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Material and tribological problems occurring during the design and utilisation of hip endoprostheses

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ABSTRACT

Purpose: The main goal of research is determination of the influence of frictional pair „endoprosthesis head - acetabular cup" material on frictional resistance and endoprostheses wear, and the stress distribution in the elements of "bone-cement-implant" system.

Design/methodology/approach: In the paper new development directions in endoprostheses are discussed with respect to construction of "head-acetabular cup" system and endoprosthesis stem, and proper material selection. The tests were carried out using dedicated simulator of the hip endoprosthesis. A quantitative and qualitative analysis of wear products was carried out. The numerical calculations of stress state in "bone-cement-implant" system were performed using ADINA System. Additionally the impact of incorrect endoprosthesis setting (jaw angle of the stem and cup) on frictional moment was determined experimentally. The stress distribution, in particular parts of "bone-cement-implant" system for selected endoprosthesis stem constructions, was presented.

Findings: Both the numerical calculations and tests carried out on the hip endoprosthesis simulator gave us many valuable information on frictional resistance value, wear mechanism and durability of new endoprostheses constructions.

Research limitations/implications: Preservation of geometrical, material and tribological similarity to the natural joints is of great significance in design of hip endoprostheses. Despite significant progress in material engineering not all similarity conditions were achieved. The replacement of a specific bone structure and natural joint with polyurethane insert and metal elements (stem, head of endoprosthesis), i.e. materials with much higher modulus of elasticity, cause the significant increase of the "bone-cement-implant" system rigidity. Frictional and wear processes occurring in the moveable system: "head-acetabular cup" and the resulting low endoprosthesis durability pose a serious problem.

Practical implications: Future development of endoprostheses alloplasty is determined by the progress in biotribology, especially frictional and wear tests of endoprostheses.

Originality/value: The tests were carried out using the hip endoprosthesis simulator, which reflects processes occurring in natural joint.

Keywords: Hip endoprostheses; Friction; Wear; Wear products; Biomaterials; Numerical simulations

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1. Introduction

Among the components of human osteoarticular system, hip joint is exposed to the highest risk of overload and degeneration changes and is subject to frequent damage.

Disease processes (rheumatoid arthritis) which intensify with age, falls, traffic accidents etc. cause that the number of the implanted prostheses is increasingly high each year.

Hip joint replacement, which consists in replacement of the diseased or damaged hip joint into a prosthesis, is considered to be one of the key accomplishment of the domain of technology and medicine of the twentieth century. Prosthesis designers were guided by the idea that implanted prosthesis could perform functions of a natural healthy joint. Therefore, it should allow for performing typical movements of the limb. Elimination of pain is also essential. However, introduction of an implant with the properties other than bone tissue to human system leads to disturbance in physiological patterns of carrying load in the joint. Furthermore, gradual decline in functional properties of the prosthesis caused by wear processes are also essential. Hence research studies in the domain of material engineering and biotribology have gained in importance in recent years [1-4]. The goal of these works is effective prevention of wear processes which occur in friction pairs in endoprostheses.

2. Modelling of joints in endoprosthesis

In order to ensure proper functioning of endoprosthesis, i.e. artificial biobearing, one should meet the demands of geometrical, material and tribological similarity.

Modelling of geometry of movable pair i.e. head and acetabular cup is relatively simple. This makes it easy for hip endoprostheses to allow for performing basic limb movements and proper human locomotion. The attempts were made during prosthesis design phase to maintain similarity of dimensions of head and cup to natural dimensions of biobearing. However, the views on the recommended heads have changed from the diameter of ϕ=28-32 mm through to the head with greater dimensions, ϕ= 44 mm and more, used today. Considerable importance is also from surface microgeometry, which impacts on friction resistance. Hence, prostheses manufactured today feature polished surfaces with roughness of Ra=0.16 µm.

Unfortunately, it was impossible to maintain material similarity during production of prostheses. Each of the currently used materials for heads and stems in endoprostheses, such as CoCrMo or Al_2O_3 alloys have considerably higher Young's modulus than those observed in natural bone. This causes excessive stiffness in bone-implant system. Titanium alloy of Ti6Al4V and new generation titanium alloys of TiAlNb seem to be promising solution since they demonstrate much lower Young's modulus than CrCoMo [5,6]. Comparison of Young's moduli for the materials used for prostheses to the modulus in the natural bone is presented in Fig. 1.

