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THE EFFECT OF THE COEFFICIENT OF FRICTION ON THE BIOMECHANICS OF CONTACT IN HIP ENDOPROSTHESIS

WPŁYW WSPÓŁCZYNNIKA TARCIA NA BIOMECHANIKĘ KONTAKTU W ENDOPROTEZIE STAWU BIODROWEGO

Key words: biomaterials, wear, resistances to motion, FEM, endoprosthesis, stresses, displacements.

Abstract Hip replacement surgery, by introducing a specific replacement head on the stem and cup, completely changes the conditions of co-operation typical for the biological correct pair. The clinical selection of endoprosthesis, apart from other conditionings, involves a dilemma between the choice of a rigid tribological node and the selection of a susceptible bearing cushioning the locomotive loads. The aim of the study is to evaluate the coefficient of friction and wear resistance of materials used for sliding contact in the endoprostheses of hip joints. On the basis of the conducted tests, it can be stated that, in the selection of material for cups of endoprosthesis, the wear resistance is important, and the coefficient of friction in contact head and cup in the prosthesis is less important. The presence of significant disproportions between the two parameters of the tribological process proves that the biomaterial is less useful on the cup. In the assessment of cooperation in the endoprosthesis, simulations of the contact of structural elements are useful, because, on that basis, in the correlation with tribological parameters, one can make conclusions about the distribution of stresses and displacements that may determine the lifetime of the implant.

Słowa kluczowe: biomateriały, zużycie ścierne, opory ruchu, MES, endoproteza, naprężenia, przemieszczenia.

Streszczenie Zabieg alloplastyki stawu biodrowego poprzez wprowadzenie określonej zamiennej głowy na trzpieniu i panewki zmienia całkowicie warunki współpracy charakterystyczne dla biologicznej prawidłowej pary. Kliniczny dobór endoprotezy, oprócz innych uwarunkowań, wiąże się z dylematem pomiędzy wyborem sztywnego węzła tribologicznego a wyborem biołożyska podatnego, amortyzującego obciążenia lokomocyjne. Celem pracy jest ocena współczynnika tarcia i odporności na zużycie materiałów stosowanych na panewki do kontaktu ślizgowego w endoprotezach stawu biodrowego. Na podstawie przeprowadzonych badań można stwierdzić, że w doborze materiału na panewkę endoprotezy ważna jest odporność na zużycie ścierne, a nieco mniejsze znaczenie ma współczynnik tarcia w kontakcie z głową endoprotezy. Występowanie znacznych dysproporcji między tymi dwoma parametrami procesu tribologicznego świadczy o słabszej przydatności biomateriału na panewki endoprotez. W ocenie współpracy w endoprotezie przydatne są symulacje kontaktu elementów konstrukcyjnych, ponieważ na ich podstawie, w korelacji z parametrami tribologicznymi, można wnioskować o rozkładach naprężeń i przemieszczeń, które będą decydować o żywotności implantu.

INTRODUCTION

The clinical choice of endoprosthesis, apart from other conditions, is associated with a dilemma between the choice of rigid tribological node and the selection of susceptible bio-bearing which amortizes the locomotive loads and better approximates the conditions in the natural hip joint. Apart from the correctness of the treatment and the elimination of the risk of complications, other important factors deciding on distant prognosis are load transfer conditions in the tribological contact area, the quality of the working surfaces of

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the head and the acetabulum, strength parameters of biomaterials and their stability during the exploitation of the endoprosthesis. The constructions of the hip joint endoprostheses authorized for use are characterised by a metal or ceramic hard head that cooperates with various types of cups. The cups can be made of a cushioning material of high molecular weight polyethylene or from the hard materials like metals or ceramics. The latest trend is the usage of hybrid cups, which combine 3 layers: component for wear-resistant sliding contact, an amortization component, and a component for fixing in pelvic bones. Currently, there are about 56 types of cemented and uncemented artificial joints available for use. However, their selection is related to a whole range of conditions. An orthopaedic surgeon is aware of the fact that the quality of the patient's bone tissue decides on the vitality of endoprosthesis **[L. 1–6]**. The surgeon faces the dilemma of whether to use cement or cementless endoprosthesis and has to choose the best suitable friction-wear combination. Patient's locomotion must be diagnosed and biomechanical parameters determined. Finally, one needs to match geometrical elements of the endoprosthesis to anatomical shapes in the zones of fixation.

The aim of the study is the evaluation of the coefficient of friction and wear resistance of materials applied to cups to the sliding contact in hip endoprosthesis.

Hip replacement surgery, by introducing a specific replacement head on the stem and cup, completely changes the conditions of co-operation typical for the biological proper pair.

Moving elements of endoprosthesis interact on each other and on the surrounding tissues in a different ways than in the natural hip joint so, as a result, there occur a disability of the biolubrication and cooperation between stresses and displacements. The causes of losing functionality of an artificial joint are complex but possible to assess in future research.

