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Tribological Characteristics of Hip Joint Endoprostheses

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Abstract—We have studied the friction pairs for a head–insert kinematic node of human hip endoprostheses and rabbit hip endoprostheses, both normal (intact) and with an osteoarthritis model, in conditions of dry friction and lubrication with biological medium. We have discovered that the rabbit hip with an osteoarthritis model exhibits deterioration of tribological characteristics. From the tribological point of view, the most suitable friction pairs for human hip endoprostheses are zirconium ceramics–aluminum ceramics, Oxinium–aluminum ceramics, aluminum ceramics–aluminum ceramics, and aluminum ceramics–polyethylene, which have shown the smallest coefficient of friction, the lowest adhesion bond strength when sheared, and minimal dependence of these parameters on the value of external load.

Keywords: arthroplasty, hip joint, tribology, endoprosthesis friction pairs

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INTRODUCTION

Hip joint arthroplasty is one of the most efficient ways to rehabilitate movement of damaged larger joints in the skeleton. However, during the postsurgery period, a number of problems arise, and by solving these problems it is possible to diminish the occurrence of unsatisfactory outcomes. For example, aseptic loosening of an endoprosthesis, which is most commonly associated with tribological interactions, is one of the inevitable long-term complications [1–5]. The search for and discovery of new materials that can improve the functionality of an implant have allowed the performance of today's endoprostheses to be improved; however, there are still a number of unsolved problems [6–8]. In addition to the kinematic friction node of interest—between the endoprosthesis head and the insert—there are a few more types of tribocouplings: acetabulum–acetabular component, acetabular component–insert, endoprosthesis head–implant neck cone, and femoral component–hip, which concern the zone of predisplacement (within the range of 100 μm) with a partial coefficient of static friction [9]. In these tribocouplings, fretting wear takes place, forming a so-called "third body" containing endoprosthesis components, and any abnormalities in the above-mentioned nodes can cause runaway instability of the whole implant. Nevertheless, the kinematic tribocoupling node between the endoprosthesis head and the insert should be recognized as the critical friction pair that the implant lifespan relies upon. In addition, the abundance of existing tribological pairs of endoprostheses often makes the selection process difficult for an orthopaedic surgeon and is evidence that an ideal standard does not exist [1, 3, 6, 7, 10]. In this context, comparative evaluation of different friction pairs used general orthopedics hip joint arthroplasty is of theoretical and practical interest.

The aim of this study is to determine and analyze the tribological characteristics of various endoprostheses used in arthroplasty of a human hip joint and rabbit hip joints in normal (intact) and in simulated osteoarthritis conditions.

MATERIALS AND METHODS

We have studied different friction pairs of the head–insert kinematic node of human hip joint endoprostheses that comply with technical requirements applied to modern implants: metal–polyethylene, metal–metal, aluminum ceramics–polyethylene, zirconium ceramics–polyethylene, Oxinium–polyethylene, titanium nitride coating–polyethylene, aluminum ceramics–aluminum ceramics, zirconium ceramics–aluminum ceramics, Oxinium–aluminum ceramics, and titanium nitride coating–aluminum ceramics with dry friction and in the presence of biological medium, when synovial fluid is added to the friction node. A polyethylene insert represented a cross-linked polyethylene of ultrahigh molecular mass (XLPE), and metal parts were made from an alloy mostly composed of cobalt, chromium, and molybdenum. Ceramic parts were of two types of ceramics: aluminum one containing more than 80% aluminum dioxide, about 17% zirconium dioxide, and zirconium ceramics. We have examined Oxinium endoprosthesis heads individually, which are of 97.5% zirconium and

