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ASSISTANCE OF HIP RESURFACING USING FINITE ELEMENT METHOD

Abstract

Introduction and aim: The study presents the modelling of overlay elements used in hip resurfacing and their virtual application into reconstructed patient's bone structures that had been imaged in Computed Tomography (CT). The aim of the paper was the strength analysis with the use of the finite element method conducted in the hip joint with hip resurfacing endoprosthesis.

Material and methods: The material to the analysis was the hip resurfacing endoprosthesis Durom^{TM} Hip Resurfing firm Zimmer, in which both tribological elements were made from alloy Co28Cr6Mo/*Protasul*® *21 WF* (ISO 5832-12). The numerical calculations were carried out and distributions of stresses and displacements were determined for the locomotive loads in the *FEMAP NE/Nastran v. 8.3* software.

Results: The results allowed to perform strength analysis of constructional elements of the endoprosthesis and estimate their contact with pelvis bone and femoral bone of the operated hip.

Conclusion: The connection of hard metal acetabular shell with femoral component increases strength and resistance to wear, but it can also cause an excessive stiffening of the system and asymmetric concentration of stresses in the zone of the tribological contact.

Keywords: Hip resurfacing, hip joint, modelling, numerical simulations, preoperative diagnosis.

(Received: 01.09.2012; Revised: 15.09.2012; Accepted: 31.09.2012)

WSPOMAGANIE ZABIEGU KAPOPLASTYKI BIODRA Z WYKORZYSTANIEM METODY ELEMENTÓW SKOŃCZONYCH

Streszczenie

Wstęp i cel: *W opracowaniu przedstawiono modelowanie elementów nakładkowych stosowanych w kapoplastyce stawu biodrowego i ich wirtualną aplikację do odwzorowanych w tomografii komputerowej i zrekonstruowanych struktur kostnych pasa biodrowego pacjenta. Celem badań była analiza wytrzymałości z wykorzystaniem metody elementów skończonych prowadzonej w stawie biodrowym udowej endoprotezy nawierzchni.*

Materiał i metody: *Materiał do analizy to endoprotezy DuromTM hip nawierzchni Hip Resurfing firmy Zimmer, w którym oba elementy tribologiczne zostały wykonane ze stopu Co28Cr6Mo / Protasul® 21 WF (ISO 5832-12). Dla obciążeń lokomocyjnych, w programie FENAP NE/Nastran v. 8.3, przeprowadzono obliczenia numeryczne i wyznaczono rozkłady naprężeń i przemieszczeń w implantowanym biodrze.*

Wyniki: *Wyniki pozwoliły na analizę wytrzymałościową elementów konstrukcyjnych endoprotezy oraz na ocenę ich kontaktu z kością miedniczną i kością udową operowanego biodra.*

***Wniosek**: Połączenie panewki o powłoce metalowej z częścią kości udowej zwiększa wytrzymałość i odporność na ścieranie, ale również może powodować nadmierne usztywnienie systemu i asymetrycznym koncentracji naprężeń w strefie tribologicznym kontaktu.*

Słowa kluczowe: *Nakładka stawu, staw biodrowy, modelowanie, symulacje numeryczne, przedoperacyjne rozpoznanie.*

(Otrzymano: 01.09.2012; Zrecenzowano: 15.09.2012; Zaakceptowano: 31.09.2012)

1. Introduction

Alternative solutions for total hip replacement have been searched for several years [2], [4], [5], [11], [18]-[20]. One of such solutions is hip resurfacing. In the operation of hip resurfacing, the metal acetabular shell in the shape of thin-walled bowl is fixed in the acetabular part of pelvic bone on the basis of osteointegration after the removal of the rest of cartilage and subchondral layer.

The femoral component is fixed using bone cement on the femoral head. The femoral component has also a small stem that is inserted into the top of femoral head. The femoral component does not penetrate the medullary canal; the femoral neck is not removed. There is no danger of shortening of the limb and, fore and foremost, the natural antetorsion, anatomical positioning of femoral head and neck are preserved in the acetabulum.

The pressures in the contact zone are very similar to the values in the natural joint. The progress in technology and metalworking have made it possible to produce prostheses with femoral component and acetabular shell made from metal with very good mechanical and tribological properties.

Clinical observations and the analysis of lubrication mechanism of joints show that hip resurfacing has some restrictions. The contraindication to the operation is aseptic necrosis of femoral head, advanced osteoporosis, inflammatory processes in the joint. If these contraindications are not followed and some technical errors occur during the operation, fractures of the neck take place six weeks later.

2. Aim

The aim of the paper was the strength analysis with the use of the finite element method conducted in the hip joint with hip resurfacing endoprosthesis.

3. Material and methods

The material to the analysis was the hip resurfacing endoprosthesis Durom^{TM} Hip Resurfing firm Zimmer, in which both tribological elements were made from alloy Co28Cr6Mo/*Protasul*$^{®}$ *21 WF* (ISO 5832-12). The exterior surface of acetabular shell was covered with a porous layer made in “plasma-spray” technology to fix in the natural acetabulum on the basis of osteointegration. The femoral component on femoral head was fixed on cement and stabilized with inner stem.