MATERIAL AND METHODS

The following materials were selected for the tests: 316L steel, ultrahigh molecular polyethylene UHMWPE, Co28Cr6Mo Cobalt alloy, Ti6Al4V Titanium alloy, and Ti6Al7Nb Titanium alloy. Tribological tests were carried out using friction node ball-three-disks form tested material in the physical saline environment with the help of Roxana Machine Works **(Fig. 1) [L. 7]**. The testing disks with a diameter of 6.35 mm and a thickness of 2 mm were taken from the real cups by cutting and punching. The counter-samples were steel balls ø ½ " according to PN-83 / M-86452. The tests were conducted with the following parameters:

- Rotational speed 200 Rpm ±50 Rpm,
- Working temperature 36.6°C ±1.5°C,
- Load 100 N ±10 N, and
- Duration 15 min ±10 s.

Wear resistance was measured by wiping scales in the tested samples. The contact pressures resulting from tribological extrications were designated in the contact area of the sample with the counter-sample. The frictional resistance was measured during the tests, and, on the basis of this measurement, the coefficients of friction in the tested nodes were determined. Modelling and numerical FEM simulations were also performed in the following:

- The tested node to determine the stresses distribution and displacements distribution in tribological contact;
- The hip joint provided with endoprosthesis with different modular cups, taking into account the experimentally determined coefficients of friction.

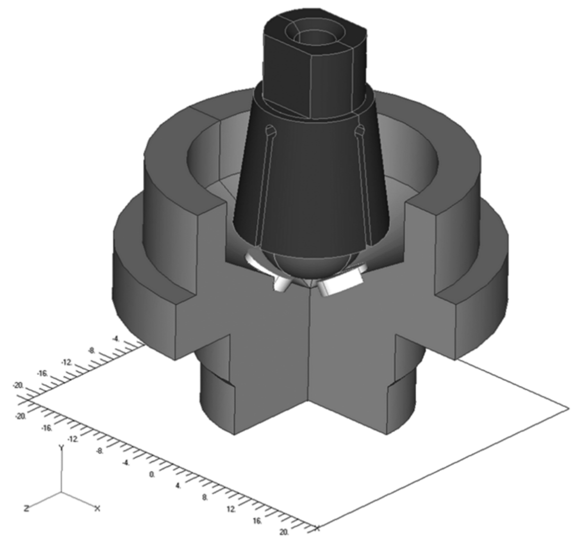

Fig. 1. The friction node in the 3-ball-disc (made of cup material) systems

Rys. 1. Węzeł tarcia w układzie kula-3 krążki z materiału panewki

RESULTS OF TESTS AND DISCUSSION

The tested materials had different wear resistance **(Tab. 1)**, **(Fig. 2)**. The elaboration of the results of tests was carried out with descriptive statistics tests. The normality of the decomposition of tested materials was checked. As a result, it was found that all variables had a normal distribution **(Fig. 3)**. Post-hoc tests showed that differences between all groups are statistically significant.

The greatest wear resistance assessed by the smallest value of the average wear defect of 0.68 mm was found for the Co28Cr6Mo alloy. Smaller wear resistance values were determined for 316L – 0.98 mm and for UHMWPE – 1.66 mm. The worst wear resistance was found in titanium alloys: Ti6Al4V – 3.25 mm and slightly better Ti6Al7Nb – 3.13 mm. The unit pressure in the contact zone was determined on the basis of average wear defects after the test run **(Tab. 2)**. For locomotion, a hip joint is annually subjected to millions of quasi-static loading cycles under bioelastohydrodynamic lubrication conditions. Unit pressure in the head and acetabular zone under physiological conditions reach as high as 20 MPa **[L. 6]**. Larger pressure values are present in endoprostheses, because tribological co-operation is performed on smaller surfaces. The head and cup may have diameters from ø22 mm, increasing by 2 mm, to ø44 mm. Exploitation of larger heads and cups causes the emission of greater amount of wear to the periarticular space. Endoprostheses ø32 mm with polyethylene cups deliver 50% more wear products than the ø22 mm **[L. 8, 9]**. The increase of the head reduces the risk of dislocations. In the wear tests, motion resistance was recorded and, on that basis, the coefficients of friction in the examined nodes were determined **(Fig. 4)**.

Table 1. Wear resistance of tested materials evaluated by average value of wear defect
Tabela 1. Odporność na zużycie badanych materiałów oceniona poprzez średnią wartość skazy zużyciowej

Material	Descriptive statistics				
	N tests	Average	Minimum	Maximum	Standard deviation
316L	30	0.98	0.70	1.25	0.15
UHMWPE	30	1.66	1.50	1.80	0.09
Co28Cr6Mo	30	0.68	0.60	0.75	0.04
Ti6Al4V	30	3.25	3.00	3.70	0.16
Ti6Al7Nb	30	3.13	3.00	3.30	0.08

