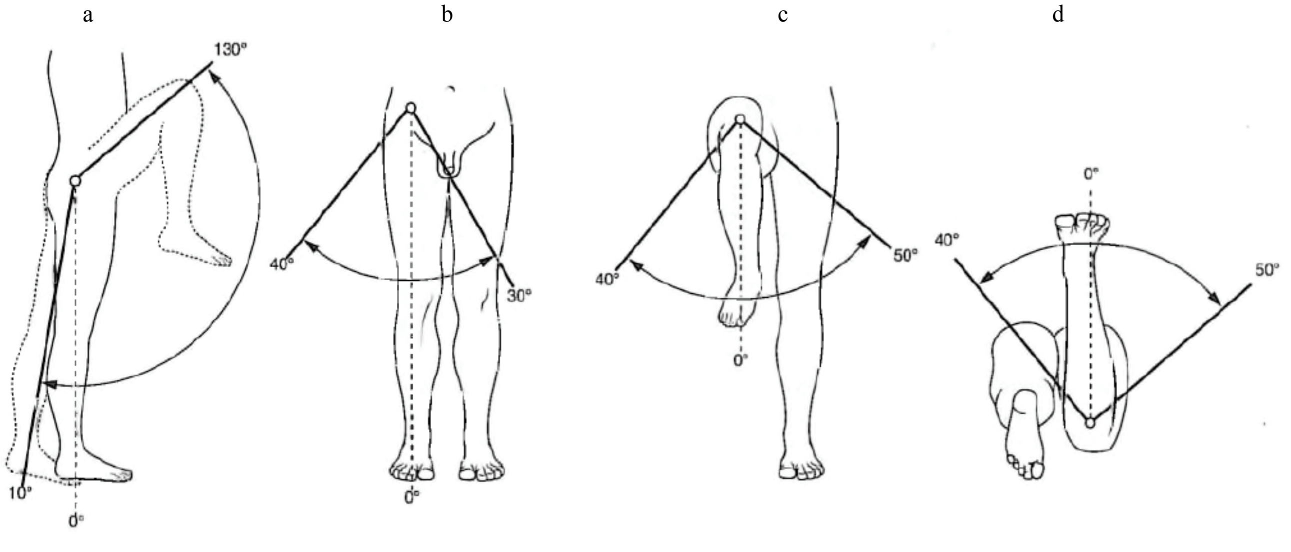

Fig. 4. The range of movements in the hip joint: a – flexion – extension: 10°–0°–130°; b – abduction – adduction: 40°–0°–30°; c, d – lateral rotation – medial rotation: 50°–0°–40° [5]

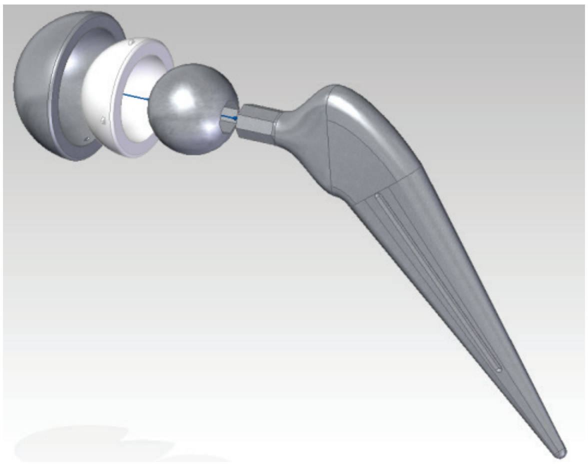

Fig. 5. The model of the endoprosthesis
of the hip joint (extruded view) [source: own study]

The structure of the shaft follows the example of the thigh bone, maintaining the value of an angle measured between the body and the neck of the bone, with the value of 125°. It is nog-shaped, tapering in distal direction with 122.5 mm in lenght (measured from the top of said angle to the end of the shaft), the length of the neck is meanwhile set at 46 mm.

The head in the shape of an orb with 30 mm diameter is mounted on octangular profile of the shaft's head, which makes the head unable to rotate around the neck. Internal diameter of the socket inlay equals the diameter of the head, meanwhile external diameter equals 40 mm. To prevent the socket inlay from slipping out of the prosthetic socket, protrusions are constructed on its external surface matching indentations on internal surface of prosthetic socket, which internal diameter matches the diameter of the external diameter of the socket inlay, with the value of external diameter set on 50 mm.

The prosthetic socket and socket inlay are placed on the properly prepared (via drilling) cotyloid cavity of the pelvic bone, being the articular surface for the hip joint (fig. 6). Both in choosing a place of mounting and in case of determining dimensions mentioned above, informations were distilled from the atlas of the human anatomy [6] and X-ray images of the structure available in on-line database.

Finite element analysis

Finite element analysis (FEA) 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.

