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ANALYSIS OF STRESSES AND STRAINS DISTRIBUTION OF POLYETHYLENE CUPS IN HIP JOINT ENDOPROSTHESIS AT VARIOUS ARTICULAR JOINTS AND FRICTION CONDITIONS

The article has been devoted to issues connected with the alloplasty and hip joint endoprostheses, that elements are being developed, which is supported by strength, tribological tests on used biomaterials, incl. polyethylene or computer modelling based on e.g. finite element method (FEM). In this paper, the results of research on the impact of the material articulations of the system head – acetabular and friction conditions on strength parameters of polyethylene components in the hip joint endoprosthesis. Numerical analysis of this friction node was carried out, using the ADINA System computer program and the simulations were performed at various friction conditions for metal/ polyethylene and ceramic/ polyethylene articulations with various UHMWPE modifications. The simulations results have shown the influence of tested material associations and friction conditions on parameters related to the strength of polyethylene cups, i.e. their displacements, stresses and deformations.

Keywords: polyethylene, UHMWPE, hip joint endoprosthesis, friction conditions, computer modelling

1. Introduction

The civilisation development is one of the factors that have to a large extent led to progress in areas such as biomedical engineering or medicine, which was caused by negative phenomena associated with it, incl. an increase in the number of accidents and diseases of the musculoskeletal system or a reduction in human motor activity. In turn, this can lead to mechanical injuries of joints (coming from overloading), cartilage damages, fractures or bone crushing, then degenerative- distortionary changes and finally to a loss of biofunctionality in the joints, becoming a source of severe, chronic pain [1]. In most cases such lesions of synovial joints are removed during joint alloplasty, as a result of excision of natural joint and inserting an implant, i.e. an endoprosthesis made of biocompatible materials in its place [1]. The aim of this joint replacement procedure is primarily to reconstruct the damaged joint through possible the best modelling of its macro- and microgeometry (mainly concerning the friction node), tribological, material and functional conditions, to eliminate pain, as well as to ensure appropriate durability of the endoprosthesis (i. e. the longest possible period of its functioning in the human body) [2-3].

In the case of the hip joint, which is most often reconstructed next to the knee joint due to their highest load, contributing to their damage and degeneration, this replacement procedure may be total or partial [4]. In turn, hip endoprosthesis consists of three basic elements, i.e. a cup implanted in a pelvic bone and a metal stem inserted in the femoral marrow cavity, which together with the head of the prosthesis may form a single unit – sometimes they are separate components – Fig. 1a [5]. In some types, an additional element is a metal basket, in which an artificial acetabulum is placed, which is presented in Fig. 1b [4,6-8]. The implant components can be fixed by pressing or screwing, but additionally, these elements are covered with a porous layer (usually HAp – hydroxyapatite, sputtered titanium or a mixture of these substances) on all or part of its surface. In turn, in the case of cement-fitted endoprostheses, the elements are fixed by means of bone cement (PMMA), whereas in hybrid prostheses stems are fitted with cement and cups are pressed into bone. In addition, it should be mentioned that fixing the endoprosthesis with bone cement is strong and is a prelude to the incomplete loading of the lower limb in the first day after alloplasty. On the other hand, cement-free joints are based on the phenomenon of osseointegration of the bone and the porous layer, the speed of this process and the durability of the joint depend on the type of porous material (titanium-based layers outgrow slowly than those based on HAp) [4,9].

The node head – acetabular cup forms a basic component of the hip joint endoprosthesis, i.e. a friction system, in which elements are made of various types of biomaterials meeting

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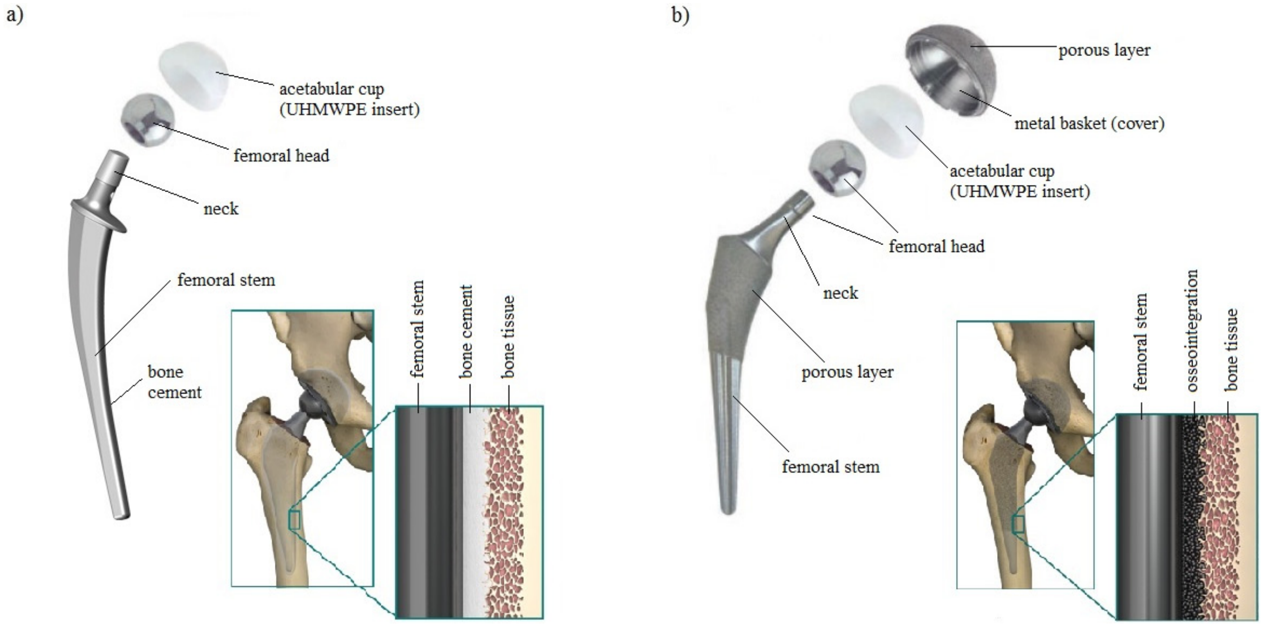