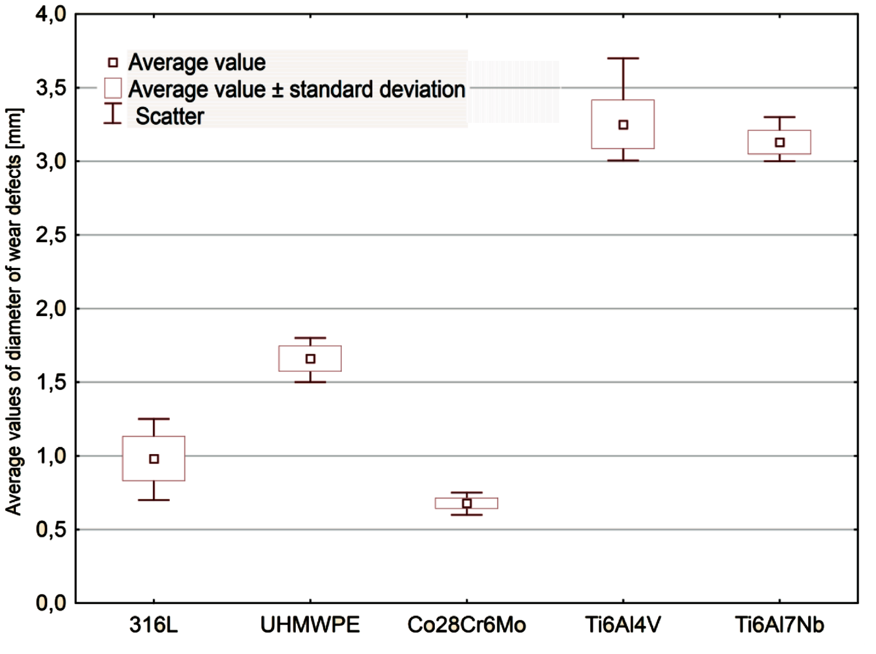

Fig. 2. Results of the wear resistance tests for materials designated for cups
Rys. 2. Wyniki badania odporności na zużycie materiałów przeznaczonych na panewki

The highest value of the coefficient of friction was found for 316L steel. The combination of a metal head with a UHMWPE bush gives about 10 times less friction compared to the 316L steel. The coefficient of friction of metal-UHMWPE pair with stable characteristics amounts μ = 0.06–0.08 and steel-steel μ = 0.7–0.8. Due to these very high resistance movements, the steel-steel combination has only historical conditions and currently it is not used in endoprosthetic constructions. This combination was used by Professor Adam Gruca who first implanted endoprosthesis in 1949 in Warsaw. UHMWPE is a very good sliding material that additionally has a load cushioning feature. It was first used by John Charnley in 1962. However, it has poor strength parameters. In addition, it is exposed to slow oxidation, especially in the environment of body fluids that accelerates its degradation **[L. 5, 10] (Fig. 5)**. Modern technologies producing polyethylene elements are being constantly improved, and it has also been applied in combination with metallic materials in hybrid cups **[L. 11, 12]**. Introducing a new type of polyethylene with much greater hardness and oxidation resistance provides favourable biomechanical and tribological conditions in individual solutions.