The method of modeling and simulating included [6], [7]-[10], [14]-[16]:

- Three-dimensional modeling of geometry of the endoprosthesis in *FEMAP 8.2 Modeler*. Cut off acetabular shell of a chosen diameter and appropriate wall thickness set in the program allowed to obtain the geometry of the acetabular shell (Fig. 1a). The geometry of the component on femoral head was acquired in the same way, but additionally, inner-cylindrical stem, which played the role of a stabilizer, was modeled (Fig. 1b);
- Virtual imaging of the patient’s three-dimensional anatomical osteoarticular system (Fig. 2). The selection of an object for implantation was conducted on the basis of CT diagnostics and programs for analysis and reconstruction of images;
- Modeling of bone bed in the natural acetabulum and the conical surface on femoral head before the application of the endoprosthesis (Fig. 3);
- Virtual application of the modeled endoprosthesis to the patient’s imaged structures positioned in accordance with the anatomical conditions (Fig. 4).

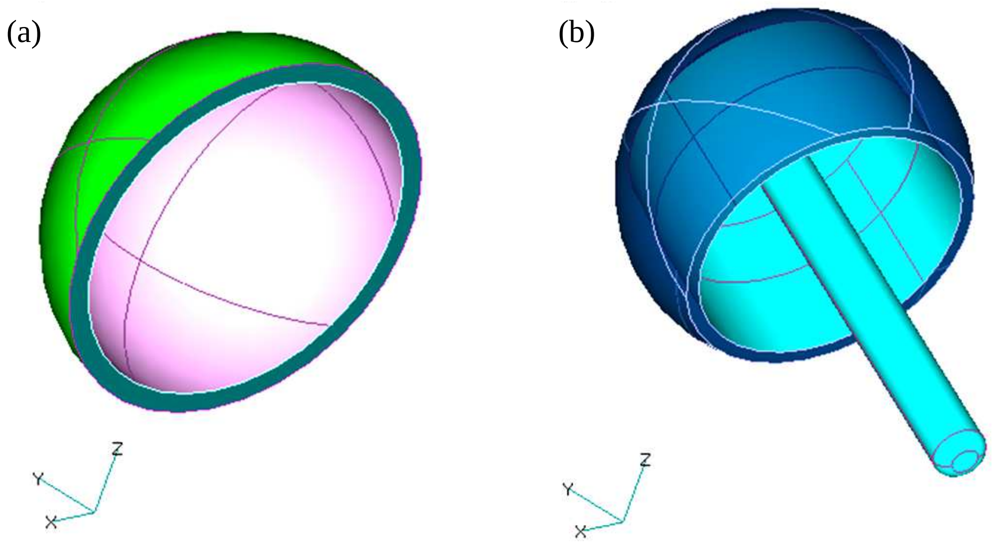

Fig. 1. Geometry of artificial acetabular shell (a) and femoral component (b) modeled in *NE/Nastran v. 8.3 Modeler*
Source: Elaboration of the Authors