Fig. 1. The construction of hip endoprosthesis and methods of its attachment – (a) cement-fixed and (b) cementless

biological, strength, tribological and technological requirements [6,10-11]. Their appropriate selection is one of the factors influencing significantly on the frictional resistance, wear resistance and absolutely on the endoprosthesis durability. In the case of these types of implants, the following joint articulations are applied [4,12]:

- ceramic/ metal head – ceramic cup (alumina Al_2O_3 or zirconium ZrO_2 ceramics),
- ceramic/ metal head – polyethylene cup (mainly UHMWPE and its modifications),
- metal head – metal cup.

The variety of these materials is associated with different strength parameters. This – in turn – is connected with the endoprosthesis durability, which is however limited by wear processes of cooperating surfaces of friction node elements, mainly polyethylene inserts, that are the weakest components [13]. This material is characterised by a low wear resistance and to ageing due to activity of UV radiation and oxygen, causing accelerated photooxidation, cracking and increasing the material brittleness. These processes can lead to bone tissues damages, deformations, chemical changes and loosening of implant components and necessity of reimplantation [14-15]. Relatedly, strength and tribological tests of the implants as well as individual elements of the endoprostheses have been carried out to obtain information on frictional and wearing processes in implanted joint endoprostheses in the human body. These tests also enable to determine the values of strength parameters of applied materials or roughness of the surface layers of used elements [3]. These research can be performed on tribotesters and simulators, as well as based on computer aided engineering works – CAE, using increasingly modern equipment and computing environments to model and simulate various issues, incl. tribological ones [1,16]. For joint components (including primarily polyethylene components used for knee and hip endoprostheses), experimental and numerical tests can be carried out using finite element method (FEM) tools, which results have been presented in past publications that mainly concerned the determination of coefficients of friction for various materials used for the friction pairs of the system head – cup [1,17]. The effect of load acting on the implant on this factor and on polyethylene wear has been also analysed [17-18]. For example, in the papers [1], [17] and [19], the authors published conclusions from tribological studies carried out on a hip joint simulators or tribotesters, determining the coefficient of friction values for various associations of materials of the pair head – acetabular cup (incl. polyethylene, ceramic and metal cups). In turn, the paper [18] has presented the results of tests concerning the wear of both metal and polyethylene components, determining the dependence of the coefficient of friction and linear wear on the number of cycles for given material associations. On the other hand, in the work [20] it has been published the results of obtained numerical tests using the ADINA program and the Finite Elements Method (FEM), presenting the distributions of stresses, reduced deformations and displacements in the system implant's head – cup at different implant loads and for different material associations of the friction node. Also authors of work [13] studied stresses and strains in this system at different material pairs and loads, showing that they are similarly low as that in natural conditions . In turn, in the paper [21] the author has presented results of numerical tests for various arrangements of endoprosthesis, which were concerned wear of polyethylene cups, whereas in the work [22] modelling studies based on the movable cellular automaton (MCA) method indicated the promising use of metallic alloys with biocompatible ceramic coatings in friction pairs to increase the service life of hip resurfacing. Also authors of work [23] applied FEM to determine abrasive wear of UHMWPE for acetabular cup – head from CoCr alloy at different tilt angles. In turn, in the paper [24] scientists have showed results of numerical tests for implants with standard holes, which fulfill strength requirements at maximum strains and assumed load system, whereas work [25] has been concerned research results of pressure and cup deformation, which was carried out at different friction conditions (wet and dry) and for two geometric configurations.

Therefore, the research with the use of numerical simulations was carried out with the aim of analysis of parameters related to the strength properties of polyethylene elements, which are used as components in the friction nodes of hip joint endoprostheses. Stresses, displacements and strains (deformations) of polyethylene cups were assessed at different material associations of head – acetabular system and at the resulting friction conditions.

2. Experimental – numerical tests of friction node: hip endoprosthesis head – polyethylene cup

Conducted numerical research for scientific and didactic purposes, using FEM methods, has concerned the modelling of tribological processes for various material associations of the hip joint endoprosthesis friction node. Moreover, these studies have aimed to show the influence of the tested associations and friction conditions on the parameters related to the strength properties of polyethylene cups, mainly on their displacements, stresses and deformations.

2.1. Physical model of friction node endoprosthesis head – cup

Physical model of the friction node: hip joint endoprosthesis head – cup, which is presented in Fig. 2, has been developed in Autodesk Inventor Professional 2019, which is one of the standard 3D mechanical design software. Basic geometric dimensions studied system elements: implant's head and cup were determined based on data from various manufacturers.

Research were carried out on the following material associations: metal (CoCrMo alloy)– polyethylene and ceramics (Biolox®delta Al_2O_3) – polyethylene, whereby these friction pairs, applied in further numerical simulations, have been collected in Table 1 [1,14,17,19-20]. In turn, strength parameters of materials used in numerical tests have been correlated in Table 2 [1,14,17,19-20].