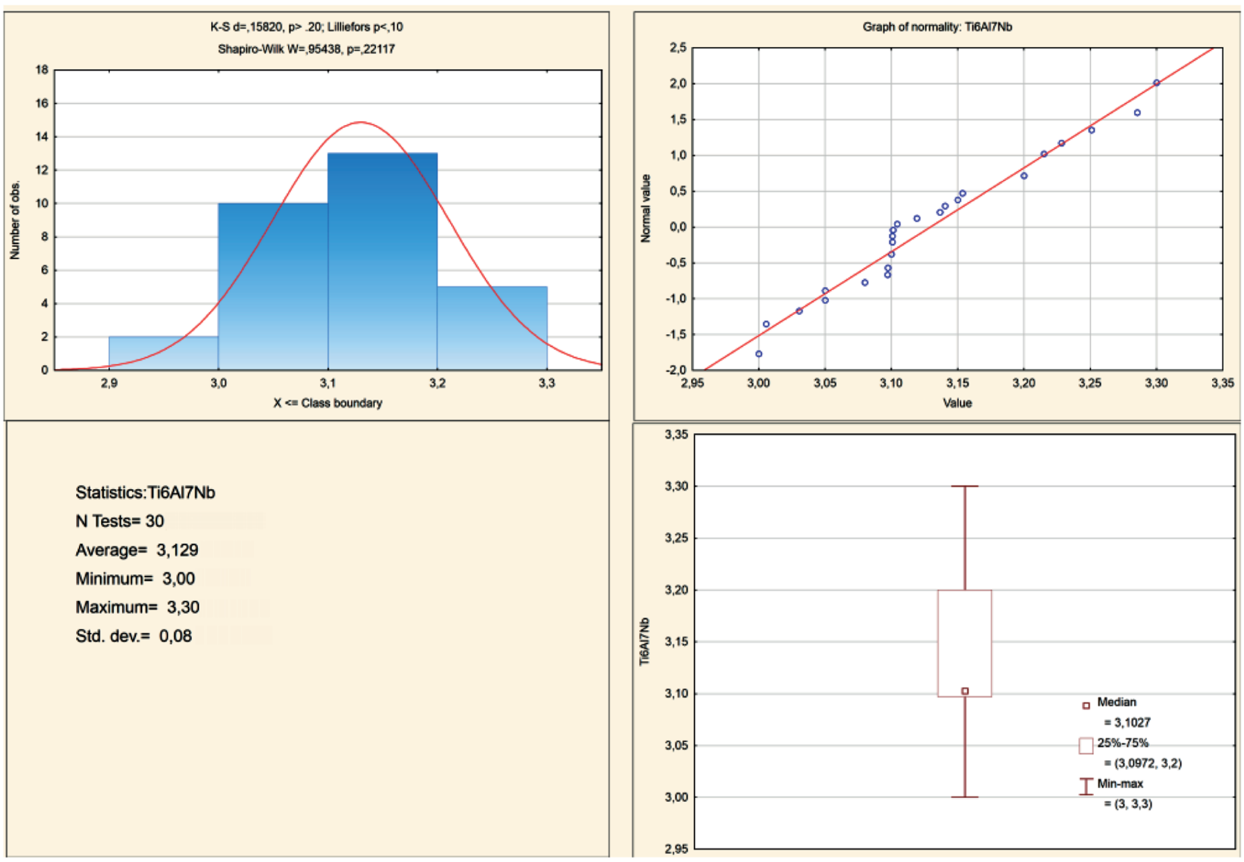

Fig. 3. Sample analysis of normal distribution for Ti6Al7Nb
Rys. 3. Przykładowa analiza normalności rozkładu dla Ti6Al7Nb

Table 2. Pressure in the tribological contact zone after the end of the research run
Tabela 2. Naciski w strefie kontaktu tribologicznego po zakończeniu biegu badawczego

Material	Average diameter of defect [mm]	Load force [N]	Surface area of defect [mm^2]	Contact pressure [MPa]
316L	0.98	40.82	0.75	54.43
UHMWPE	1.66	40.82	2.16	18.90
CoCrMo	0.68	40.82	0.36	113.39
Ti6Al4V	3.25	40.82	8.29	4.92
Ti6Al7Nb	3.13	40.82	7.69	5.31

The Co28Cr6Mo alloy tests point to a coefficient of friction of μ = 0.30–0.38 with a significantly higher value than the UHMWPE, but with the best wear resistance among the tested materials. Such parameters with the same good strength make it commonly used in friction pairs of endoprostheses. Approximate coefficients of friction values were found in the two tested titanium alloys: Ti6Al4V – μ = 0.33–0.40 and Ti6Al7Nb – μ = 0.20–0.48. Values of coefficients of friction for these alloys would be acceptable if it were not for very poor wear resistance, which is the worst of the tested biomaterials **(Fig. 2)**. Ti6Al7Nb is more promising due to better wear resistance and a lower coefficient of friction. However, this material should not be applied

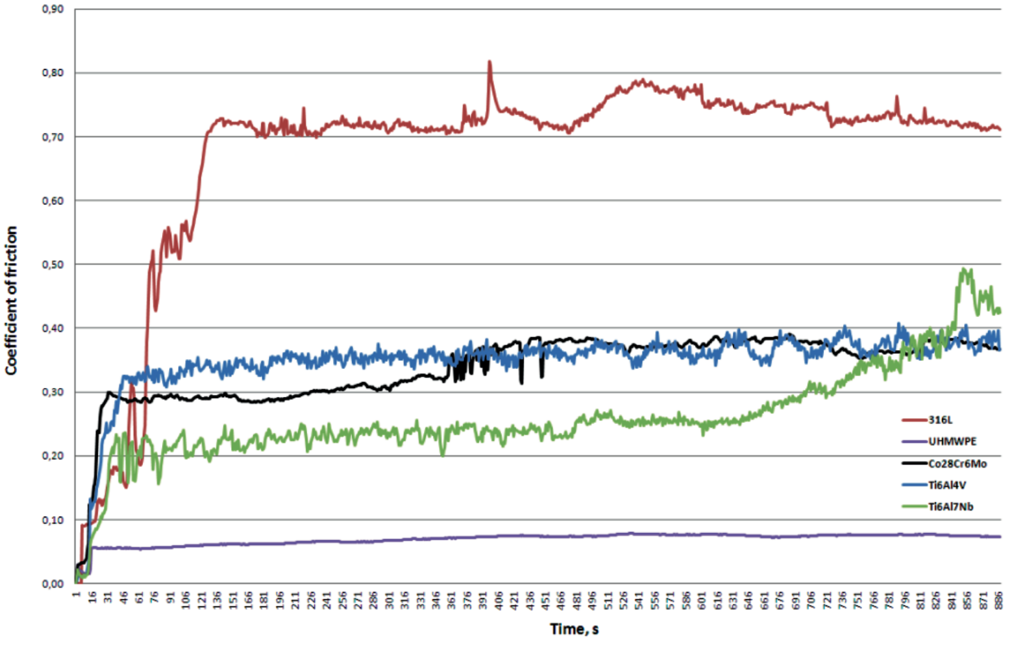

Fig. 4. The representative coefficients of friction in the examined nodes
Rys. 4. Reprezentatywne współczynniki tarcia w badanych węzłach