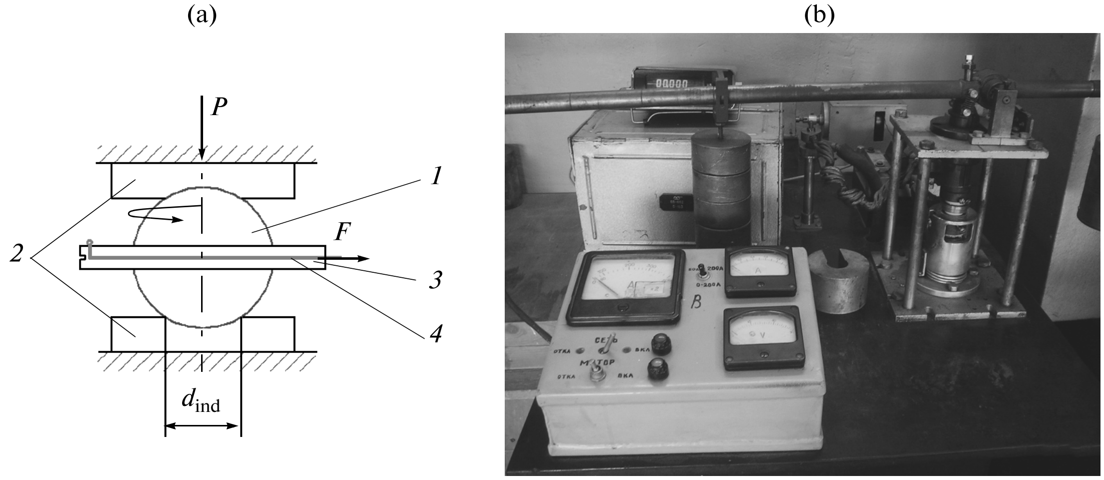

Fig. 1. (a) The scheme of operation and (b) the general view of a single-ball adhesiometer. *1*—endoprosthesis head; *2*—insert samples; *3*—disk; *4*—head rotation wire.

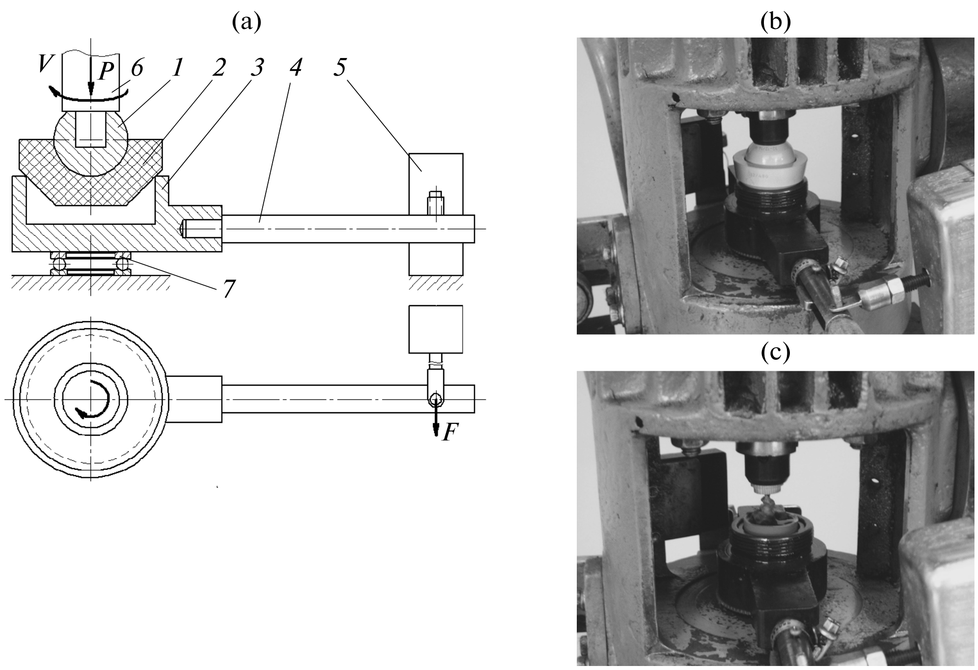

Fig. 2. (a) The scheme of operation and general views of FBFU during observations of (b) endoprostheses and (c) rabbit hip joints: (*1*) endoprosthesis head, (*2*) endoprosthesis insert, (*3*) cup, (*4*) lever, (*5*) sensor of force of friction *F*, (*6*) drive shaft, and (*7*) roller thrust bearing.

2.5% niobium, and endoprosthesis heads covered with titanium nitride.

