ANALYSIS OF WEAR OF CONTACT SURFACE OF THE HEAD AND PROSTHESIS STEM FROM THE STANDPOINT OF MATERIALS USED

SZAREK Arkadiusz

Czestochowska University of Technology, Faculty of Mechanical Engineering and Computer Science, Institute of Mechanical Technology, Częstochowa, Poland, EU, arek@iop.pcz.pl

Abstract

Modular hip joint endoprostheses allow for fitting the head size and offset (distance from the centre of the head to the mechanical axis of the prosthesis) with the prosthesis size. This is possible through application of the external lock cone, mainly with dimensions of d = 12, L = 11, D = 14, and the internal cone with the same dimensions in the head. Proper mounting of the head on the stem causes a firm and stable fixation of the head-stem system. It is essential for the analysis of the materials currently used for stems and heads with extremely varied strength parameters that their effect on intensity of wear of the head and stem is also taken into consideration. The examinations were based on the heads made of materials FeCrNiMnMoNbN, 316L, CoCr, Al_2O_3, ZrO_2 which were in contact with stem materials such as Ti6Al4V, CoCrMo, 316L. Based on the components removed from human body, it was demonstrated that the use of prosthesis causes micro-displacements on the contact surfaces of the stem and bone head and wear of these surfaces. Evaluation of wear was carried out based on the analysis of the surface geometrical structure (SGS) of the internal cone in the bone head. For this purpose, the measurements were conducted using GOM ATOS II 3D scanner. The results of the SGS measurements for the internal surface of the heads in contact are presented. The examinations of the artificial joints in modular endoprostheses showed the wear between the surfaces of the stem and head resulting from rotational and axial movements of the head on the stem cone. The magnitude and extent of the wear depend mainly on the patient's weight, intensity of use (physical activity), range of movement in the artificial joint and type of stem and head materials.

Keywords: Biomaterials, tribological examinations, destruction of hip joint, modelling and simulation

1. INTRODUCTION

On the one hand, development of civilization has brought higher life expectancy and, on the other hand, limited physical activity of humans, consequently leading to the increase in the number of diseases and dysfunctions of motor organs, making it the most frequent cause of disability [1, 2, 8]. The joints damaged due to the disease and following an injury lose their biofunctionality and represent the source of strong and chronic pain. Treatment of such pathological conditions is usually possible only by removal of the natural joint and replacing it with an artificial one with the design inspired by the anatomical human joint. In general, the total modular hip joint prosthesis is composed of the metal stem fixed in the marrow cavity of the femur, ceramic or metal head set on the conical stem tip and ceramic, metal or polyethylene acetabulum fixed in the pelvis or the acetabulum cage, which is illustrated in **Figure 1a)**. On the surface of the artificial joints, friction resistance and wear should be minimal (if any). The heads are set on conical surfaces of stems, where, due to its design and accuracy, the mobility is locked and there is no possibility of movement between the surfaces. However, the clinical practice shows that displacements and wear of the components are observed on the surface of contact between the head and stem. The most popular materials for the heads are: FeCrNiMnMoNbN, 316L, CoCr, Al_2O_3, ZrO_2, whereas stems are mainly made of such alloys as Ti6Al4V, CoCrMo, 316L. Comparison of these materials is presented in **Figure 1b)**.

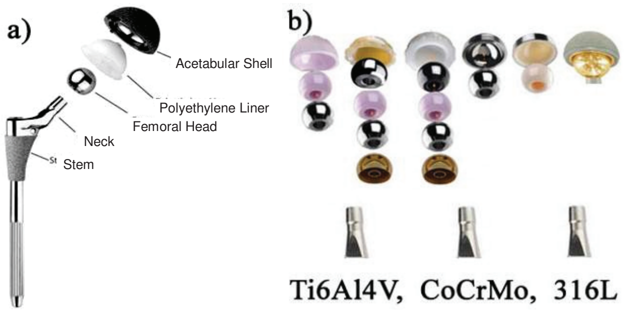

Figure 1a) The individual components of a total hip replacement; **b)** materials for the heads and stem

Variation of anthropometric parameters of patients causes that proper recreation of the anatomical system is affected by the whole range of factors whose proper interpretation allows for maximal replacement of the joint and, consequently, proper, painless, long and failure-free operation of the artificial joint [5].