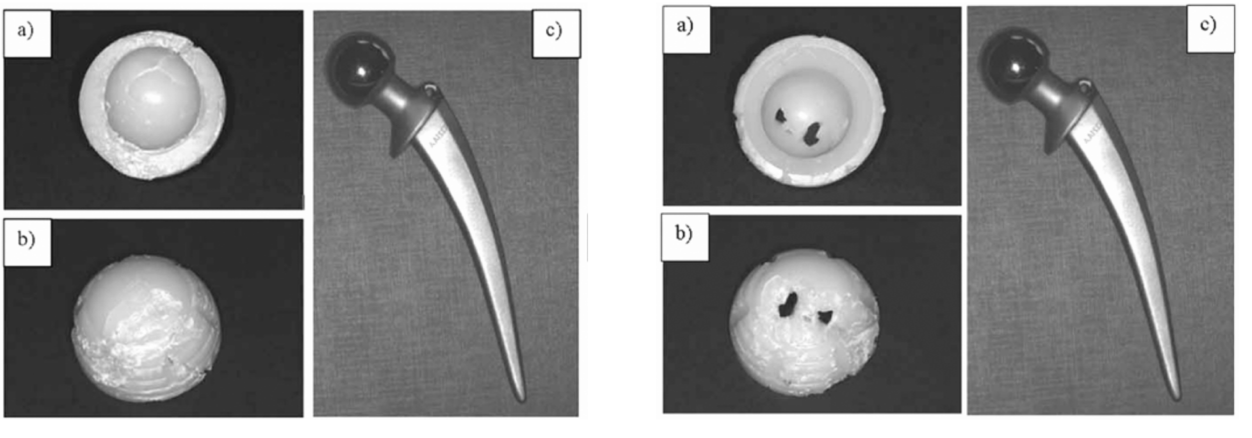

Fig. 5. Cemented endoprostheses of Weller type removed due to the complications after the alloplasty operation: a) cup from Sulene PE from the view of the side of contact with head, b) cup from Sulene PE from the view of the side of contact with cement, c) stem from Protasul-10 connected with head from Protasul-21WF [L. 6]
Rys. 5. Endoprotezy cementowe typu Weller usunięte z powodu powikłań po zabiegu alloplastyki: a) panewka z Sulene PE w widoku od strony kontaktu z głową, b) panewka z Sulene PE w widoku od strony kontaktu z cementem, c) trzpień z Protasul-10 spojony z głową Protasul-21WF **[L. 6]**

directly to the tribological layer of the cup. Therefore, the study involving the modification of the structure of this alloy and the production of coatings that would provide the wear resistance of the cooperating surface of the cup are conducted **[L. 13–15]**. In the implanted artificial joint, because of the cooperation of the head and the concave of the cup, there is both boundary friction and mixed friction. The motion resistance result from the applied tribological pairs and is substantially different from the movement resistance that occurs in the natural joint [**L. 3, 4, 6, 16–19**]. The wear products caused by friction in the movement area of the prosthesis with a size of 0.1 μm to 40 μm (come mainly from cup) access the periarticular tissues and can cause an allergic reaction. The correct co-operation between the head and the cup depends on the distribution of stresses and displacements, both in the tribological zone of collaborations of biobearing elements (in the head and cup) as well as in the farther bone structures. The wear and loosening of the cup are the most serious problems in the future prognosis **[L. 20–22]**. The improvement of the tribological cooperation of the used bearing pair, especially lowering wear and reducing the generation of friction products, may have an impact on conditions of the articulation of endoprosthesis and the length of her survival in the organism. Based on the conducted tests it can be stated that, in evaluation of biomaterial for the cups of endoprosthesis, the wear resistance is important, and the movement resistance characterized by coefficient of friction is less important. The presence of significant disproportions between the two parameters of the tribological process proves that the biomaterial is less useful on the cup of endoprostheses. This is the case for 316L and titanium alloys.