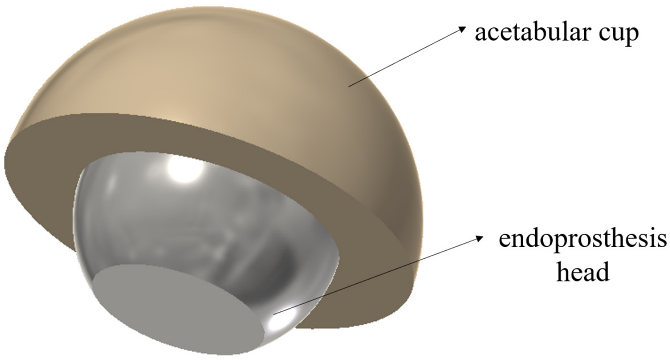

Fig. 2. Physical model of friction node: hip joint endoprosthesis head – cup developed in Autodesk Inventor Professional 2019

TABLE 1

Material associations of the friction node endoprosthesis head – polyethylene cup and their friction coefficients

Endoprosthesis head/ cup	UHMWPE	HXLPE	HXLPE + Vit. E (ePoly)
stop CoCrMo	0.059	0.15	0.13
Biolox®delta Al_2O_3	0.10	0.18	0.09

TABLE 2

Strength parameters of endoprosthesis head and cup materials used in the performed simulations

Material	Young's modulus E[Pa]	Poisson's coefficient ν	density ρ [kg/m^3]
CoCrMo alloy	$2.0\div2.1\cdot10^{11}$	0.3	$8.3\cdot10^3$
Biolox®delta Al_2O_3	$3.8\div4.2\cdot10^{11}$	$0.21\div0.27$	$3.9\cdot10^3$
UHMWPE	$0.7\div1.0\cdot10^9$	$0.4\div0.46$	$9.6\cdot10^2$
HXLPE	$0.35\div3.5\cdot10^9$	0.46	$9.4\cdot10^2$
HXLPE +Vit. E (ePoly)	$5.2\div5.5\cdot10^8$	$0.45\div0.46$	$9.4\cdot10^2$

2.2. Research methodology. Numerical model of studied system: endoprosthesis head – cup

Numerical tests of the friction node: endoprosthesis head – polyethylene acetabular at various material associations have been carried out using the ADINA System 9.4 computational environment. The model of this system has been developed in the ADINA Structures module and due to the axial-symmetry of the whole system as well as its individual elements, its geometry has been simplified by modelling it in the YZ system (Fig. 3) and defined in accordance with the physical model performed in Autodesk Inventor Professional 2019. In turn, applied materials (in accord with parameters presented in Table 2) have been modelled as linear elastic and isotropic. Hence, data related to strength and physical properties, i.e. Young's modulus, Poisson's coefficient and density – were entered into a numerical model in accord with parameters presented in Table 2.

Polyethylene cup was immobile through divesting it of all degrees of freedom. Moreover, the system was subjected to a load, i.e. displacement (Fig. 3c), which value was implemented to model. Friction conditions have been also determined according to data from Table 1 and the model was discretised into 2D axisymmetric Solid Elements.

3. Results and discussion

The results of the simulations were performed in the Post-Processing module of the ADINA program and then the influence of various material associations and friction conditions of the

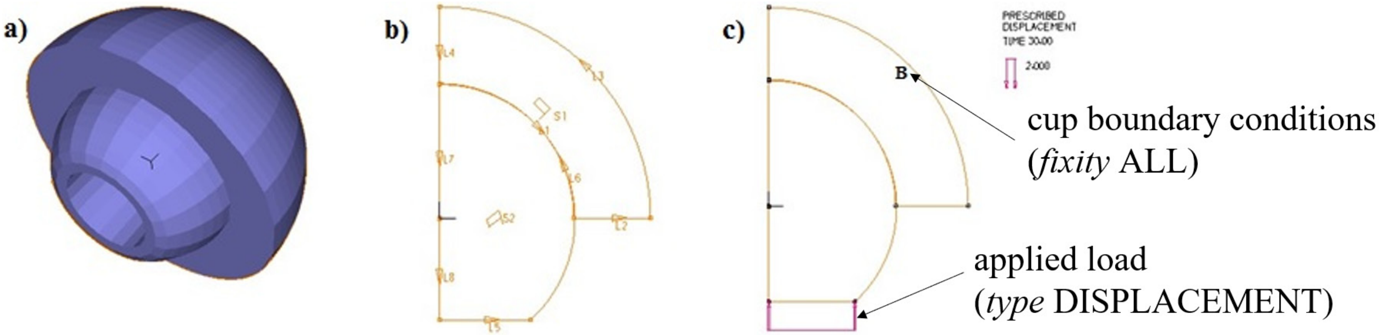

Fig. 3. Numerical model of endoprosthesis friction node: a) volume model, b) system simplification, c) system with applied load and boundary conditions

system hip joint endoprosthesis head – cup on displacements, stresses and deformations of the polyethylene acetabular (which were determined from numerical model) was analysed. In the Fig. 4 and Fig. 5 the displacements of PE cups in Y and Z direction at different material associations of the studied system are presented. In turn, Fig. 6 concerns the effect of these associations on the effective strains of polyethylene acetabular, whereas Fig. 7 and Fig. 8 presents the results of cup deformations (YY-Strains and YZ-Strains).