We have also studied the tribological characteristics of rabbit hip joints in a healthy state and with osteoarthritis. For test material, we used the experimental observations of 9 laboratory rabbits with a model of post-traumatic hip osteoarthritis.

We ran our research using a single-ball adhesiometer (*GOST* (State Standard) 16429-70) [11] (Fig. 1) and an upgraded four-ball friction unit (FBFU) (*GOST* (State Standard) 9490-75) (Fig. 2) with a graded change of axial load P from 500 to 10 000 N per friction node for endoprostheses and from 60 to 100 N for rabbit joints. For a rotating element, we used endoprosthesis heads of 28, 32, and 36 mm in diameter, which were pressed against the inserts of corresponding size with force P.

After the FBFU was upgraded by means of installing a planetary gear reducer and a frequency converter, the rotation speed of the drive shaft was 1 rpm. The

FBFU was fitted with a strain gauge type force measuring system with an 1925IS-M (1925ÈÑ-Ì) sensor, $P_{nom} = 0.5$ kN, with further conversion via an analog-to-digital converter (ADC) and output to the computer as a chart, force of friction *F*–time.

Based on *P*, *F*, and d_{ind} values, the following values were calculated: pressure p_r at the friction contact, strength τ_s of adhesion bonds when sheared, and value f_m, representing the molecular (adhesion) component of the coefficient of friction [11]. Thus, we obtained the pattern of τ_s as a function of p_r for different friction pairs in the presence and absence of biological medium, which enabled determining the value of f_m and its change in these conditions. The value of τ_s correlates with wear, while the value of f_m correlates with energy losses in moving tribocouplings [11].

RESULTS AND DISCUSSION

As a result of analysis of tribological properties of rabbit hip joints, we have revealed an increase of strength τ_s of adhesion bonds when sheared and of coefficient f_m in the samples with a model of osteoarthritis and in conditions of dry friction (Fig. 3). We have also noticed the dependence of these parameters on the load and pressure. The value of f_m somewhat decreases and the value of τ_s somewhat increases along with the growth of load *P* and pressure p_r. It is necessary to point out slight influence of the load and pressure upon these friction parameters of a healthy joint.

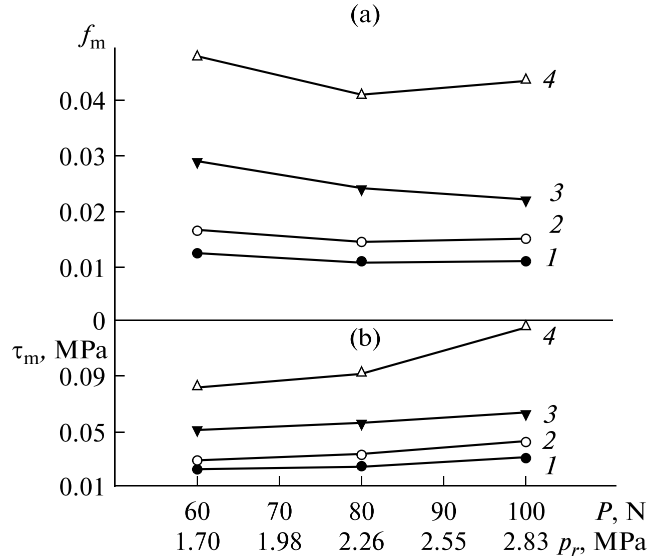

Fig. 3. Dependence of (a) the adhesion component of the coefficient of friction f_m and (b) the strength of adhesion bonds when sheared τ_s of rabbit hip joint on load *P* and pressure p_r: (*1*) intact joint, biological medium as lubricant; (*2*) intact joint, dry friction; (*3*) osteoarthritis, biological medium as lubricant; and (*4*) osteoarthritis, dry friction.

Studies of various friction pairs of endoprostheses (their designations are provided in Table 1) have proved the differences of tribological characteristics depending on the load and pressure at the contact, rigidity of the friction node, and the presence of lubrication (Fig. 4 and 5).