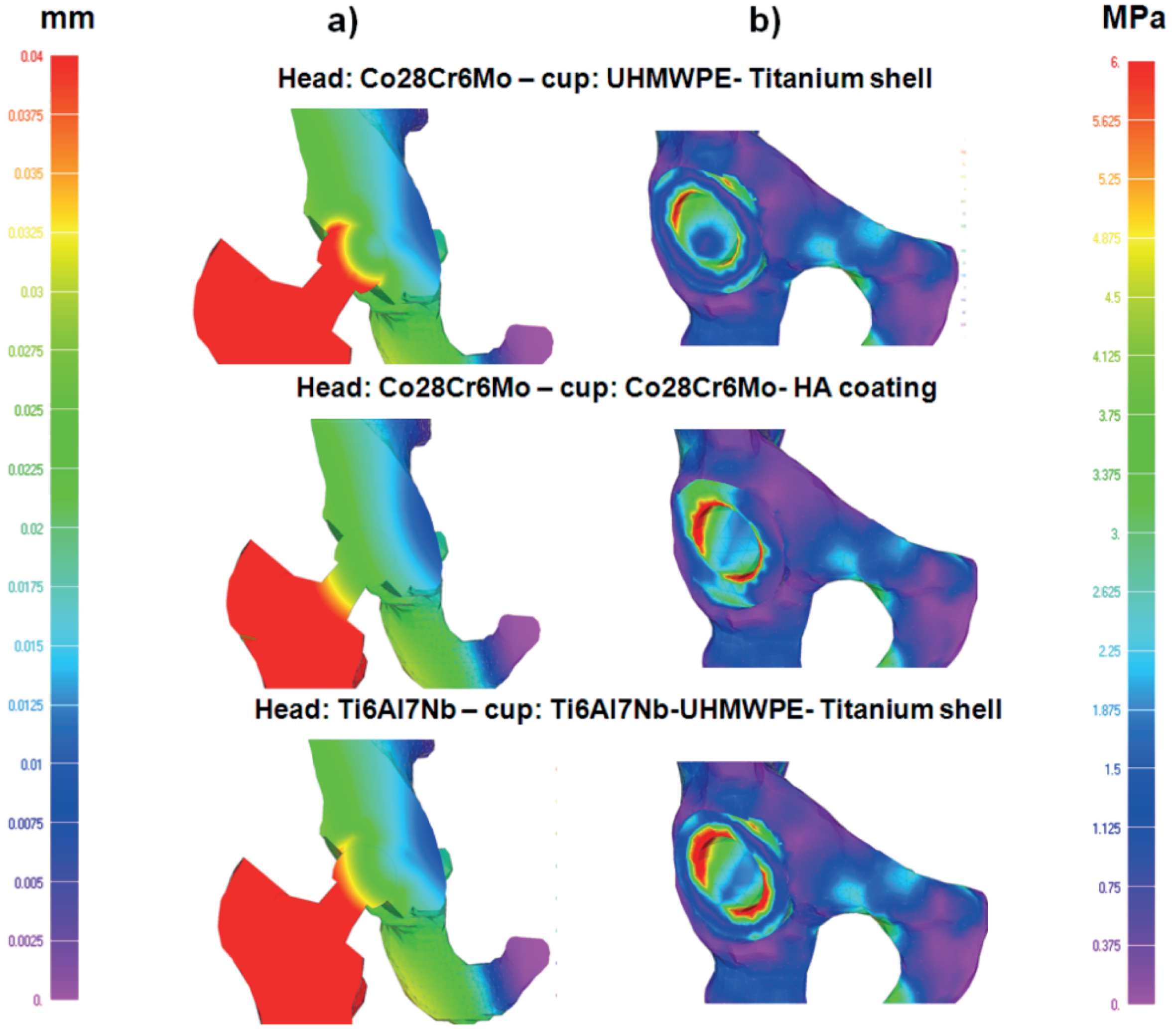

Fig. 6. FEM analyses in cementless endoprostheses models: a) maps of distribution of resultant displacements in the global models, b) maps of reduced stresses in the cup

Rys. 6. Analizy MES w modelach endoprotez bezcementowych: a) mapy rozkładu przemieszczeń wypadkowych w modelach globalnych, b) mapy naprężeń zredukowanych w panewce

Designated values of the coefficients of friction were used in the developed numerical analysis of FEM. This method is based on the modelling of pelvic rim structures based on CT, selection, modelling, and virtual application of the prosthesis for the anatomical structures of the patient, setting boundary conditions (constraints and locomotive loads) and assuming the material and tissue parameters on the global solid model. In the further procedure, the method is based on the determination of the complex condition of the load that is subjected to bone structures and the biobearing structure. Appropriate contacts are planned as follows: in the area of the implantation of endoprosthesis – node contact, in the tribological zone – contact with head movement in relation to the cup with setting of the coefficient of function. In the exemplary presentations of the results, the maps of displacements distributions and reduced stresses in a cementless endoprosthesis

(Alloclasic Zweimiller) and a cemented one (Weller) **(Figs. 6, 7** and **8)** are presented. The simulation under load conditions of both limbs indicates that maximum displacements of 0.04 mm occur in the stem and head of the prosthesis. The range of maximum displacements is greatest in contact with the Co28Cr6Mo with UHMWPE and the smallest, only limited to the stem, for head and cup made of Co28Cr6Mo **(Fig. 6)**. The loss of stem retention may occur during locomotive activities, and transferring loads and micro movements can expand the femur. The distribution of displacement in the tribological zone of cooperation depends primarily on the construction material of the cups **(Figs. 6** and **7)**. In the analysed distribution of resultant displacements in the cup, there is a characteristic asymmetry of their values. The determined displacement gradients are as follows: for the endoprosthesis – head: Co28Cr6Mo – cup: Co28Cr6Mo – 0.01 – 0.28 mm; for the endoprosthesis – head: Ti6Al7Nb – cup: Ti6Al7Nb-UHMWPE – 0.01 – 0.34 mm; end for the endoprosthesis – head: Co28Cr6Mo – pan: UHMWPE – 0.01–0.40. This asymmetry causes ovalization of cups, especially made from UHMWPE. It is a process, among other things, that determines the degradation of these cups and generates excessive amounts of wear into the periarticular space **(Fig. 5)**. The reduced stresses distributions in the analysed cups of the endoprostheses were varied in the range of 0 to 6 MPa. The largest stress area with maximum values occurred in combination of head of Ti6Al7Nb – cup of Ti6Al7Nb – UHMWPE. The lower range of reduced maximum stresses was found for the following associations: head: Co28Cr6Mo – cup: Co28Cr6Mo, head: Co28Cr6Mo – cup: UHMWPE. In the wear resistance tests of titanium alloy cups, the worst parameters were found **(Fig. 2)**. In correlation with the numerical simulation results, indicating the asymmetry of displacement and the stress concentration of reduced stresses on the inner edge of the cup, it can be stated that this is not a suitable association in the biomechanical and tribological aspects **(Figs. 6** and **7)**.