One of the main factors which have a decisive effect on the intensity of wear of artificial human joint components is proper choice of the materials in contact and the size and intensity of the load to the artificial biobearing [9]. During everyday activities, human joints transfer a substantial load. The studies [3, 4, 7] have found that human gait in its individual phases is changed in terms of direction and value of the vector of the resultant *R* in the hip, knee and ankle joints. The position of the centre of gravity *S* is also changed, moving to the side opposite to the loaded limb. Values of forces that act in the hip, knee and ankle joint during the swing phase is presented in **Figure 2** [4, 7].

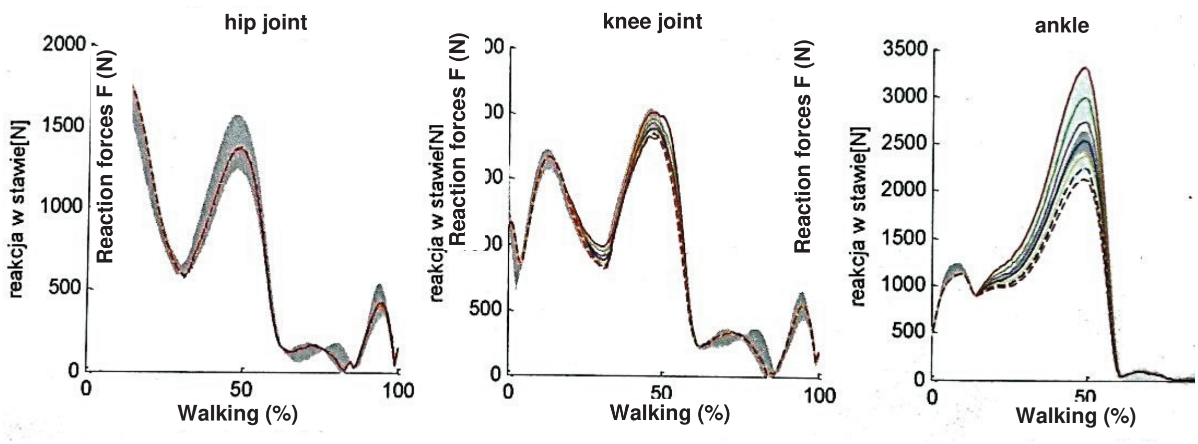

Figure 2 Values of reaction in individual joints of lower limb during human gait

2. MATERIAL AND METHODS

The study utilized the components of artificial biobearings in the form of endoprosthesis heads used in human body. Modular prostheses with the cone dimensions of $d = 12$, $L = 11$, $D = 14$ were used as a research material, with heads with offset ranging from -2 to +2 and diameter of 28 mm. The components were used in comparable load conditions: life from 10 to 13 years, patient's body weight (BW) from 735 to 820 N.

The components were removed from human body due to the wear of the friction pair of head and acetabulum or aseptic loosening of prostheses.

The components were used for tribological examinations to evaluate the coefficient of friction μ and friction force F_t. Furthermore, the 3D scanner (GOM ATOS II) was used to evaluate the geometrical structure of the surface.

3. RESULTS AND ANALYSIS

The friction processes that occur under specific tribological conditions are accompanied by energy loss and mechanical damage due to wear. In order to determine the dynamic and energy-related effect of friction, it is necessary to determine the coefficient of friction μ and friction force F_t [6, 9].

The coefficients of friction μ for selected articulations were examined empirically using the Friction Tester equipped in the strain gauge sensor with measurement precision of 0.0001 N. The examination was performed according to the ASTM D1894 standard. The coefficients of friction μ were evaluated and the values of the friction forces were calculated, with F_{min} and F_{max} being the approximated values that may occur in the case of a specific material configuration in the analysed group of patients, whereas F_A represented the real value of the coefficient of friction in the concrete configuration of the material of stem and head in the patient. The values of forces that result from fixation of the head on the prosthesis cone were neglected. The results obtained in the study are presented in **Table 1**.