3.1. Analysis of influence of material associations on acetabular displacements

Based on the undermentioned results (Fig. 4) it can be seen that at the lowest friction coefficient of the head – acetabular system (μ = 0.059), i. e. for the CoCrMo – UHMWPE pair, the maximum movements of the cup in the Y direction are 1.256 mm ($1.256 \cdot 10^{-3}$ m), whereas when we use an element with HXLPE (increasing the coefficient to μ = 0.15), this value decreases by approx. 257 mm, i.e. ~20.5%. Moreover, studies show that for both UHMWPE and modified (HXLPE and ePoly) cups, increase of the friction coefficient causes a decrease in the maximum values of cup movements in Y direction, with them being located close to the friction node and decreasing as they move away from it.

In turn, from the results of displacements in Z direction (Fig. 5), it can be concluded that for the pair with the lowest coefficient of friction (CoCrMo alloy – UHMWPE) the maximum values were 1.854 mm and the minimum values were –0.7003 mm. With an increase in the friction coefficient from μ = 0.059 to μ = 0.18 (Biolox delta – HXLPE), the maximum values decreased approx. 1.03 times, while the minimum increased to 0.6027 mm (or by 14%). Moreover, it can be also stated that in the cases with ceramic heads maximum displacements in the Z direction are larger than in the pairs with metal heads.

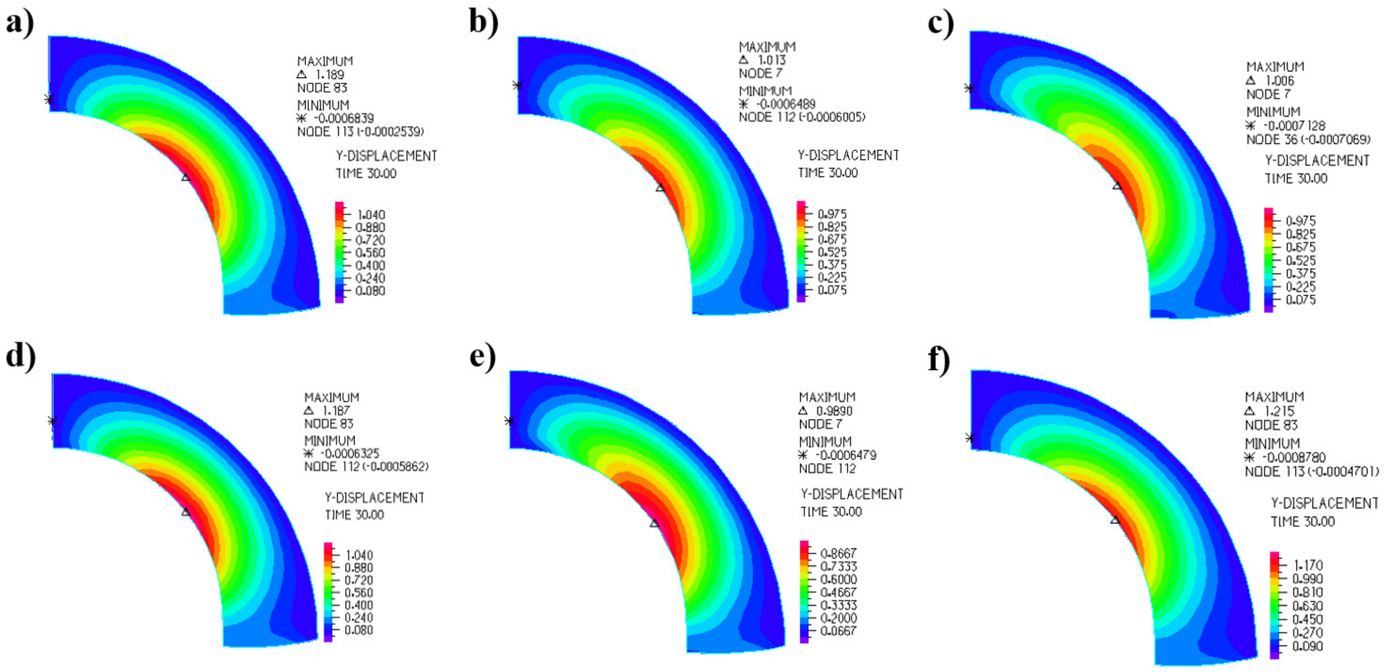

Fig. 4. Acetabular diplacements in Y direction for friction node at various material associations of the system endoprosthesis head – cup: a) CoCrMo alloy – UHMWPE, b) CoCrMo alloy – HXLPE, c) CoCrMo alloy – ePoly, d) Biolox delta – UHMWPE, e) Biolox delta – HXLPE, f) Biolox delta – ePoly