It was much more difficult to maintain tribological similarity in the developed endoprostheses. Reconstruction of natural lubrication mechanisms which occur in healthy joints by movable pair: head - acetabular cup turned out to be impossible.

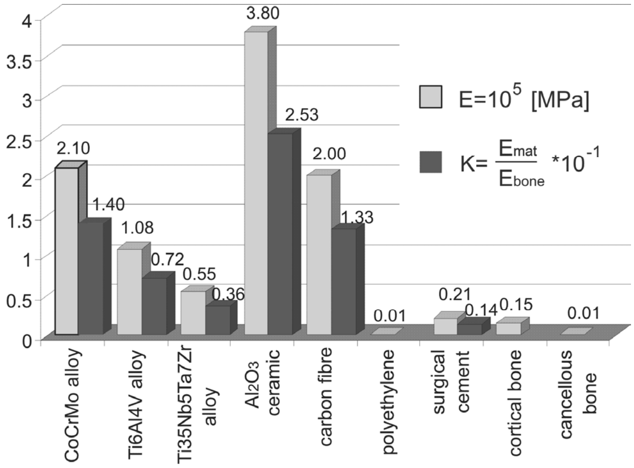

Fig. 1. Comparison of Young's modulus for the materials used for endoprostheses to the bone modulus

Hence friction coefficient in endoprostheses amounts to µ=0.1-0.3. It is several times higher than coefficient of friction in natural joint, which amounts to µ=0.001.

A breakthrough discovery was application of polyethylene for cups in endoprostheses in the sixties of the 20th century by Prof. Charnley [7]. Application of "polyethylene-metal" frictional pair ensured relatively low frictional resistance but they did not eliminate wear [8]. Polyethylene is the material which is less resistant to wear and wear products in the form of tiny particles are harmful to human body. The realization of this fact triggered search for other material couplings such as "metal-ceramics", "ceramics-ceramics" and "metal-metal".

3. Destructive processes occuring in joint alloplasty

Striving for longer life of the implanted endoprostheses is one of the major challenges of biomedical engineering of the 21st century. The increasingly high number of implanted prostheses, at the life of from 10 to 15 years, poses a serious problem for both patients and doctors or manufacturers. Hence a number of clinics carry out observation of patients with implanted prostheses in order to determine main causes of damage to the prostheses.

According to observations conducted by J. Cwanek [9] the most frequent types of malfunctions in Weller cement endoprostheses include:

- falling of the cup into pelvis minor (6.8%),
- displacement of the cup in pelvis (16.4%),
- stem loosening (22%),
- stem loosening with cup damage (24.7%),
- excessive wear in cup (30.1%).

As results from this list, the most frequent cause of aseptic loosening of endoprosthesis is excessive wear in the cup and stem loosening.

In recent studies, doctors report another type of damage to endoprostheses [10,11], i.e. "sprains" which frequently occur for small head diameters.

According to the author's investigations, there are two tribological systems in hip joints with implanted endoprosthesis (Fig. 2) [12]:

- head - acetabular cup system, where large dislocations can be observed at lower velocities,
- prosthesis stem - cement - bone system, where micromovements can be observed.

The following destructive processes can be observed in head-acetabular cup system:

- vertical and horizontal migration of the cup,
- increasing roughness in the surface of both head and cup,
- friction wear and deformation (creeping) of the cup,
- change in dimensions of the cup as a result of wear and rise in the value of clearance between the head and the cup,
- migration of wear products,
- cup detachment.