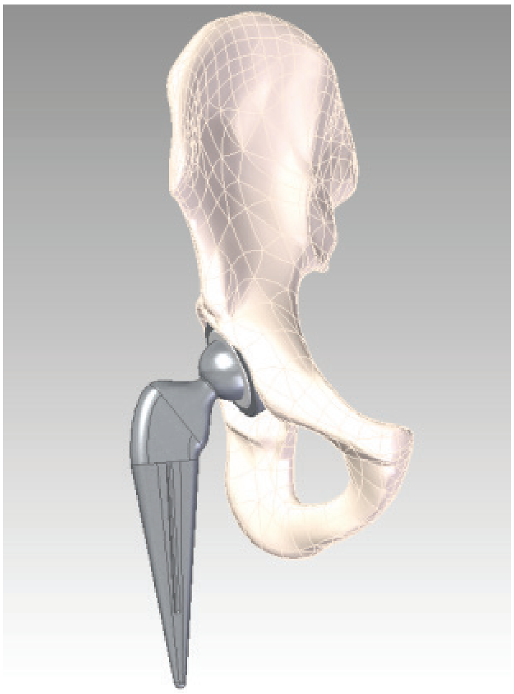

Fig. 6. The pelvic bone with mounted endoprosthesis
of the hip joint (front view) [source: own study]

Main principle of FEA is to divide geometric model into finite elements uniting in nodes, which effects in creating discrete geometric model, split in simply shaped subareas, called the finite elements. During performing of calculations with the use of FEA 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 of the data analysis follows, consisting in uniting individual elements as a whole using equilibrium conditions and displacement compatibilities, which results in receiving a set of algebraic, simultaneous equations, posing as mathematical description of analyzed problem. Afterwards mentioned equations are being solved using values of equilibrium conditions, and their outcome used to compute sought quantities, i. e. tensions. [13–16].

Study of stress distribution in the pelvic bone before and after the procedure of hip replacement

Given model was used to perform a series of preliminary studies with the use of finite element analysis method in the environment of Solidworks Simulation software.

The fixing and loading of model are shown at fig. 7. During preparatory phase it was crucial to fix the model (fig. 7 – green), in order to achieve a stiffness of designed system approximate to the stiffness of the pelvic girdle resulting from its anatomical structure and a connection with the spine in particular. Next, places of force application were established, simulating effects of daily activities performed by the patient.

Before hip replacement, the force was applied perpendicularly to the longitudinal axis of the femur bone (fig. 7 – violet), and after the procedure – on the surface of the endoprosthesis' shaft (fig. 7 – brown). Values of forces have been linked with the equivalent of body weight of the patient, initially being equal to 80 kg or 784.8 N, which comprised 100 % of body weight (% BW). Following values were equal to 150 and 200 % BW. Moreover, the factor of cartilage presence was considered to determine its impact on the stress distribution and deformations in the pelvic bone before the replacement procedure.

In order to achieve credible results, materials (of which the element would be made) were assigned to each element with properties presented in tab. 1.

Table 1

Table of materials [5, 6, 17, 18]

Material	Element	Young's modulus, MPa	Poisson's ratio [–]
Titanium alloy Ti-6Al-4V	Prosthetic socket, shaft, head	104800.31	0.31
Cortical bone	Pelvic bone	17400	0.39
	Femur bone	17600	0.30
Polyethylene PE-HD	Socket inlay	1000	0.40
Cartilage	Hip joint articular surface	122	0.35