Table 1 The values of the coefficient of friction and friction forces for the materials in contact

Material head	Material stem	Coefficients of friction μ	Friction forces F (N)		
			min.	max.	real
316L	Ti6Al4V	0.22	402.6	449.2	449.2
316L	CoCrMo	0.22	402.6	449.2	442.1
316L	316L	0.25	457.5	510.5	465.6
Al_2O_3	Ti6Al4V	0.39	713.7	796.3	795.3
Al_2O_3	CoCrMo	0.33	603.9	673.8	644.2
Al_2O_3	316L	0.31	567.3	632.9	628.3
CoCr	Ti6Al4V	0.64	1171.3	1306.7	1258.9
CoCr	CoCrMo	0.58	1061.5	1184.2	1104.8
CoCr	316L	0.51	933.5	1041.3	987.9
FeCrNiMnMoNbN	Ti6Al4V	0.49	896.7	1000.4	991.9
FeCrNiMnMoNbN	CoCrMo	0.24	439.2	490.1	482.3
FeCrNiMnMoNbN	316L	0.36	658.9	735.1	698.3
ZrO_2	Ti6Al4V	0.22	402.6	449.2	432.8
ZrO_2	CoCrMo	0.19	347.7	387.9	375.2
ZrO_2	316L	0.13	237.9	265.4	243.4

The experiments carried out in the study showed that the highest coefficient of friction that occurs in the analysed group of materials is μ = 0.64 and occurs in the case of material configuration of the head (CoCr) and stem (Ti6Al4V). The minimal value of force necessary for moving the head on the stem for the patient with BW = 807 N was F_A = 1307 N. Scratches with the depth of 110 µm are observed in the area of the tip of the conical connection. The effects of tribological processes are presented in **Figure 3**.

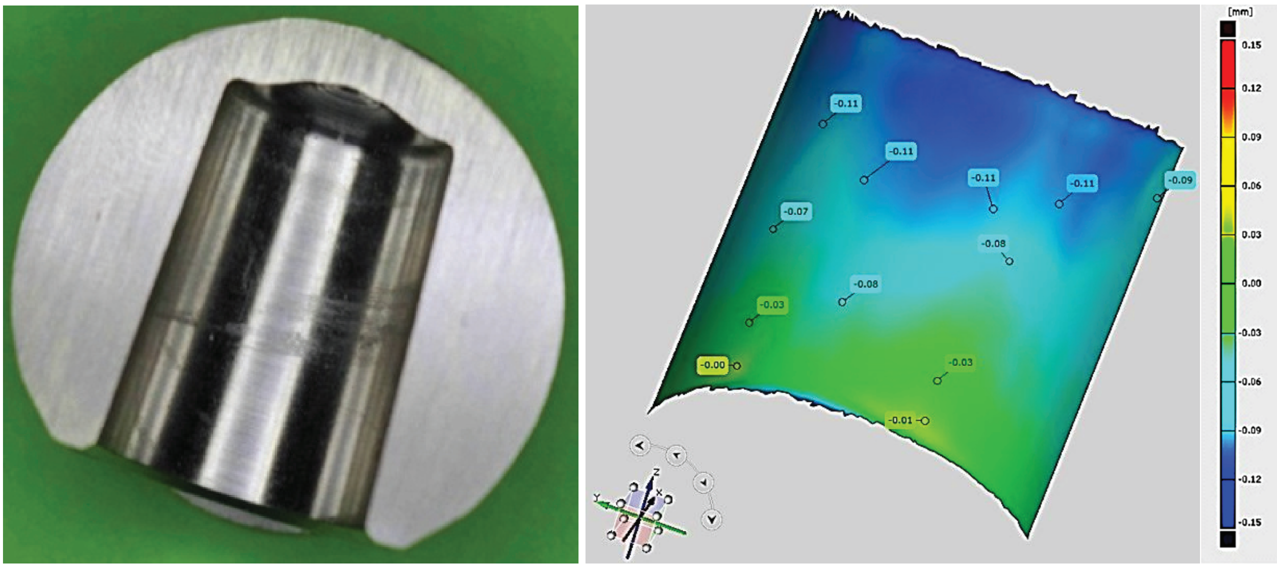

Figure 3 The effects of tribological case of material configuration of the head CoCr and stem Ti6Al4V

The smaller wear of the internal surface of the endoprosthesis head in the analysed group of metal heads was found for the material configuration of the head made of 316L steel and the stem made of Ti6Al4V. The components were used in the patient with *BW* = 819 N. For the materials in contact, the coefficient of friction is μ = 0.25 and maximal depth of scratches was 60 μm, present in the final and middle part of the contact of the head and stem. The wear area is presented in **Figure 4**.