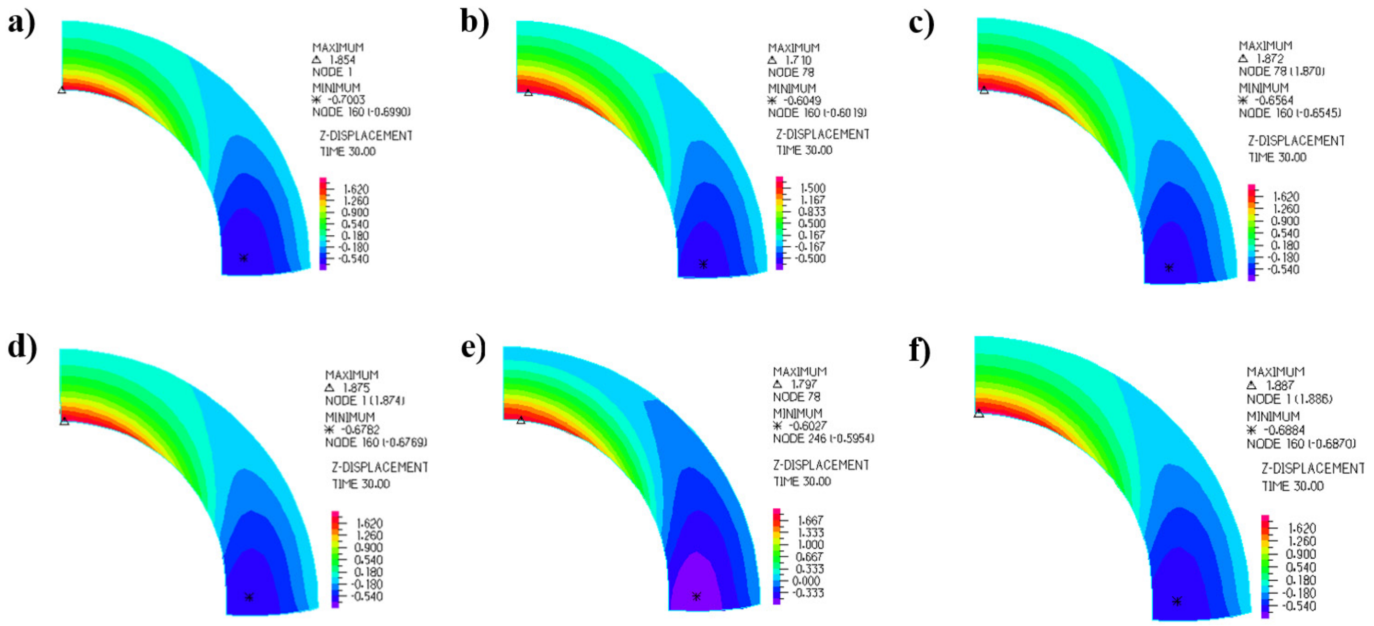

Fig. 5. Acetabular diplacements in Z direction for friction node at various material associations of the system endoprosthesis head – cup: a) CoCrMo alloy – UHMWPE, b) CoCrMo alloy – HXLPE, c) CoCrMo alloy – ePoly, d) Biolox delta – UHMWPE, e) Biolox delta – HXLPE, f) Biolox delta – ePoly

3.2. Analysis of influence of material associations on acetabular effective stresses

On the other hand, from the results related to distribution of effective stress (Fig. 6), it can be concluded that the highest values of maximum and minimum of these parameters are found in systems with HXLPE and UHMWPE cups, which is mainly due to the differentiation of Young's modulus of these materials. In addition for pairs with UHMWPE and ePoly, there is a decrease in maximum and minimum stress when the friction coefficient increases. For example, for the CoCrMo – UHMWPE friction system ($\mu = 0.059$), the maximum stress is $415.1 \cdot 10^6$ Pa, while increasing the coefficient of friction to $\mu = 0.10$ (Biolox delta – UHMWPE pair), a decrease of $27.2 \cdot 10^6$ Pa was noted. It can also be concluded from the results that for each tested material association of this system, the further away from the friction node, the lower stresses are.