We have discovered that for all the studied friction pairs of human hip joint endoprostheses, strength τ_s of adhesion bonds when sheared grows with the increase of pressure p_r at a moving friction contact (Fig. 4). At that, the degree of influence of p_r upon τ_s is different for 'soft' and 'solid' friction pairs: polyethylene inserts provide for significantly smaller influence of p_r upon $\tau_ï$ (for a healthy rabbit as well).

In the friction pairs with a polyethylene insert we have noticed the growth of coefficient f_m occurring with the growth of load and pressure, unlike in 'solid' tribological pairs. At that, the best readings for f_m at light and medium loads (within the range of 500–4000 N), corresponding to a static state and slow and medium-speed walking, have been shown in zirconium ceramics–aluminum ceramics, Oxinium–aluminum ceramics, and aluminum ceramics–aluminum ceramics friction pairs. The highest value of coefficient f_m has been revealed in tribological pairs with a polyethylene insert and in samples of titanium nitride coating–aluminum ceramics and metal–metal. In the range of 4000–6300 N, which corresponds to fast walking, the friction readings from the majority of samples are aligned except for titanium nitride coating–aluminum ceramics, metal–metal, and titanium nitride coating–polyethylene friction pairs—these remain high. At the maximum loads in the range of 8000–10000 N, the value of the coefficient f_m in aluminum ceramics–polyethylene, Oxinium–polyethylene, zirconium ceramics–polyethylene, metal–polyethylene, and zirconium ceramics–aluminum ceramics pairs has been lower than in other friction pairs.

Table 1. Designations of friction pairs in the studied endoprostheses

Friction pairs	Designation
Metal–polyethylene	1
Aluminum ceramics–polyethylene	2
Oxinium–polyethylene	3
Zirconium ceramics–polyethylene	4
Aluminum ceramics–aluminum ceramics	5
Metal–metal	6
Titanium nitride coating–polyethylene	7
Zirconium ceramics–aluminum ceramics	8
Oxinium–aluminum ceramics	9
Titanium nitride coating–aluminum ceramics	10

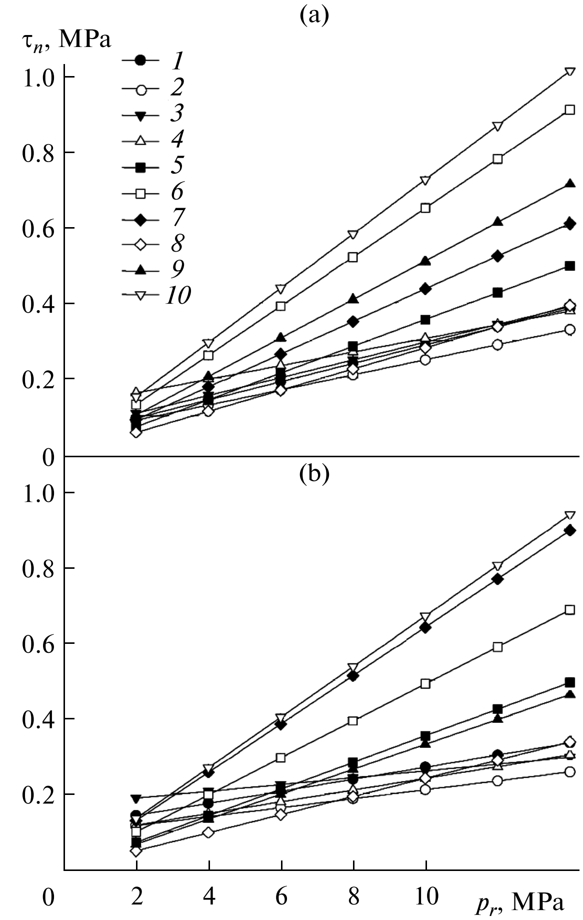

Fig. 4. Dependence of the strength of adhesion bonds when sheared τ_s of kinematic nodes of endoprostheses with heads of 28 mm in diameter at (a) dry friction and (b) with biological medium as lubricant on pressure p_r.