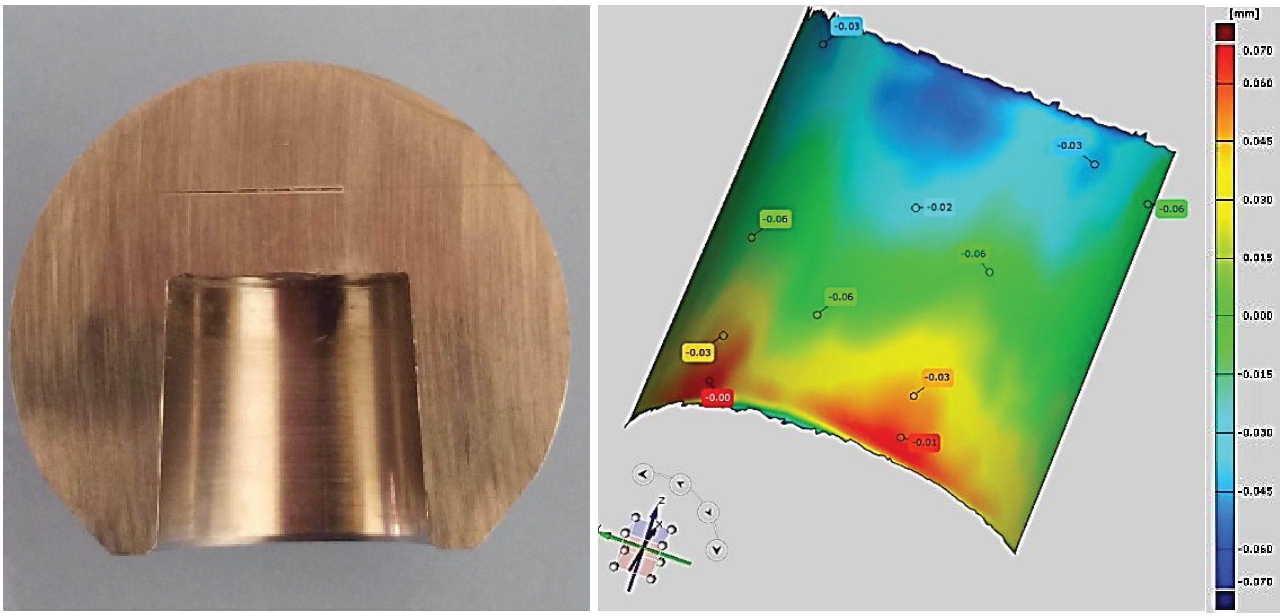

Figure 4 The effects of tribological case of material configuration of the head 316L and stem Ti6Al4V

In the case of ceramic heads, the highest wear was found for the internal surfaces of the heads made of Al_2O_3 in contacts with the stem made of CoCrMo. The components were used in the patient with *BW* = 790 N. For the materials in contact, the coefficient of friction is μ = 0.25 and maximal depth of scratches was 60 μm. The contact surface was characterized by even, annular wear with the intensity increasing towards the depth of the prosthesis head. In this case, comparison of materials also showed noticeable locations of inclusion of oxides in the materials used. The effects of tribological processes are presented in **Figure 5**.