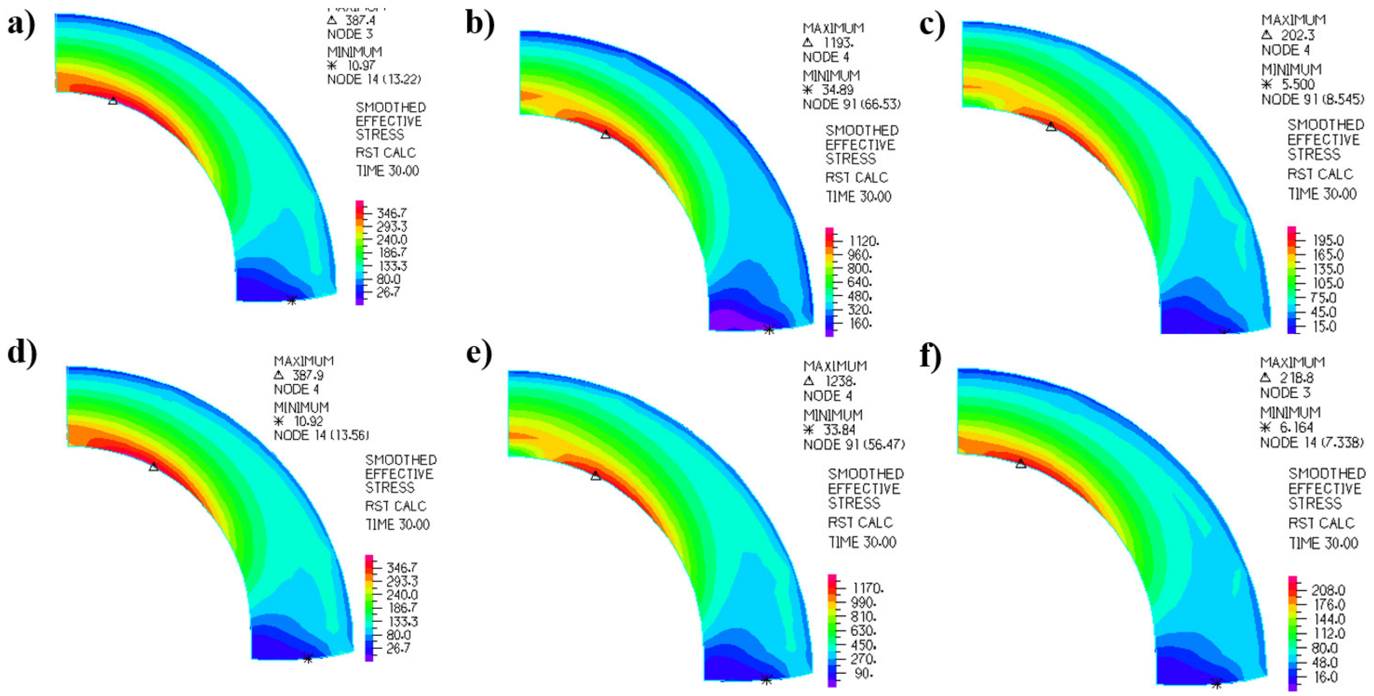

Fig. 6. Acetabular effective stresses for friction node at various material associations of the system endoprosthesis head – cup: a) CoCrMo alloy – UHMWPE, b) CoCrMo alloy – HXLPE, c) CoCrMo alloy – ePoly, d) Biolox delta – UHMWPE, e) Biolox delta – HXLPE, f) Biolox delta – ePoly

3.3. Analysis of influence of material associations on acetabular deformations

The below results concerned about the cup deformations indicate that for the associations with HXLPE and ePoly cups, minimum and maximum values of deformations YY increase when the friction coefficient is increased. For example, for the pair CoCrMo – HXLPE ($\mu = 0.15$) the maximum value of this parameter is 0.1597, and for the association of this type of cup with a ceramic head with an increase in the friction coefficient of 0.03, the maximum value of deformation is increased by 0.017. Moreover, on the basis of these simulations, it can be concluded that for all material associations of the tested system, YY deformation values occur in the upper parts of the acetabulum, closer to the friction node, while going down, they decrease.

In turn YZ-strain distributions show that for both metal and ceramic head pairs the maximum strain values YZ decrease when the friction coefficient increases. For example, for the Biolox delta – E-Poly pair ($\mu = 0.09$), the maximum values are 0.1824, while a twofold increase in the coefficient of friction for the system of HXLPE cup with ceramic head leads to a decrease in the maximum values of 0.0106 (i. e. 5.8% of the aforementioned value). Moreover, these results show that the highest deformations YZ are located in the lower parts of the acetabulum, closer to the outer edge of the acetabulum, and the lowest – near the inner edge, at the friction node.

On the other hand, the results concerning the distribution of ZZ deformations indicate that for pairs of individual cups with metal head the maximum values decrease with the increase of friction coefficient. For example, CoCrMo – ePoly ($\mu = 0.13$) has a maximum deformation of 0.069944, while an increase in the coefficient of friction of 0.02 (CoCrMo – HXLPE) contributes to a decrease in the maximum values of 0.00551 (by ~7.88% of the above mentioned value). Studies also show that in the case of associations with ceramic head, an increase in the friction coefficient of this system contributes to the reduction of the maximum ZZ strains. For example, for the Biolox®delta – ePoly pair ($\mu = 0.09$), the maximum values are: 0.07209, while a twofold increase in the friction coefficient for the HXLPE – ceramic head system leads to a decrease in the maximum values of 0.00604 (i.e. by ~ 8.4% of the aforementioned value). Moreover, these results also show that for each material association of the studied system, the highest ZZ strains occur in the lateral and lower parts of the cup and going up, these deformations fall.

According to the previously conducted tests, friction coefficient in the contact endoprosthesis head – acetabular cup primarily depends on two factors, i.e. material types of frictional pair and their surface roughness [20]. Determined and applied in numerical research values of this parameter are within in the range of it assessed in studies showed in articles [1,14,17,19], whereby it should be mentioned that these values are many times higher than these occurring in natural human joints [16,17]. In turn, above-mentioned results of strains and stresses correlate with results of research presented in article [20], where authors in addition showed an impact of load on stress and strain distribution in the system head – acetabular cup, because a load increase can cause an increase in these parameters of polyethylene cups. Whereas, in paper [1] experimental and numerical research proved that stress value on the contact surfaces of elements of friction pair: endoprosthesis head – acetabular cup under the same load conditions strictly depends on the type of matched materials, which was also showed in above-mentioned studies carried out for the purpose of this article. Furthermore, it can be concluded that application of materials with extremely differing