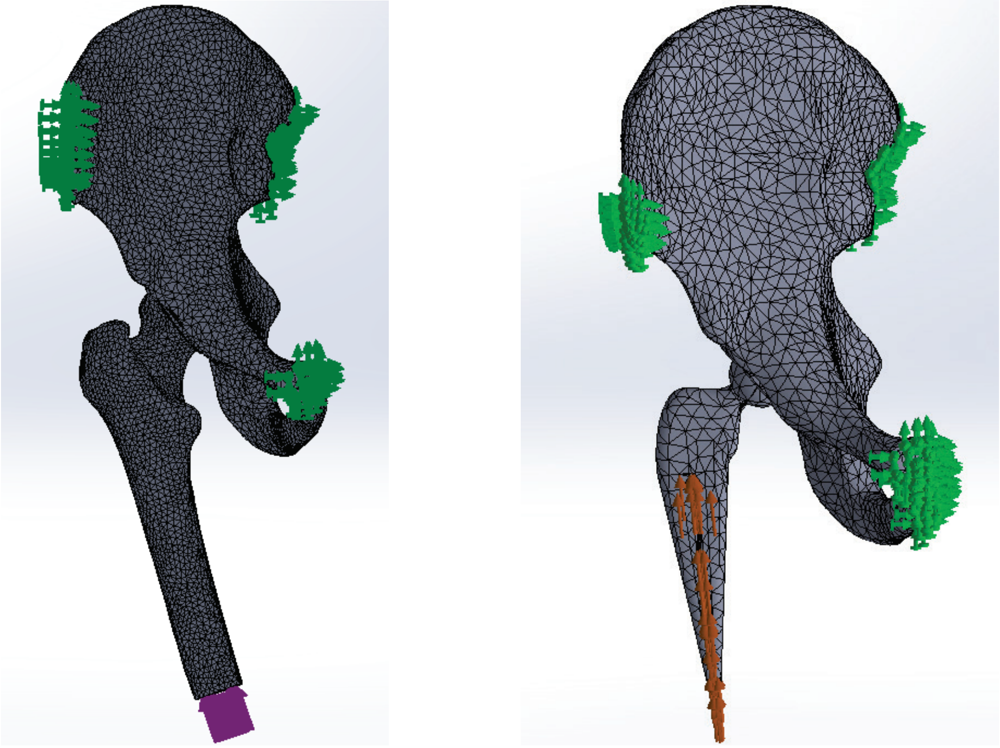

Fig. 7. The model before (left) and after (right) hip replacement procedure

The calculated stress distribution in neck of the natural femur bone and endoprosthesis in hip joint area are shown at fig. 8 and 9. The values of stresses given at tab. 2 and 3 allow to evaluate the presence and condition of cartilage on the stress.

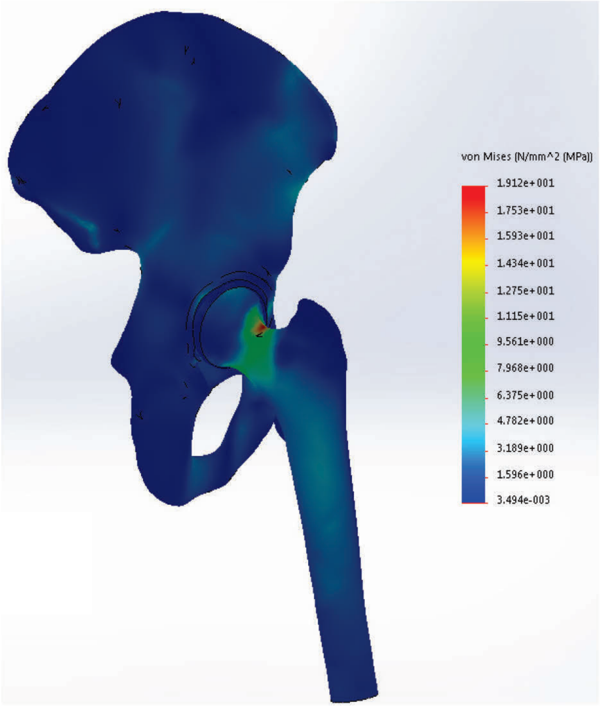

Fig. 8. Visualization of stress distribution in the model of the hip joint

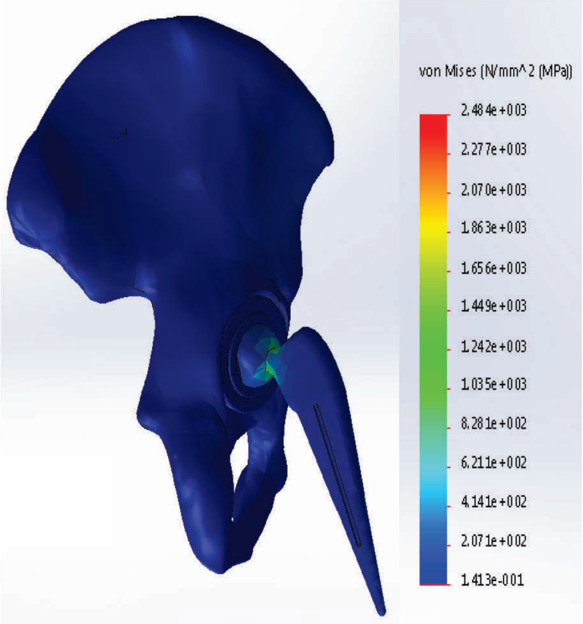

Fig. 9. Visualization of stress distribution in the model after the hip replacement procedure

Table 2

Maximum stress (in MPa) in the model

% BW	Before replacement		After replacement
	Intact cartilage	Destroyed cartilage	
100	1.91E + 01	1.82E + 01	2.48E + 03
150	2.95E + 01	2.74E + 01	4.33E + 03
200	4.04E + 01	3.67E + 01	7.38E + 03

Table 3

Maximum stress (in MPa) in the pelvic

% BW	Before replacement		After replacement
	Intact cartilage	Destroyed cartilage	
100	9.59E + 00	1.00E + 01	4.01E + 02
150	1.46E + 01	1.52E + 01	6.45E + 02
200	2.16E + 01	2.03E + 01	9.46E + 02

Study shows, that the biggest stress accumulates on the neck of the femur or the endoprosthesis, which confirms, that both femur and endoprosthesis are the most vulnerable to fracture in that area. When it comes to pelvis, the lack of cartilage causes slightly more stress on the bone than with healthy cartilage. After hip replacement, the value of stress affecting the pelvic bone rises.

SUMMARY

Preliminary studies with the use of finite elements analysis, resulting in obtaining basic data on changes in pelvic girdle as a result of applied loads before and after hip replacement procedure, are excellent basis for planning future studies on hip joint, both more directed and complicated. On the other hand they can act as an addition to the medical diagnosis, presenting potential benefits of said procedure.

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