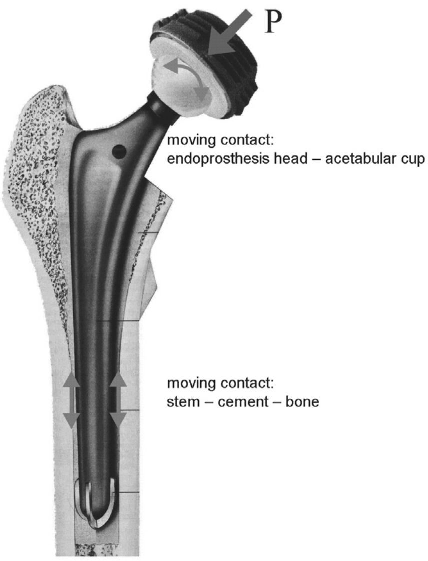

Fig. 2. Tribological system

In endoprosthesis stem-cement-bone system, the following destructive processes might occur:

- vertical and horizontal displacement of stem,
- bone atrophy (in proximal part of femur) as a consequence of improper load in the bone,
- chipping of bone cement (or hydroxyapatite layer in the case of cementless fixation),
- metalosis,
- endoprosthesis stem loosening.

According to a variety of studies, a weak components in all types of endoprostheses (both hip and knee endoprostheses) is polyethylene. UHMWPE acetabular cups or inserts (in knee endoendoprosthesis) are subject to quicker wear. Wear products in the form of microparticles migrate within the body, causing a range of negative effects. Figs. 3 and 4 presents the examples of wear products (polyethylene particles). Metal wear products can also be generated in friction zone (Fig. 5).

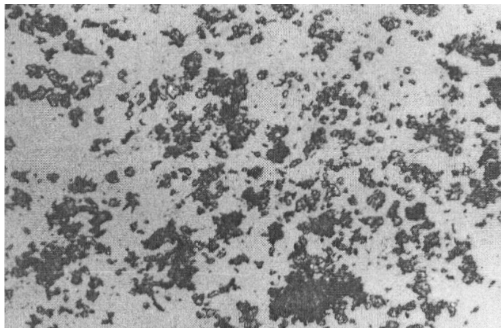

Fig. 3. Wear products - metallographic microscope

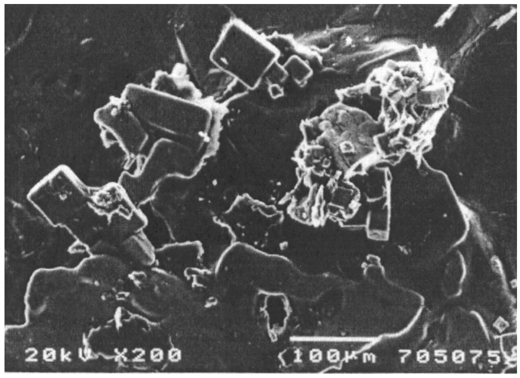

Fig. 4. Wear products - scanning microscope

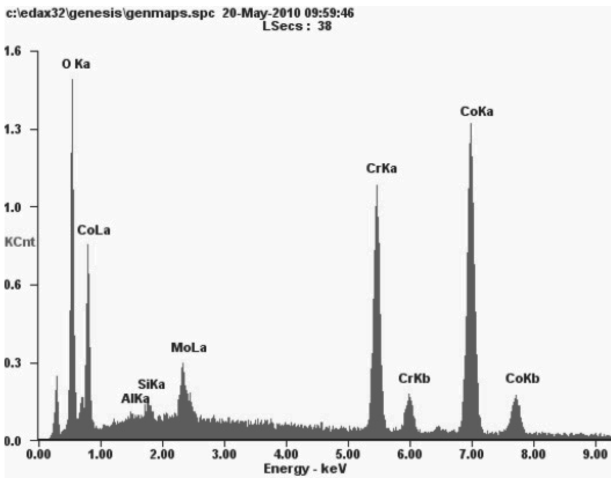

Fig. 5. Chemical composition of wear products in metal cups

Minimizing of friction component wear, thus limitation of the amount of wear products remains a key research problem.

4. Stress in stem-cement-bone system

Determination of the impact of prosthesis design on the way the load is transferred and stress distribution in bone-implant system, thus on its life is possible through application of modern computer systems. The obtained results of numerical simulations allow for explanation of the causes of destructive processes which occur in the area of the implanted joint and to forecast the efficiency of the implantation [13-17].