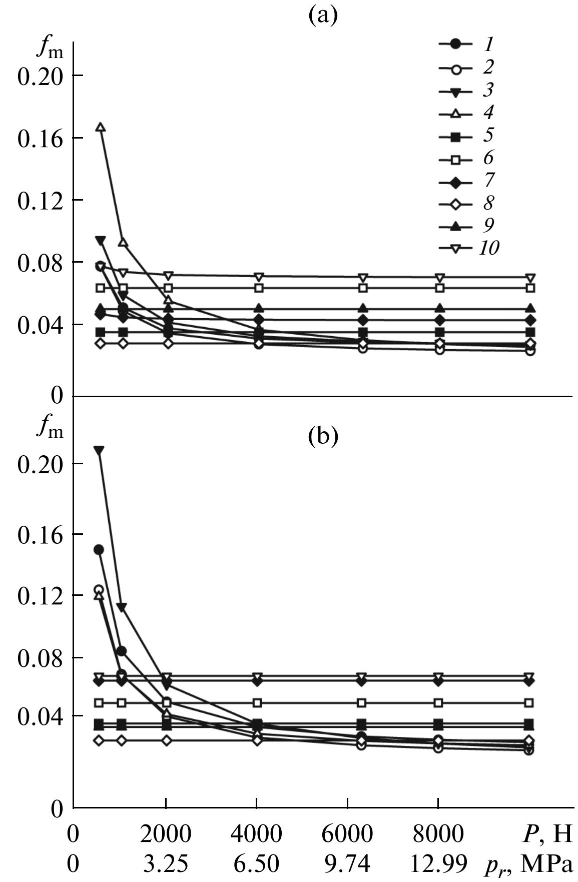

Fig. 5. The adhesion component of the coefficient of friction f_m of tribological pairs of endoprostheses with heads of 28 mm in diameter at (a) dry friction and (b) with biological medium as lubricant as a function of load P and pressure p_r.

The results of comparing "solid" and "soft" friction pairs have shown a smaller dependence of tribological characteristics on the presence of synovial fluid in 'solid' pairs, best expressed in the range of 500–4000 N (Fig. 4, 5). τ_s and f_m values have changed considerably in conditions of biological medium in pairs with a polyethylene insert; in 'solid' tribological nodes we have noticed a slight difference between dry friction and friction in biological medium, especially in the friction pairs with homogenous materials (e.g. aluminum ceramics–aluminum ceramics and metal–metal). Apparently, this is also driven by synovial fluid plasticizing the near-contact zone of the contacting surfaces in these friction pairs.

Estimation of the average value of coefficient f_m with the whole range of loads for endoprostheses of different head diameters has shown (Fig. 6 and 7) that the most efficient friction pairs are the following: zirconium ceramics–aluminum ceramics, aluminum ceramics–aluminum ceramics, and Oxinium–aluminum ceramics.

Enlargement of the endoprosthesis head diameter in the majority of samples with a polyethylene insert is accompanied by the decrease of coefficient f_m. As for 'solid' friction pairs and the titanium nitride coating–polyethylene pair, we have not detected any dependence of coefficient f_m on the endoprosthesis head diameter, load, and pressure.

As a result of comparing the coefficient f_m of rabbit hip joints with the zirconium ceramics–aluminum ceramics friction pair that has shown the lowest value of the coefficient of friction among endoprostheses at the same value of pressure, 1.7–2.83 MPa, we have concluded that the adhesion component of the coefficient of friction in a rabbit's healthy hip joint is 2–2.18 times lower than in the endoprosthesis. In this context, the given parameter in the synthetic friction pair is comparable with the parameter of osteoarthritis model in a rabbit hip joint (Table 2).