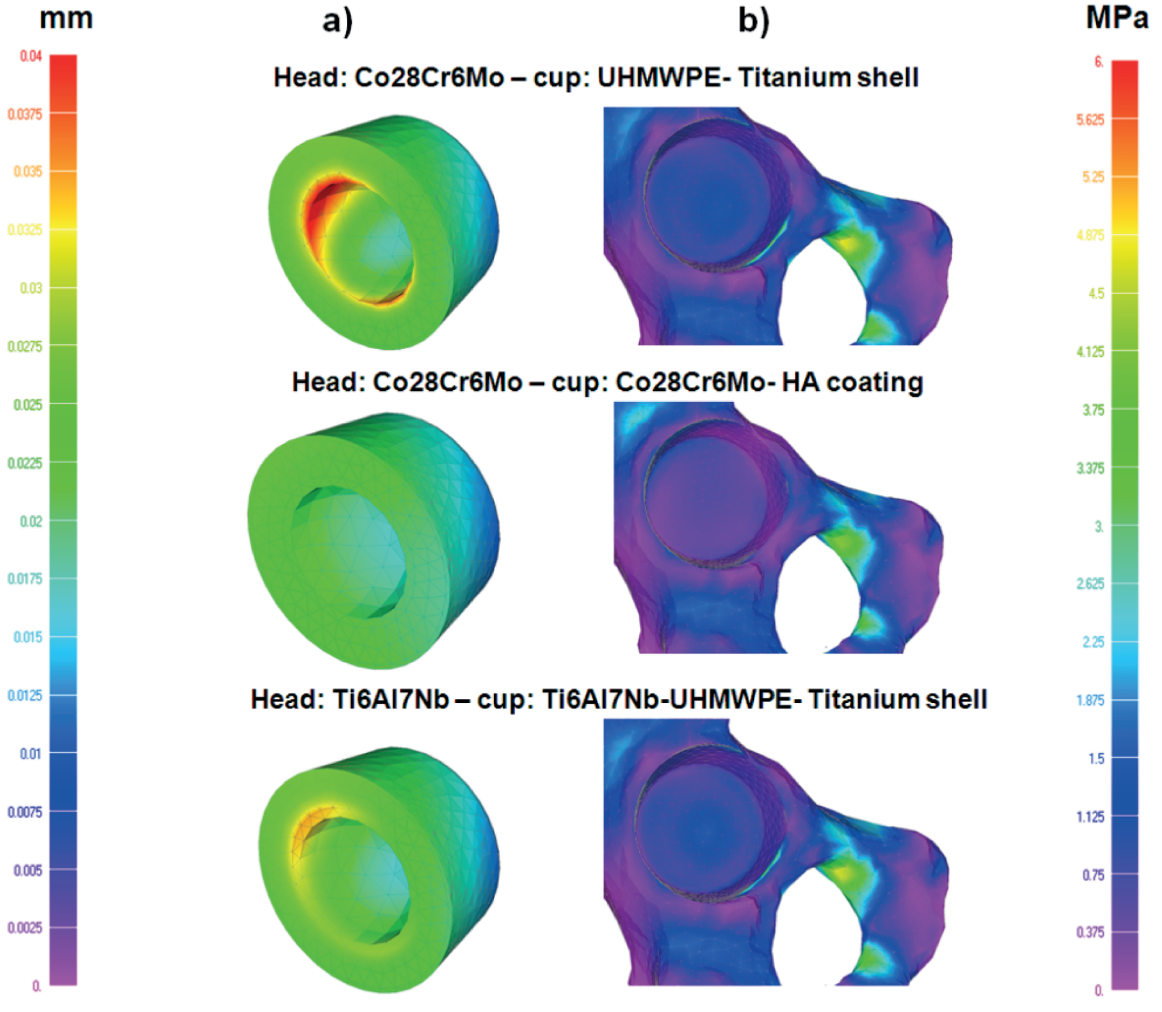

Fig. 7. The results of FEM analysis: a) distribution of resultant displacements in cup, b) maps of distribution of reduced stresses in pelvic bones resulting from contact with the cup

Rys. 7. Wyniki analizy MES: a) rozkład przemieszczeń wypadkowych w panewce, b) mapy rozkładu naprężeń zredukowanych w kości miednicznej wynikające z kontaktu z panewką

The reduced stresses resulting from contact with pelvic bone were analysed in the numerical models **(Fig. 7b)**. In all cases, a slight asymmetry of stress was observed. Their values did not exceed the physiological capacity of bone tissue and there was compression stimulation that optimized the osteointegration process.

The asymmetry of displacement, resulting in the avalisation of cups, was noticed in cemented endoprostheses (Weber endoprostheses) with UHMWPE cups **(Fig. 8)**. The occurrence of the ovalisation UHMWPE cups was confirmed by observations of cemented endoprosthesis that were removed due to loosening **(Fig. 5)**.