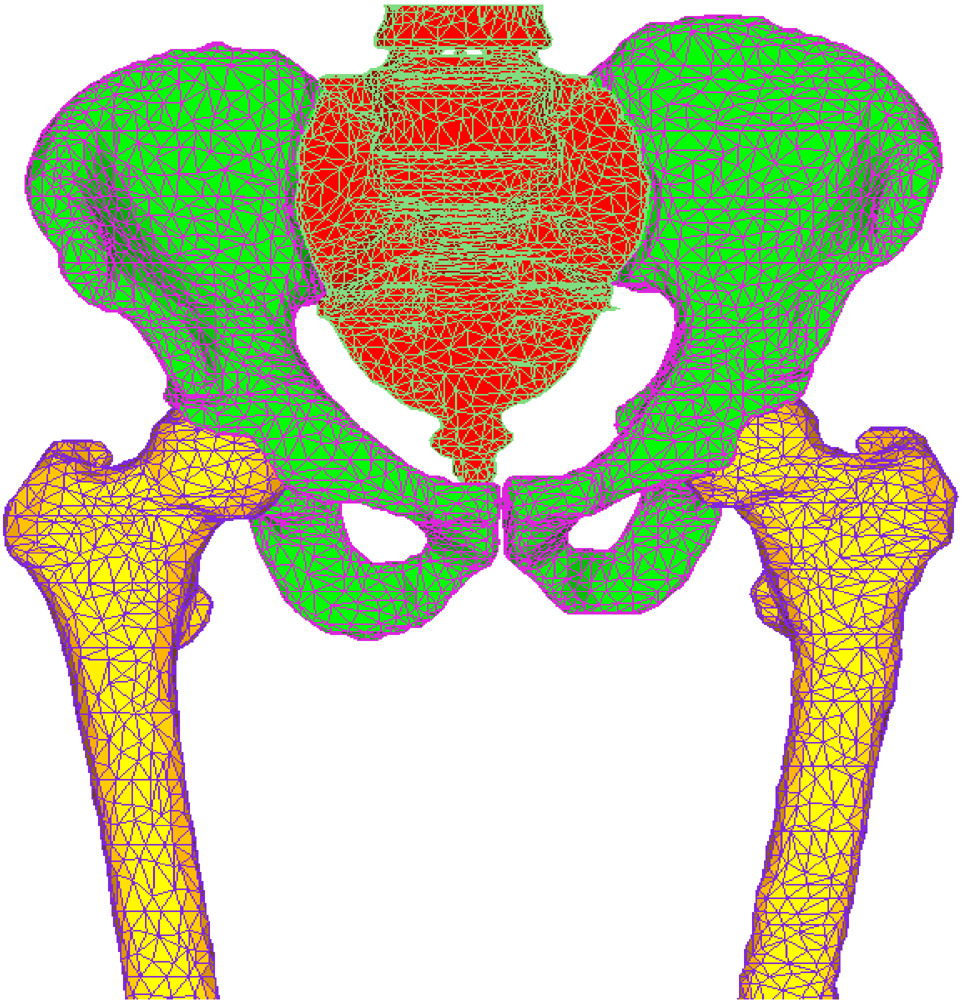

Fig. 2. Three-dimensional model of the real osteoarticular structures (man age 62) obtained on the basis of CT diagnostics, reconstruction of images and application to the *NE/Nastran v. 8.3 Modeler* program
Source: Elaboration of the Authors

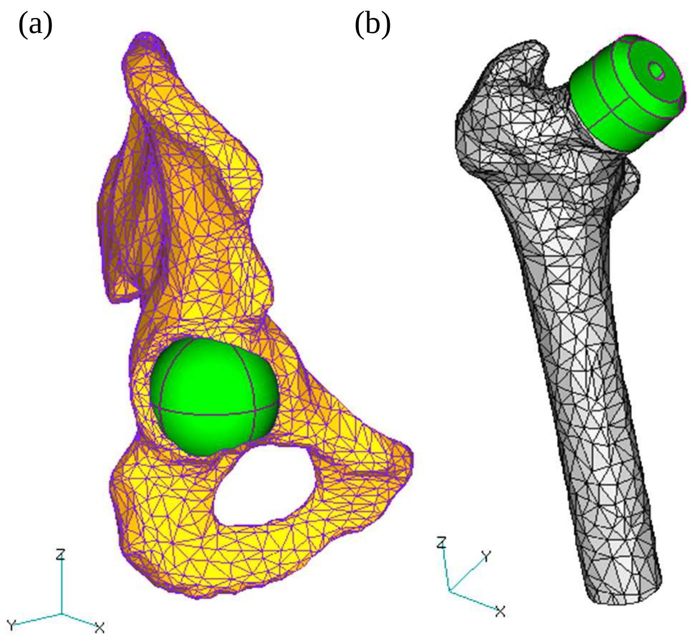

Fig. 3. Three-dimensional configuration of acetabular part of pelvic bone (a) the surface of femoral head before the application of endoprostheses (b)
Source: Elaboration of the Authors

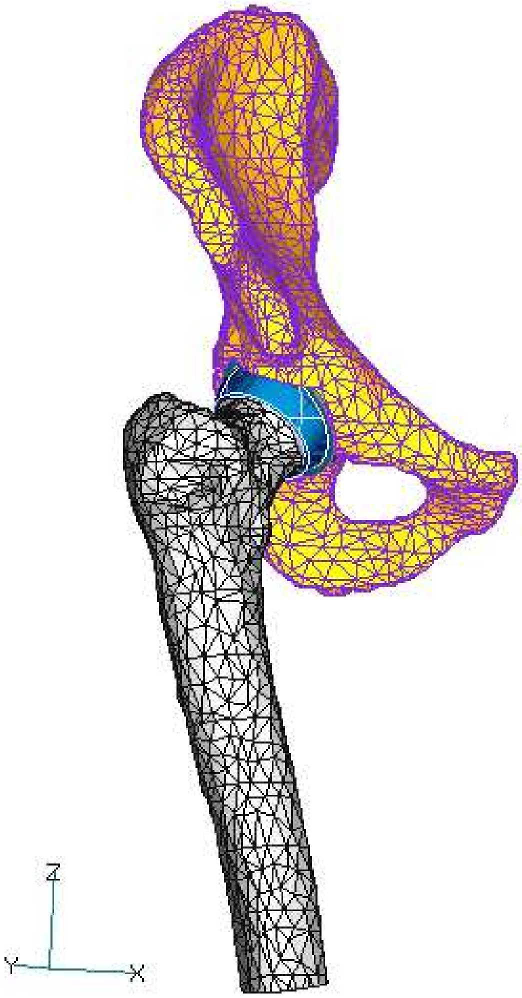

Fig. 4. Virtual application of endoprostheses to the patient's bone structures
Source: Elaboration of the Authors

- Biomechanical analysis of the research model with the aid of *FEMAP/NE Nastran v. 8.3.* The analysis contains strength parameters of considered structures (Tab. 1).

Table 1. Resistance parameters of materials

Mechanical properties / Material	Modulus of elasticity [E, GPa]	Poison's ratio [–]
Cortical bone	5 – 22*	0,2 – 0,4*
Cancellous bone	0,1 – 5**	0,2 – 0,46**
Co28Cr6Mo/Protasul® 21WF	210	0,3

* in numerical solutions for cortical bone, the following factors were received: E = 16,8 GPa, $\nu = 0,29$

** in numerical solutions for spongy bone, the following factors were received: E = 3,1 GPa, $\nu = 0,46$

Boundary conditions were determined in the following ways:

- Restrains were set on the pelvic bone: in pubic symphysis and in sacroiliac joint (Fig. 5), knots had all degrees of freedom taken away and the place of pelvic bone was described by positioning of the pelvic girdle.
- Three-dimensionally compound, quasi-static load was set on the zone of implantation of artificial hip joint in the conditions of standing on two feet. One included body weight P, surface reaction Rp, influence of abductor muscles Ma, influence of illotibial tract M,T as well as rotating moment of femoral bone Ru.
- In the zone of tribological cooperation of acetabular shell and component, the contact with the ability to move towards the acetabular shell was modeled. Coefficients of friction [14]: Co28Cr6Mo-Co28Cr6Mo were determined in tests [8], [10], [14] and the coefficients of static $\mu s1 = 0,3$ and kinematic $\mu_1 = 0,1$ frictions were assumed.
- Isotropic properties of bone tissue building femoral bone and pelvic bone were presumed.