Numerical simulations carried out by the authors of this study allowed for determination of the effect of material and design characteristics of femur prosthesis component in hip joint on the processes connected with its biofunctionality. In order to achieve this, numerical calculations were performed for stress distribution in three-dimensional model of healthy femur and after implantation of Weller II cement prosthesis stems (Centrament) and Centega anatomic stem.

In order to develop discrete models, 20-node 3D solid elements were used. Calculations were carried out by means of ADINA software [18].

Distribution of reduced stress σ_{zr} in the layer of both cortical and spongy tissues in the model of femur before and after implantation of Weller II prosthesis stem is presented in Fig. 6.

In healthy femur, load is transferred through the head of the femur to cortical tissue in proximal metaphysis, where it is transferred peripherally to further part of bone shaft. The highest values of reduced stress of σ_{zr} = 25 - 46 [MPa] can be observed along the bone shaft, in internal and lateral areas.

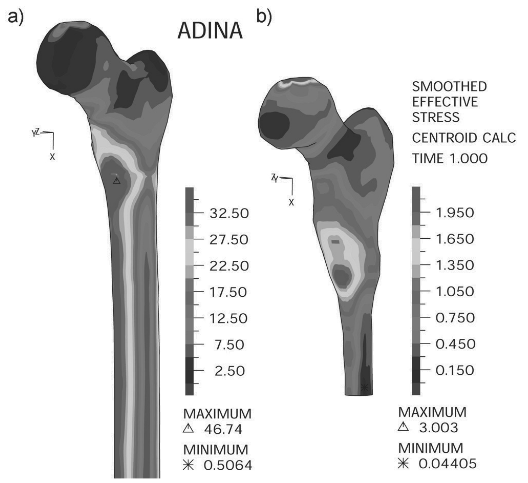

Fig. 6. Distribution of reduced stress σ_{zr} [MPa] in the area of cortical bone (a) and trabecular bone (b) in the model of healthy femur

The obtained results of calculations conform significant changes in the way the load is transferred in femur, caused by implantation of endoprosthesis stem. Implantation of each of the studied endoprosthesis stems leads to unloading bone tissue adjacent to the implant, depriving it of proper stress which occurs in natural hip joint, ensuring stimulation of bone mass. These changes are particularly noticeable in the area of proximal metaphysis in the femur. Fig. 7 presents distribution of reduced stress σ_{zr} [MPa] in the area of cortical and trabecular bones after implantation of Weller stem made of CoCrMo alloy.

In the area of trabecular bone, the highest values of reduced stress can be observed in medial area, which results from changes in the way the load is transferred in the bone.

Change of stem material, from CoCrMo to titanium alloys, causes rise in the value of reduced stress in the area of bone tissue. The effect of the stem material on the value of reduced stress is particularly noticeable on the internal side of proximal metaphysis in the femur. No significant effect of the stem material type on changes in the value of reduced stress was observed in further part of the femur shaft.

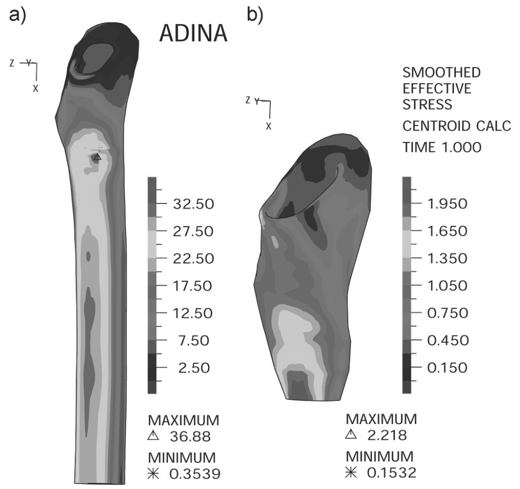

Fig. 7. Distribution of reduced stress σ_{zr} [MPa] in the area of cortical bone (a) and trabecular bone (b) of the femur after implantation of Weller stem (CoCrMo)

Comparison of maximal values of reduced stress in the area of cortical bone in the femur after implantation of Weller, Centrament and Centega stems are compared, respectively, in Fig. 8.