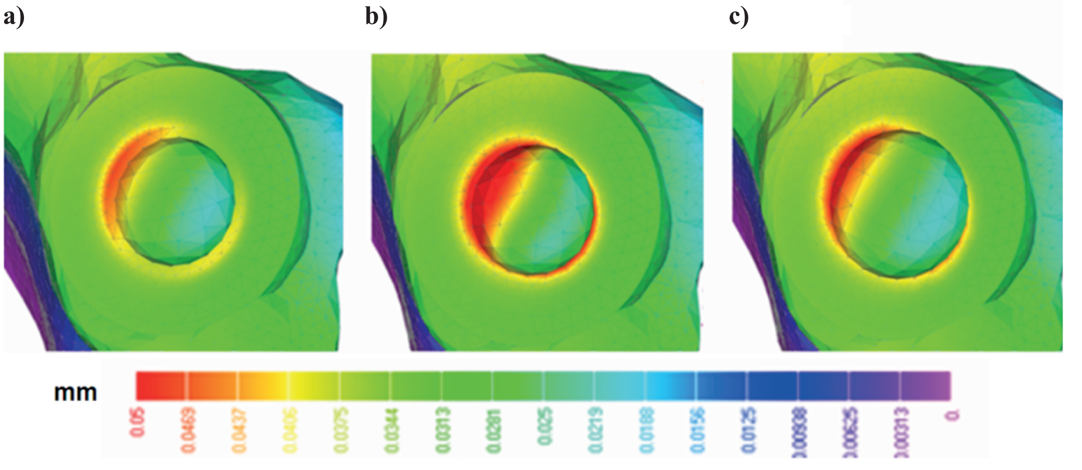

Fig. 8. The distribution of resultant displacements in cups fixed in pelvic bones using cement: a) Co28Cr6Mo – UHMWPE with inner diameter ø 28 mm, b) UHMWPE cup with inner diameter ø 28 mm, c) UHMWPE cup with inner diameter ø 32 mm; (heads of endoprostheses of Co28Cr6Mo)

Rys. 8. Rozkłady przemieszczeń wypadkowych w panewkach osadzonych w kości miednicznej na cemencie: a) panewka dwuwarstwowa Co28Cr6Mo – UHMWPE o średnicy wewnętrznej ø 28 mm, b) panewka UHMWPE o średnicy wewnętrznej ø 28 mm, c) panewka UHMWPE o średnicy wewnętrznej ø 32 mm; (głowy endoprotez z Co28Cr6Mo)

The stresses and displacements that are transferred to hard structures can stimulate bone formation, but they can also exceed the threshold of physiological tissue capacity and cause inflammation and osteolysis. That situation can lead to the loosening of the implant and the necessity of reimplantation **[L. 6, 23]**. The analysis of the spread of stresses and displacements in the contact area of the head and the acetabulum, in the construction of the artificial biobearing and in the structures of the proximal end of the femur and pelvic girdle of the pelvic bone, may indicate the causes of loosening resulting from the construction and material parameters of the endoprosthesis and clinical and anatomical conditions. The improvement of the tribological cooperation of the applied bearing pair, especially lowering wear and lowering the coefficient of friction, may affect the condition of the articulation of the prosthesis and the length of its survival in the body.

The factors that determine the process of the wear of the head and cup of endoprosthesis are the following: the unit pressure in the tribological contact area and their distribution, resistance to motion, the type of co-operating materials its structure and the stereometry of the surface layer, as well as the biomechanical extortion related to the nature of the patient's locomotion. The dominant phenomena are abrasive wear, fatigue wear, and displacement and deformation and degradation of biomaterials. The simulations of contact of structural elements are useful in the evaluation of biomaterials for cooperation in endoprotection, because, on that basis, in correlation with tribological parameters, one can make conclusions about the distribution of stress and displacement that may determine the lifetime of the implant. Due to the assurance of the proper biomechanics of contact, at the present level of imaging diagnostic methods, the surgical operation should be preceded by CT imaging of the pelvic girdle, modelling of its structures, optimal geometrical selection of the elements of the prosthesis, and their positioning **[L. 24, 25]**. Such a procedure can improve the conditions of load transfer and improve tribological cooperation in the implanted joint.

CONCLUSIONS

On the basis of the conducted tests, it can be stated that, in the selection of material for cups of endoprosthesis, the wear resistance is important, and the coefficient of friction in contact head and cup in the prosthesis is less important. The presence of significant disproportions between the two parameters of the tribological process proves that the biomaterial is less useful on the cup of endoprostheses.

The simulations of the contact of structural elements are useful in the evaluation of biomaterials for cooperation in endoprotection, because, on that basis, in correlation with tribological parameters, one can make conclusions about the distribution of stresses and displacements that may determine the lifetime of the implant.

So far, despite the tremendous progress in the field of breeding and multiplication of chondrocyte, matrices for their application, treatment procedures using stem cells and tissue transplants, medical scientists cannot reproduce normal hip function. Moreover,, advanced biomaterial technologies and the modern system of artificial joint construction encounter significant restrictions in biocompatibility, abrasive and fatigue wear, and reliability.

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