4. Results and discussion

The variable static loads were set after digitalizing the objects and setting the boundary conditions. According to Huber-Misses-Hencky hypothesis, distributions of reduced stresses (HMH) (Fig. 6 - Fig. 10) and resultant displacements for the tested structures (Fig. 11) were determined.

The distributions of reduced stresses and resultant displacements in endoprostheses and bone structures were presented in the scale imposed by the program on the included numerical solutions. Scales enabling the detailed analysis in the selected zone of the object were also used.

In the analysis of stresses in the structures of the implanted joint, the circumferential asymmetry of their distribution in the zone of contact of the component on femoral head and in the zone of contact of acetabular shell in the pelvic bone was characteristic in the range from 13,70 to minimal 0,80 MPa (Fig. 7).

The maximal stresses of 13,70 MPa concentrated in the zone contacting with acetabular shell, while in lower part of acetabular shell, they received the value of 4,50 MPa. The asymmetry occurred also in the femoral component of head in the part contacting with the roof of the acetabular shell and the maximal values of stresses amounted 13,70 MPa. In the zone contacting with the prepared femoral head, one observed peripheral accumulations of maximal values of 16,65 MPa.

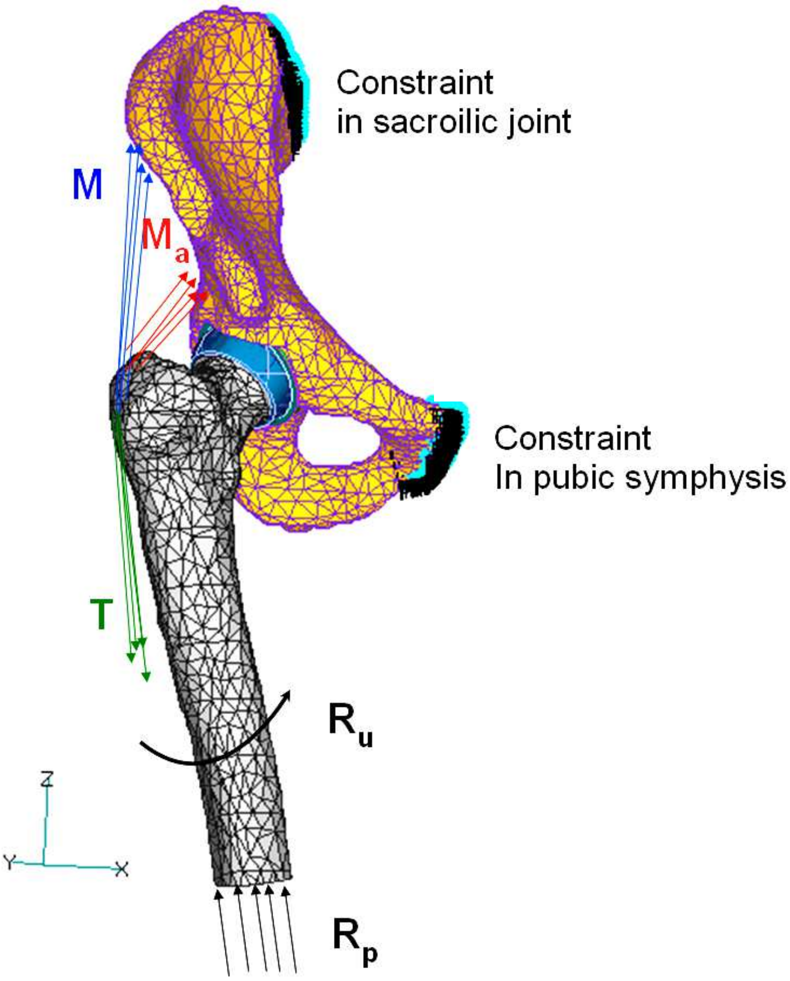

Fig. 5. Conditions of loads and constraints of the numerical model
Source: Elaboration of the Authors

In the construction of the femoral component, accumulations were characteristic on small stem for its stabilization in the proximal extremity of femoral bone (Fig. 7 & Fig. 8). These accumulations had values of 18,50 MPa. The concentration of stresses were visible in the construction of femoral component especially on small stem to the stabilization component in the femoral extremity The stresses in the middle upper part of stem occurred. It is noticeable that the accumulations occurred in the medial upper part of the stem. The stresses analysis of this element illustrates the effect of bending of the stem which supports transferring of bending loads by the neck of femoral bone.

The stresses analysis points to their asymmetrical distribution in the neck of femoral bone (Fig. 6 & Fig. 8).