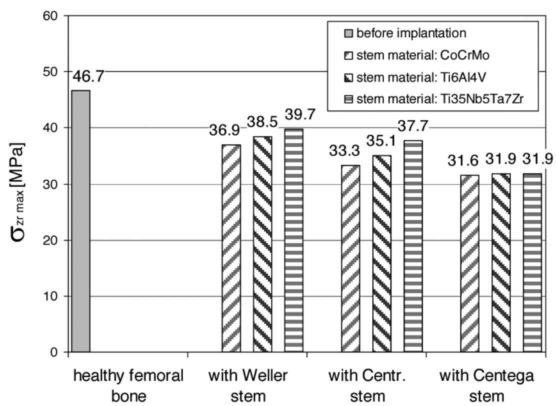

Fig. 8. Maximal values of reduced stress σ_{zr} [MPa] in the area of cortical bone in the model of healthy femur and after implantation of Weller, Centrament and Centega cement prostheses for different materials of implant stem

Considerable effect on life and stable fixation of endoprosthesis is also from stress distribution in the stem and the layer around the implant. Existence of the areas of high stress concentration, both in the stem and in cement coating, might lead to destruction of the stem or to occurrence and propagation of cracking in the cement, being a cause of implant loosening.

Distribution of reduced stress σ_{zr} in Centega stem endoprosthesis and the cement layer is presented in Fig. 9.

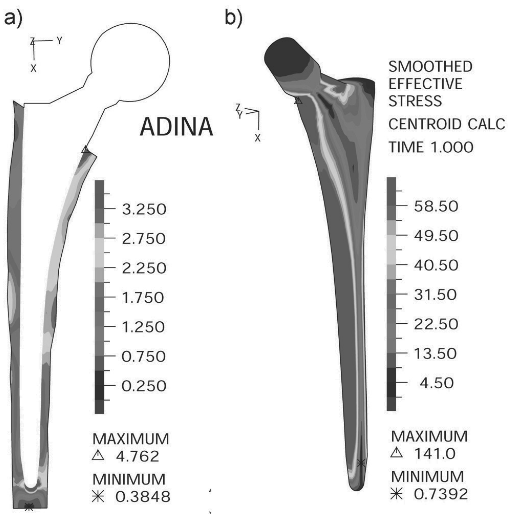

Fig. 9. Distribution of reduced stress σ_{zr} [MPa] in the layers of cement (a) and Centega stem (b) made of CoCrMo alloy

The highest values of reduced stress can be observed in the layer of cement in medial side of prosthesis stem and result from the way the load is transferred from the implant to the adjacent bone.

Reduction in stem stiffness is accompanied by a rise in stress in cement coating located at internal side of proximal part of implant blade, which might lead to cracking of cement layer and, in consequence, to loosening and damage to the prosthesis.

5. Tribological investigations carried out on simulator in the Metal Forming Institute in Poznań

Valuable information about mechanical and tribological processes which occur during use of endoprostheses might be obtained through investigations carried out on simulators [10,12].

The Metal Forming Institute in Poznań has a full set of simulators used for investigations of hip joint and knee joint prostheses and spinal column implants. Tribological investigations are carried out under supervision of Prof. Monika Gierzyńska-Dolna.

The goal of laboratory tests on hip joint simulator is:

- to determine the effect of frictional pair of head-cup on frictional resistance and cup wear,
- to determine the effect of geometry of frictional pair (head diameter) on tribological processes,
- to assess the effect of the angle of cup shift and deviation from prosthesis stem axis on frictional resistance,
- to investigate the amount and chemical composition of wear products.

An essential factor which conditions proper functioning and life of endoprostheses is implantation of parts of an implant in proper anatomical position. Erratic arrangement of the cup and stem causes accelerated wear in endoprosthesis and limitation of the scope of joint mobility. The likelihood of joint dislocation is also increased. Therefore, new programs of investigations take these factors into consideration.

Fig. 10 presents a simulator for investigations of hip joint prostheses from the Metal Forming Institute in Poznań.