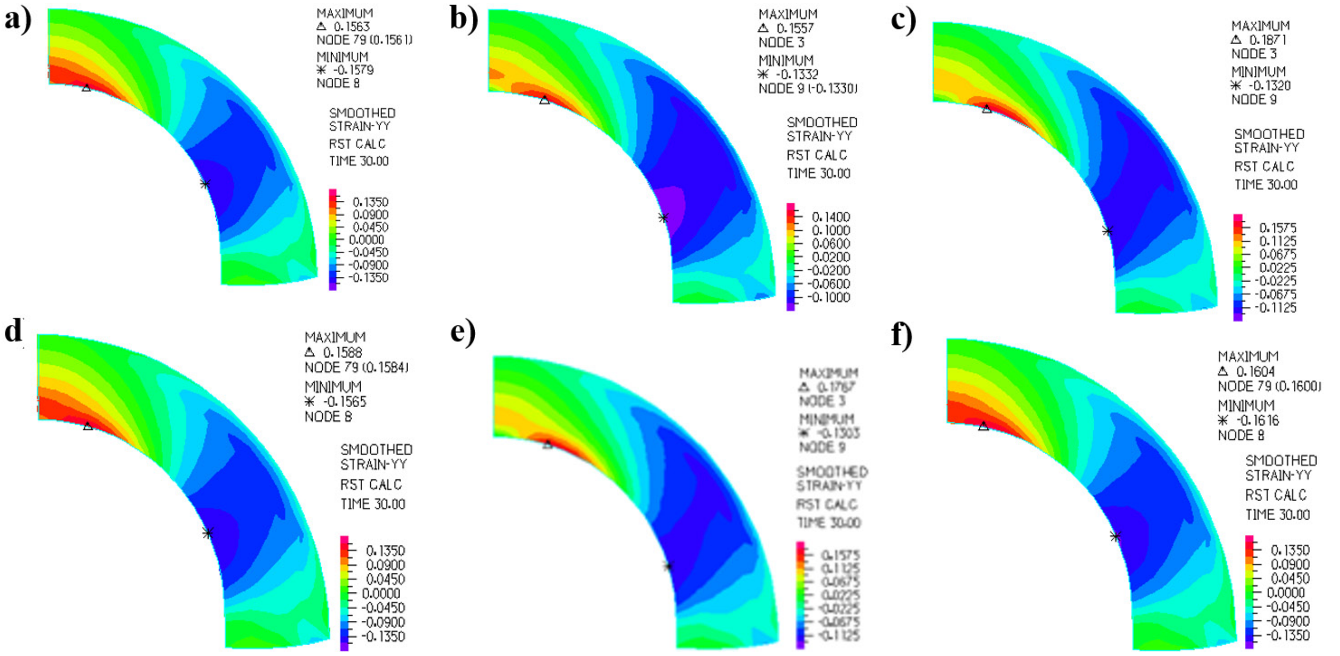

Fig. 7. Acetabular deformations (YY-Strains) for friction node at various material associations of the system endoprosthesis head – cup: a) CoCrMo alloy – UHMWPE, b) CoCrMo alloy – HXLPE, c) CoCrMo alloy – ePoly, d) Biolox delta – UHMWPE, e) Biolox delta – HXLPE, f) Biolox delta – ePoly

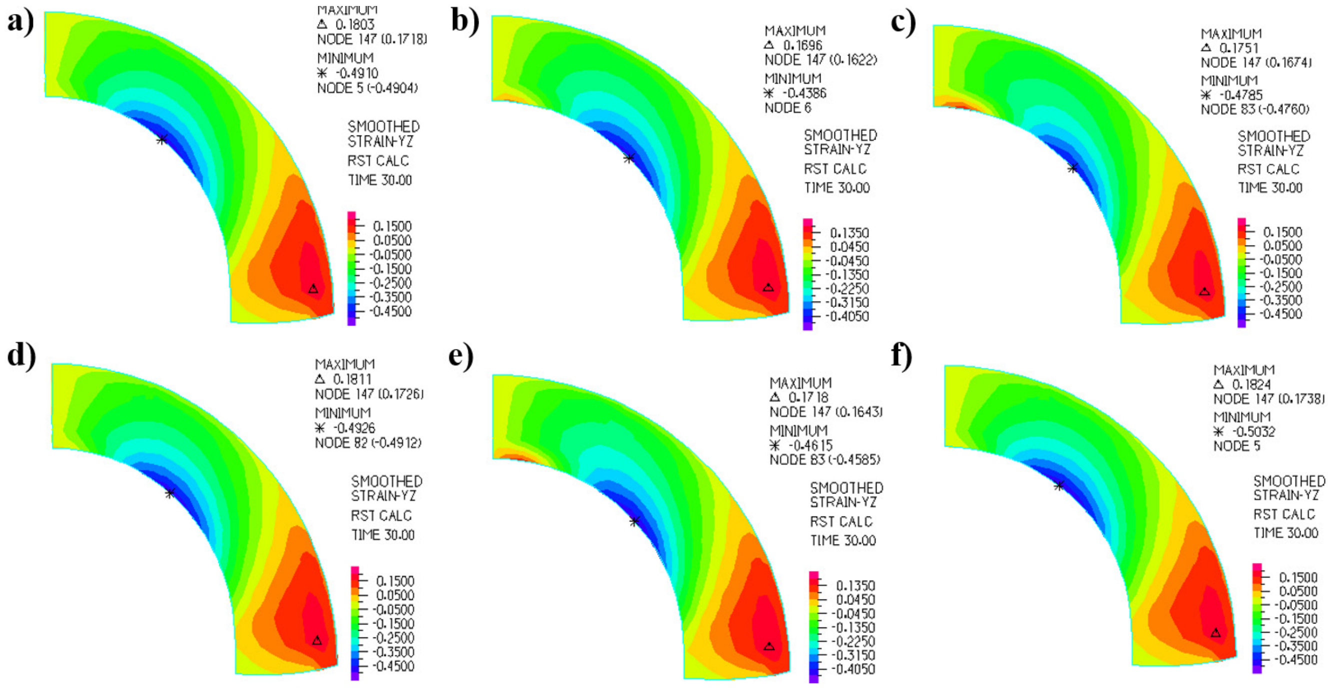

Fig. 8. Acetabular deformations (YZ-Strains) for friction node at various material associations of the system endoprosthesis head – cup: a) CoCrMo alloy – UHMWPE, b) CoCrMo alloy – HXLPE, c) CoCrMo alloy – ePoly, d) Biolox delta – UHMWPE, e) Biolox delta – HXLPE, f) Biolox delta – ePoly