Such distribution increases the risk of fracture of the neck of femoral bone. The circumferential asymmetry of stresses is disadvantageous both for the construction of endoprosthesis and as for their fixing zones. The construction of endoprosthesis may be exposed to increased tribological wear in the zones of the maximal stresses.

In the conditions of exploitation, the ovalisation of the acetabular shell and femoral component may occur.

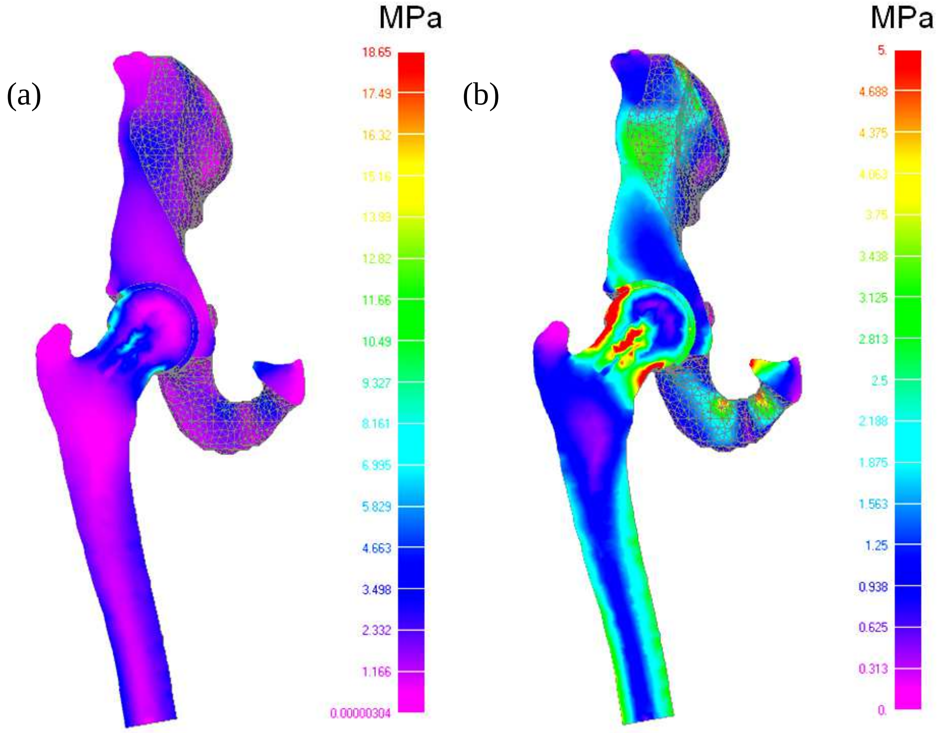

Fig. 6. The maps of stress distributions reduced in vertical section through the hip joint after hip resurfacing operation: (a) in automatic scale, (b) in narrow scale

Source: Elaboration of the Authors

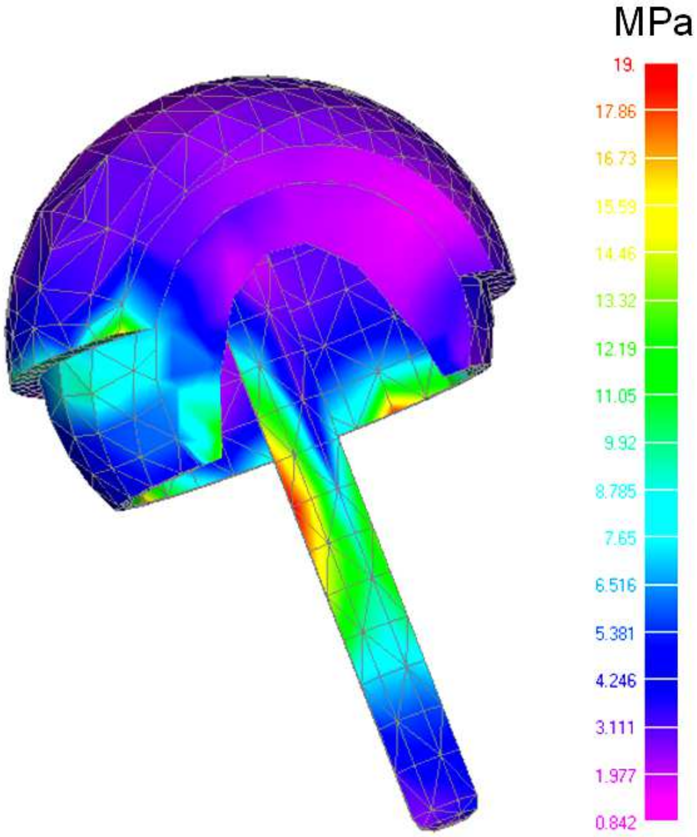

Fig. 7. The maps of stress distributions reduced in contacting elements of femoral component and acetabular shell

Source: Elaboration of the Authors

The products of wear from alloy Co28Cr6Mo may be generated to the contact zone of the endoprosthesis and the bone. The locomotive loads in the contact of femoral component and acetabular shell are transferred by metal elements and such character of their transmission, due to the stresses parameters, causes the stress concentration in these elements.

It is different from the elastic transfer of contact loads which occur in the natural head and acetabulum covered with the joint cartilage and lubricated with the synovial fluid. In the proper natural joint the concentration of stresses occurs in the bone structures of head and acetabular shell distant from the motion contact zone.