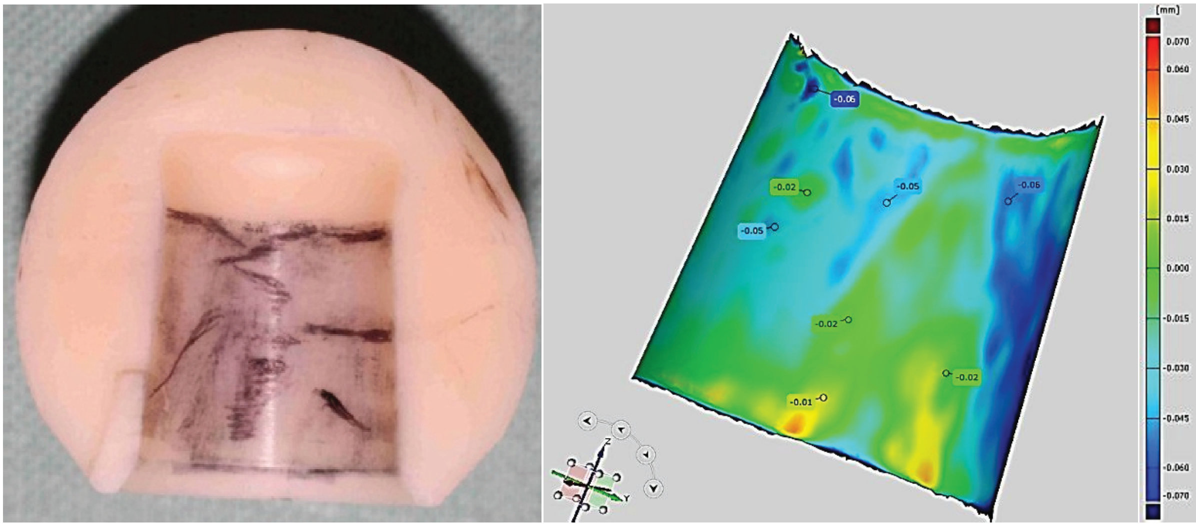

Figure 5 The effects of tribological case of material configuration of the head Al_2O_3 and stem CoCrMo

The smallest wear among all the materials analysed was found for the head made of ZrO_2 and the stem made of alloy CoCrMo. The components were used in the patient with BW = 798 N. For the materials in contact, the coefficient of friction is μ = 0.13 and maximal depth of scratches was 40 μm. The surface analysed was characterized by individual scratches with zigzag shape. The wear area is presented in **Figure 6**.

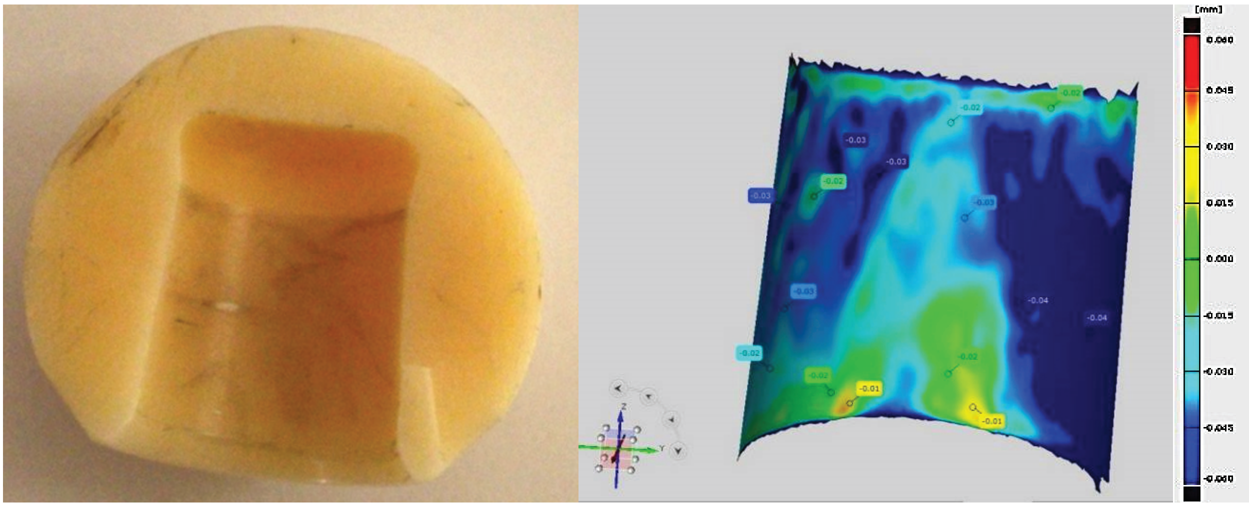

Figure 6 The effects of tribological case of material configuration of the head ZrO_2 and stem CoCrMo

The particular focus during the analysis of the intensity of wear should be on resistance to scratching for the materials used in the joint, hardness of the materials, coefficient of friction in the analysed pair of materials and state of stresses in the area of contact between the stem and head. The studies [9] lead to the conclusion that in the case of COCrMo-CoCrMo materials (**Figure 7a**.), the biggest stress was recorded in the final part of the contact of the head and stem, where reduced stress is σ_{ZY} = 221 MPa in the area of the head σ_{ZY} = 226 MPa in the area of prosthesis.