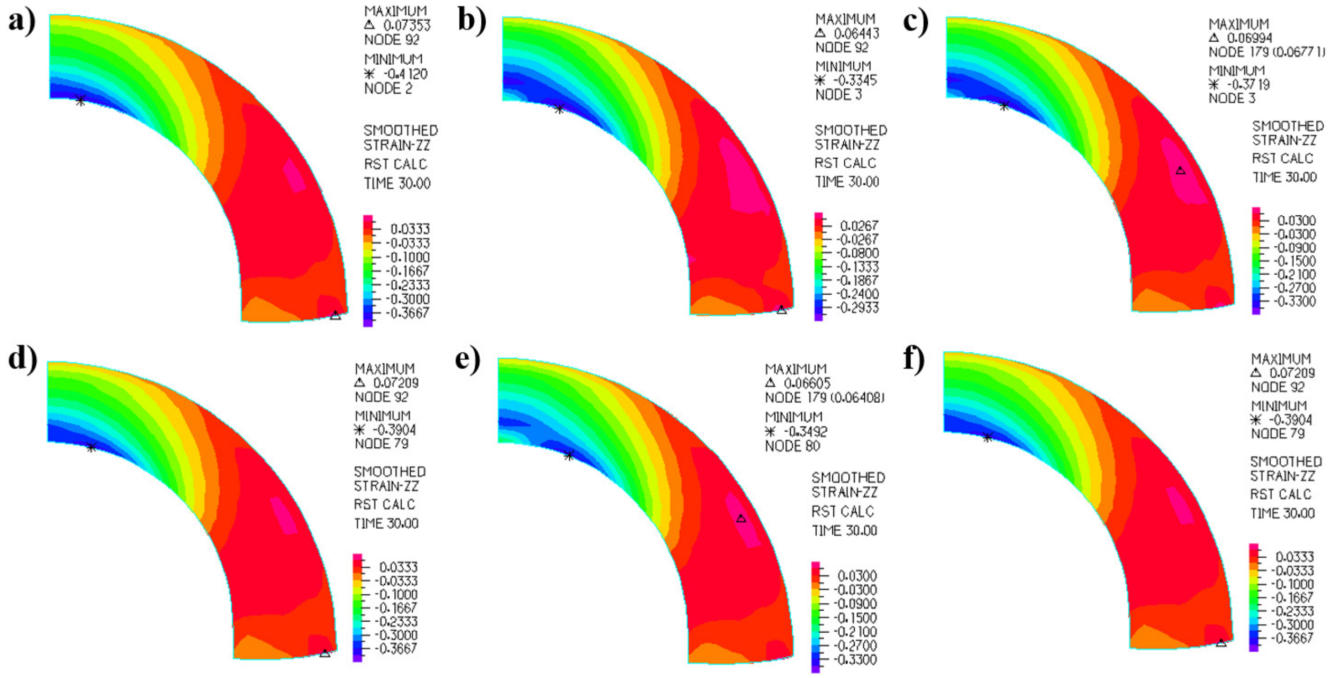

Fig. 9. Acetabular deformations (ZZ-Strains) for friction node at various material associations of the system endoprosthesis head – cup: a) CoCrMo alloy – UHMWPE, b) CoCrMo alloy – HXLPE, c) CoCrMo alloy – ePoly, d) Biolox delta – UHMWPE, e) Biolox delta – HXLPE, f) Biolox delta – ePoly

strength parameters can result in intensification of wear of contact surfaces and forming of wear products [1,20]. It can be also stated that friction contact of these endoprosthesis components: head and polyethylene cup in bioactive body environment is one of the main causes of wear and in the result excessive implant exploitation. Hence, currently scientists in cooperation with medical specialists, applying experimental and numerical studies, focus on using of new or improved biomaterials (providing minimal friction and wear) for endoprostheses elements and application of technologies which allow to modify the surface properties of their contact surfaces. Additionally, these FEM derived strains, stresses and displacements parameters can be believed to be the best measure for prediction of long-term wear for UHMWPE in comparison to other analyses [1,26-27].

4. Conclusion

Modelling of the friction system of hip endoprosthesis allows to visualize the stresses, displacements or deformations that may occur in this zone and have a negative impact, contributing to the processes of acetabular destruction with inadequate selection of material associations of the friction pair. Hence it can be showed that durability of endoprosthesis depends on its weakest element, which is polyethylene cup, whereas implant construction highly affects wear of this component.

The above results of numerical simulations show that an increase in the friction coefficient for associations with all tested types of polyethylene cups, contributes to a decrease in the maximum and minimum values of inserts displacements in the direction Y as well as to a decrease in maximum values of Z-displacements. In turn, the highest stresses of these elements occur in systems with HXLPE cups and the lowest in ePoly ones, with the increase in the coefficient of friction causing a decrease in the maximum values of this parameter in these cases. However, the strain tests YY, YZ and ZZ show that for all associations, both with ceramic and metal heads, an increase in the coefficient of friction leads to a decrease in maximum strains YZ and ZZ and an increase in strains YY.

The above analysis proves that material properties and, consequently, contact conditions of given pairs head – cup influence the strength parameters of polyethylene cups. Furthermore, the simulations of the contact of endoprosthesis components are useful in the evaluation of biomaterials for cooperation in this implant, because on that basis and in correlation with tribological parameters, it can be concluded about the distribution of stresses and displacements, which may determine the lifetime and durability of endoprosthesis. The appropriate association of the acetabular with the head allows to adjust the optimal design of the endoprosthesis, therefore numerical modeling and tests on tribotesters or simulators play a major role in the design of endoprosthesis elements and whole implants.

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