On the figures 6b and 8, it is possible to observe the load of the head of femoral bone directly under the metal component, where the stresses achieve values of tenths of MPa and increase only in the stabilizing stem and in the internal structure of the femoral neck.

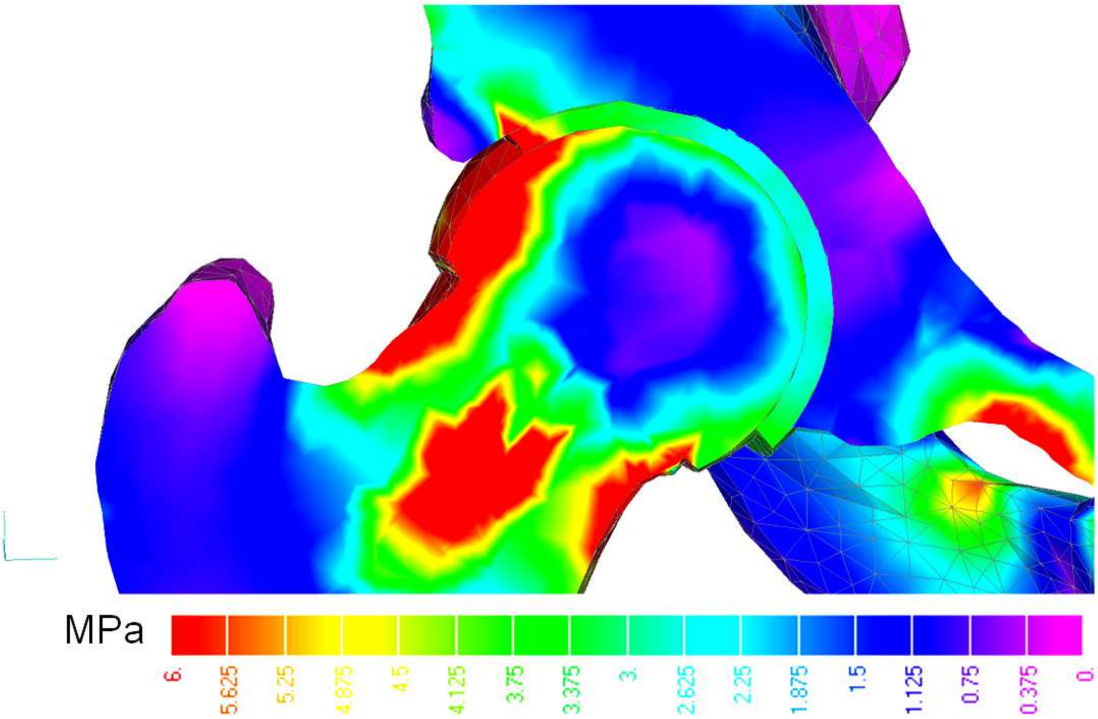

Fig. 8. Distributions of stresses reduced in the zone of fixing of the constructional elements of the endoprosthesis

Source: Elaboration of the Authors

The distributions of stresses in the distal part of femoral bone increase to 4,10 MPa. It may result from the presence of the medullary canal and decrease of the cross-section of femoral bone. In the upper contact zone of acetabular shell with pelvis structures, the stresses maintain in the range of 2,20 MPa. It is an advantageous effect which may improve the osteointegration process of the artificial acetabular shell with the bone.

On the figure 10, the maps of distribution of stresses reduced for the statically increased load in particular steps were presented. The growing load increases the values of stresses in the zone of the implanted hip, but the character of distribution is very similar.

The figure 11 presents the distributions of displacements in hip resurfacing endoprosthesis and in the bone structures. The displacements in the periatricular structures are very little, reach 0,3 MPa and have regular distribution. The cause of such little displacements is very hard and enduring structures of endoprosthesis made from metal as well as significantly greater surface of contact of component of the endoprosthesis' and the acetabular shell as opposed to standard endoprostheses used in total alloplasty operation where head and acetabular shell diameters are significantly lower. [10], [15]-[17].