Both stem and the head are loaded similarly, which, for the displacement of the components with respect to each other should not cause the excessive wear of one of them. In the case of the connection of the system of the ceramic head and Ti6AL4V prosthesis (**Figure 7b**), values of stresses in the area analysed are σ_{ZY} = 184 MPa for the prosthesis and σ_{ZY} = 253 MPa for the head, which, in the case of mutual displacement of the components or even minimal micro-movements, may lead to intensification of the wear of the ceramic head.

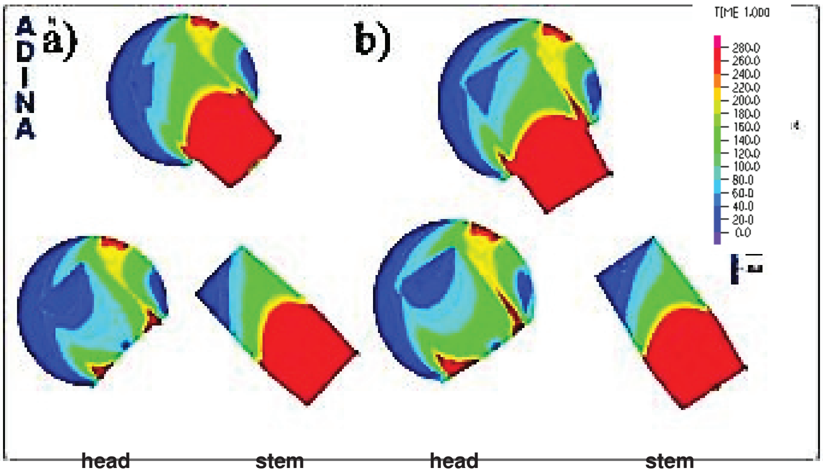

Figure 7 Character of stress in the system of head **a)** CoCrMo - CoCrMo **b)** Ti6AL4V - Al_2O_3

4. CONCLUSIONS

The wear of the artificial joint is observed for all contacts surfaces which are not integrated using the additional materials such as bone cements. The highest intensity of wear occurs in the friction pair (at the contact between the insert and the head). However, this study also showed that tribological processes also occur at the surface of contact between the prosthesis and the head. This phenomenon is very negative since it reflects the displacement of the head with respect to the stem, which is unwanted from the standpoint of the designers of modular endoprostheses. The functional parameters and the optimal selection of materials of the head and stem have a decisive effect on the size and intensity of wear of the contact surfaces. The experimental studies showed that the value of the coefficient of friction for the materials of the stem and the head ranges from μ = 0.13 for the materials of the head ZrO_2 and stem 316L to μ = 0.64 for the materials of the head CoCr and stem Ti6Al4V. Higher coefficient of friction should minimize the likelihood of the displacement of the head with respect to the stem. However, the topographical examinations show that if the displacement occurs, the wear intensity is very high. The lowest coefficient of friction and the lowest wear is observed for the system of ZrO_2 - 316L, which might result from the highest hardness of the materials and, consequently, highest resistance to scratching.

In the case of contact of the materials of head CoCr and stem Ti6Al4V, the intensity of wear is noticeable, with the scratches reaching the depth of 110 μm. The lowest wear during the use in the human body from the analysed group of materials was found for the ceramic heads made of ZrO_2, and, in particular, during contact with the stem made of alloy CoCrMo. The area of wear was not extensive, and the scratches with the maximum depth of 40 μm were observed on the head surface.

The main recommendation for the orthopaedic surgeons who implant prostheses that results from the study is to adjust the materials of the stem and the head to individual characteristics of the patient i.e. body weight and intensity of use. In the case of patients with high body weight, the use of head and stem materials with extremely different mechanical parameters is becoming popular again due to high stresses on the angular surfaces and unfavourable tribological parameters.

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