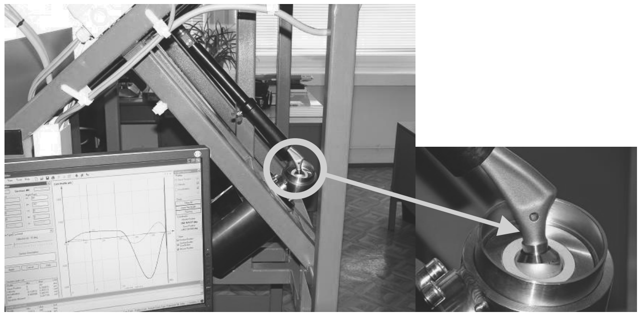

Fig. 10. Simulator for investigations of hip joint endoprosthesis

Fig. 11. presents some results of the investigations carried out in the Institute.

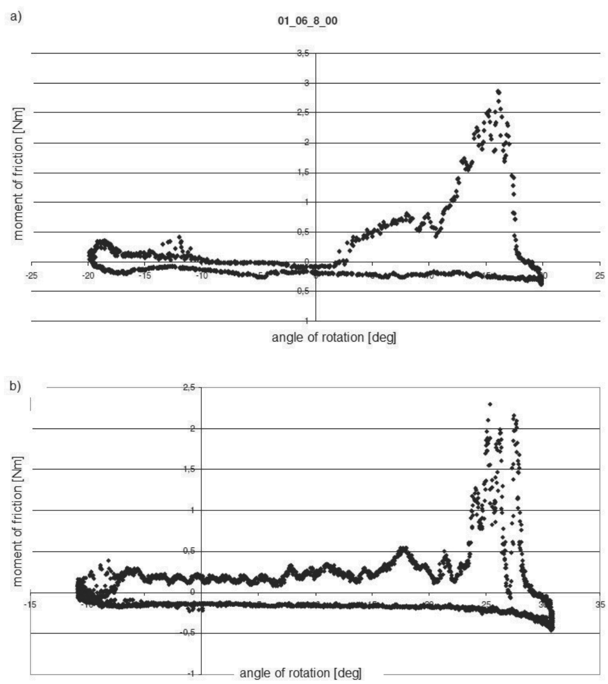

Fig. 11. Test results of the frictional moment for “metal-metal” frictional pair: a) angle of rotation: -20^0 - $+20^0$, b) angle of rotation: -10^0 - $+30^0$

6. Conclusions

1. The investigations carried out in hip joint simulator might provide a lot of valuable information about physical and mechanical processes which occur during use of endoprosthesis.
2. As confirmed by the investigations, use of metal heads and cups (Me-Me friction pair) causes rise in friction moment and might cause accelerated use of endoprosthesis.
3. Improper arrangement of endoprosthesis components during implantation is also of considerable impact on the value of friction moment, thus on wear.
4. A significant factor which should be taken into account during simulations is to analyse wear products. Analysis of the amount and chemical composition of wear products will allow for forecasting of negative processes which might occur in patients with implanted endoprosthesis.
5. The presented results of calculations confirmed significant changes in the way the load is transferred in femur, caused by implantation of endoprosthesis stem. Implantation of prosthesis stem leads to unloading of bone tissue adjacent to the implant, depriving it of proper stress which occurs in healthy hip joint, ensuring stimulation of bone mass. These changes are particularly noticeable in the area of proximal metaphysis in the femur.
6. In the case of use of flange stems of Weller II type, considerable part of load is carried to the bone through resistance surface of the flange, which might lead to excessive and undesirable load in the area of contact of the prosthesis and femur.
7. Use of non-flange endoprostheses causes changes in characteristics of bone load. The stress which occurs in proximal part of femur results from bending of prosthesis stem.
8. After implantation of Centega anatomical stem, no locations of strong concentration of stress or non-stress zones whose presence would lead to quick loosening of the implant were observed.
9. In the group of the analysed types of materials, the most favourable stress distribution in the bone was observed for stems made of titanium alloys, which proves their usefulness for hip joint replacement. Additionally, enhanced corrosion resistance and lower density compared to CoCrMo alloy support application of these materials for hip joint endoprosthesis stems.

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