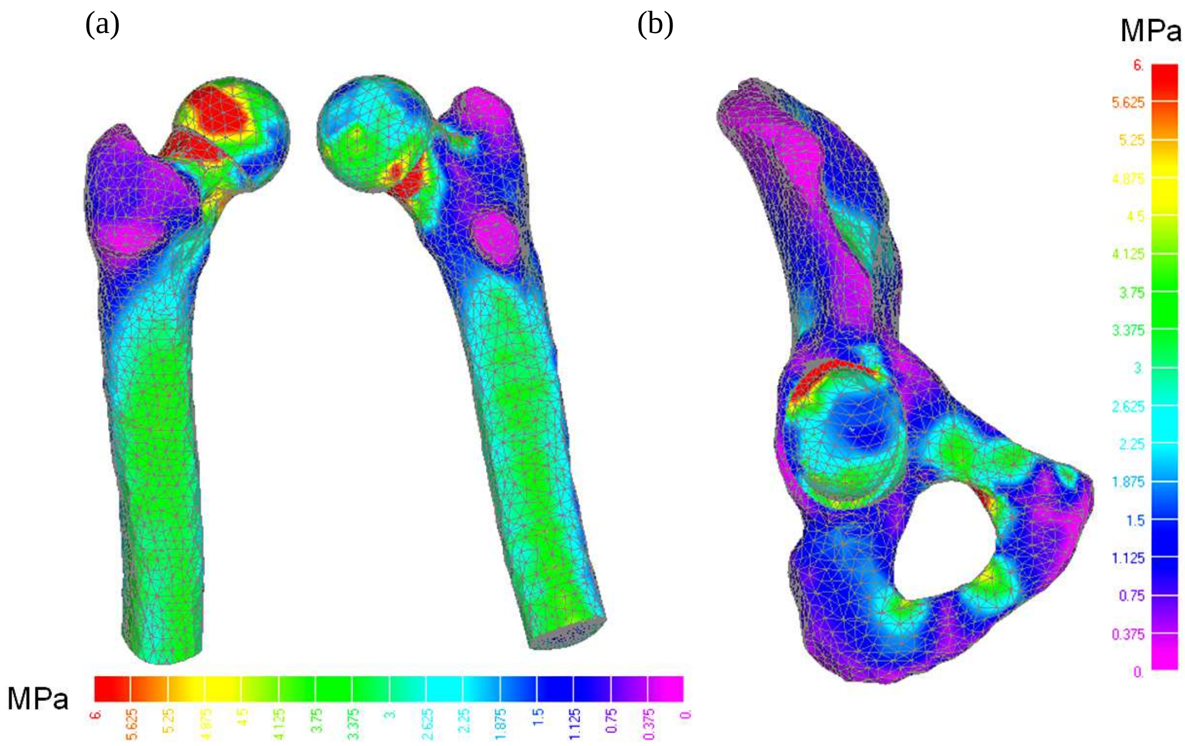

Fig. 9. The maps of stress distributions reduced after hip resurfacing operation and separation of femoral bone and pelvic bone: (a) on the upper surface of the femoral component of the endoprosthesis and in the femoral neck, (b) in the roof and in bottom of acetabular shell and in structures near prostheses in the pelvic bone

Source: Elaboration of the Authors

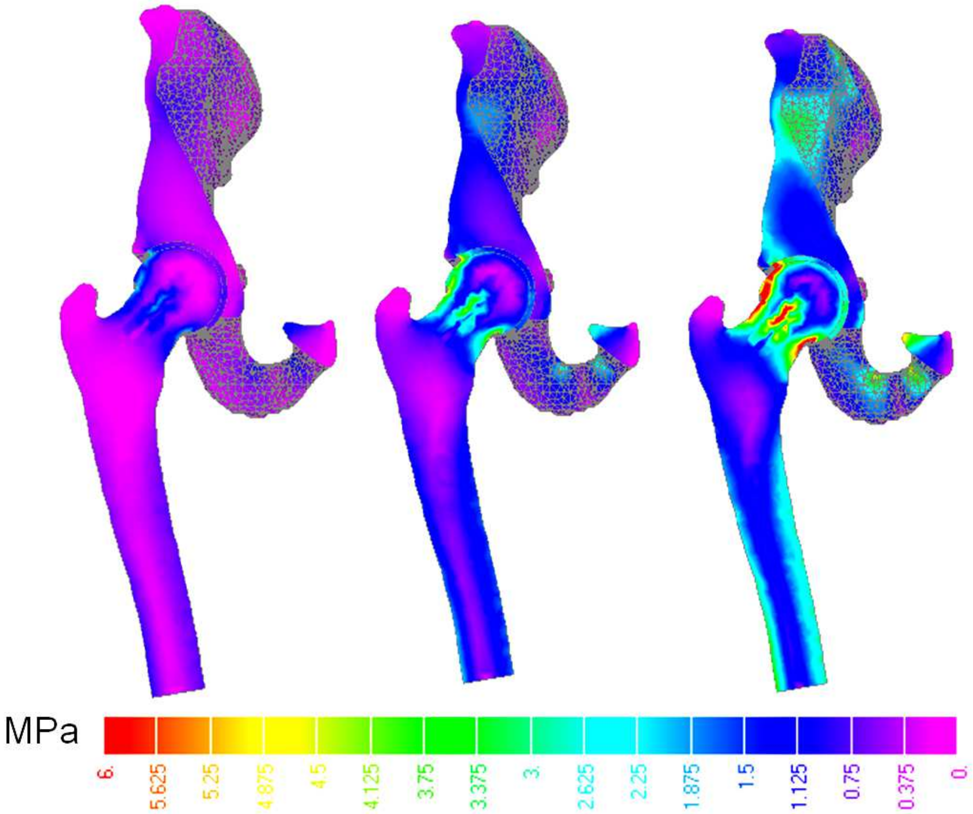

Fig. 10. The maps of stress distributions reduced at the static increase of loads

Source: Elaboration of the Authors

In the hip resurfacing, the diameter of tribological contact of femoral component and artificial acetabular shell is much more similar to the geometrical parameters of the natural joint.

Displacements taking place in periatricular structures can be particularly dangerous for anatomical structures of femoral head and neck.

They can cause cement crushing in the layer which fixes the femoral component as well as in the layer of cement which stabilizes the stem of the component in femoral head. That is why, the latest constructional solutions for hip resurfacing have the component fixed on femoral head without cement [2], [18], [20].

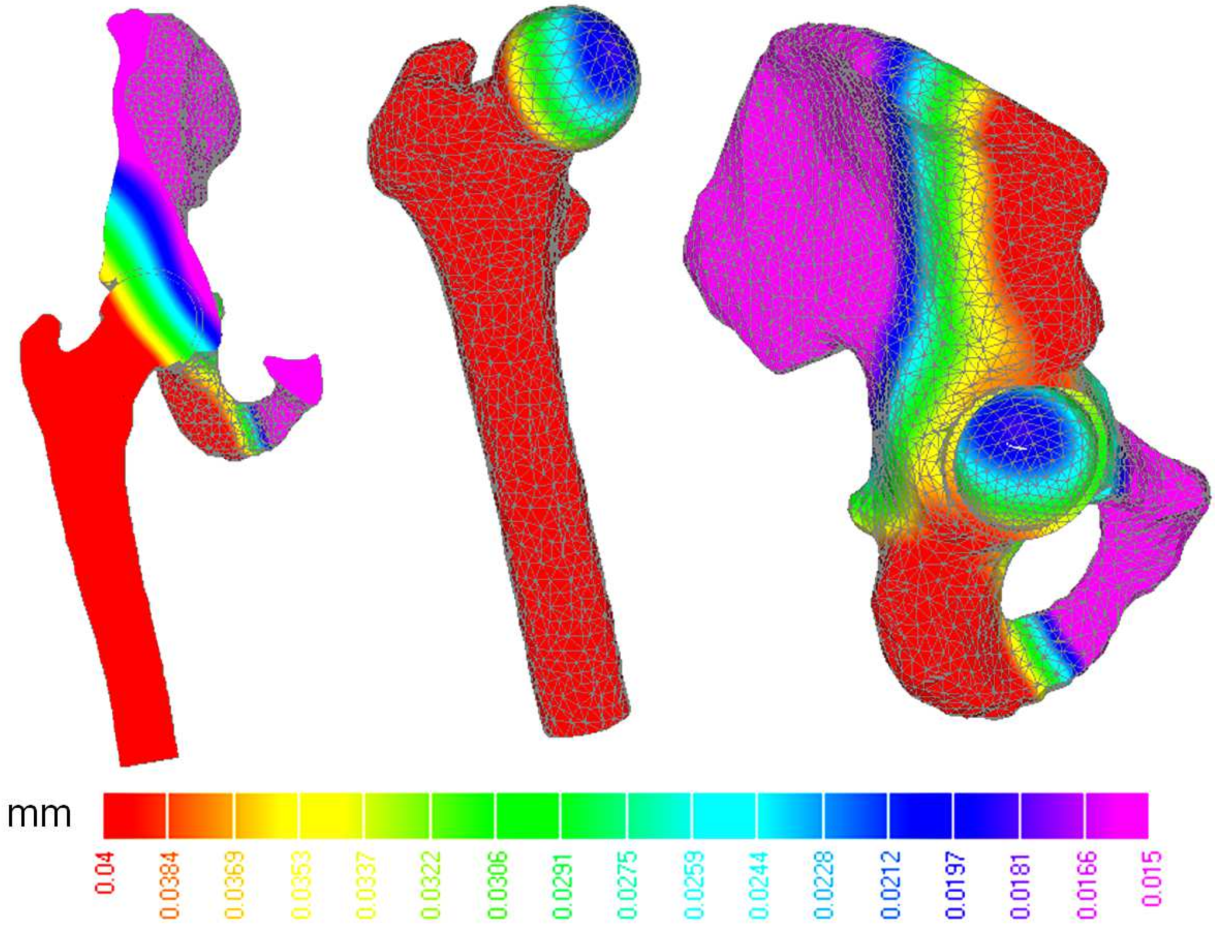

Fig. 11. The maps of resultant distributions in the endoprosthesis and bone structures
Source: Elaboration of the Authors

Summarizing the obtained results of analyses, one can conclude that stresses have not too high values, they do not exceed the physiological efficiency of tissues and can stimulate processes of bone formation.

Circumferential asymmetry of stresses is dangerous both for the construction applied in hip resurfacing and for tissues structures in which the process of effort can happen when walking, running or jumping or in other unintended extreme situations.

Because of the occurrence of asymmetrical accumulations in femoral neck, this area should be considered to be dangerous in possible hip resurfacing in old people, and one could recognize this type of operation of femoral joint as the operation performed rather in young patients.

5. Conclusions

- Such a procedure intended to build complex models imaging anatomical structure on the basis of image analysis and three-dimensional reconstruction, according to CT, together with the implanted construction of the endoprosthesis modeled in 3D can constitute a basis for strength analysis before the operation of hip resurfacing.
- The application of counting programs for stress and displacement analyses with the aid of the finite element method allow to estimate distributions of stresses and displacements in the construction of the endoprosthesis and in the adjacent tissues. It enables determination of zones of overload or lack of compression.
- The accomplished analyses prove that the state of loads of the component on the femoral head and acetabular shell was several times smaller than effort of this construction. In bone structures one did not observe the overflow of the threshold of physiological efficiency of tissues. However, the occurrence of the following circumferential asymmetries should be confirmed: in the neck which is particularly exposed to fracture in the conditions of physiological loads and in the acetabular shell which, consequently, will wear unequally.
- The connection of hard metal acetabular shell with femoral component increases strength and resistance to wear, but it can also cause an excessive stiffening of the system and asymmetric concentration of stresses in the zone of the tribological contact.

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