Thus, deterioration of tribological properties as a result of destructive-dystrophic damages of joints is a key element of pathogenesis of kinematic properties

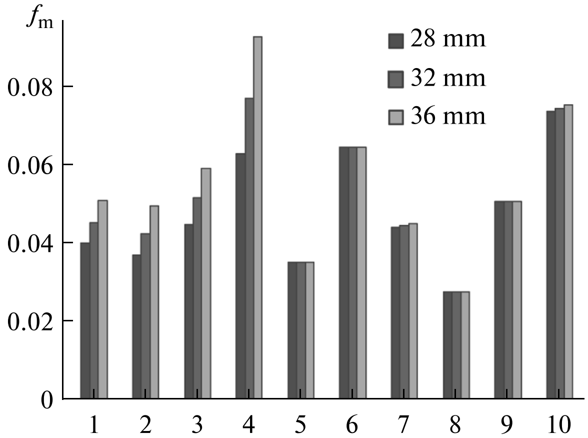

Fig. 6. The average value of adhesion component of the coefficient of friction in the range of loads 500–10 000 N for different friction pairs in dry friction.

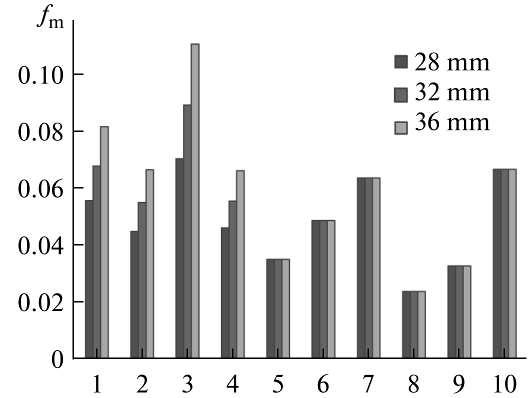

Fig. 7. The average value of adhesion component of the coefficient of friction in the range of loads 500–10 000 N for different friction pairs with biological medium as lubricant.

decompensation in a joint. The experimental model of osteoarthritis in laboratory animals shows a direct correlation of adhesion properties and the stage and depth of the process.

CONCLUSIONS

We have discovered that the rabbit hip with an experimental osteoarthritis model shows deterioration of tribological characteristics.

Progression of destructive-dystrophic diseases of a hip joint is accompanied by disruption of adhesive interactions between the surfaces of cartilage membrane and synovial medium of the joint, which leads to a nonuniform pressure at contact in tribocouplings, a decrease of the coefficient of friction, extensive wear of kinematic structures, and further secondary changes in juxta-articular tissues. After completing the arthroplasty, the functionality of a new kinematic node is also to a large extent defined by tribological interaction of the endoprosthesis parts and the surrounding tissues.

Comparative analysis of the studied friction pairs of the human hip replacement, depending on the amount of loads, has revealed certain patterns of adhesive interactions: at light and medium loads (500–4000 N) that correspond to the static state and slow and medium walking, the best tribological characteristics have been shown in the aluminum ceramics–aluminum ceramics and zirconium ceramics–aluminum ceramics friction pairs. In the range of from 4000 to 6300 N that corresponds to fast walking, adhesion component f_m of the coefficient of friction in many tribological pairs is aligned, demonstrating further improvement of parameters in the following friction pairs: aluminum ceramics–polyethylene, zirconium ceramics–polyethylene, and Oxinium–polyethylene, which has shown the best strength of adhesion bonds at the highest loads (8000–10 000 N). During analysis of the whole range of loads, the best tribological properties have been detected in the zirconium ceramics–

Table 2. Dependence of the adhesion component f_m of the coefficient of friction on pressure in rabbit's joints and the zirconium ceramics–aluminum ceramics friction pair

Friction pairs and type of lubricant	f_m as a function of p_r		
	1.7 MPa	2.26 MPa	2.83 MPa
Healthy joint, biological medium as lubricant	0.012	0.011	0.011
Healthy joint, dry friction	0.017	0.015	0.015
Osteoarthritis, biological medium as lubricant	0.029	0.024	0.022
Osteoarthritis, dry friction	0.048	0.041	0.044
Zirconium ceramics–aluminum ceramics, biological medium as lubricant	0.024	0.024	0.024
Zirconium ceramics–aluminum ceramics, dry friction	0.028	0.028	0.028

aluminum ceramics and aluminum ceramics–aluminum ceramics friction pairs.

Along with the commonly used criteria of endoprosthesis selection (peculiarities of hip anatomy, bone tissue quality, sex, age, and weight of the patient), it is necessary to take into account tribological properties of kinematic segments of the implant having different behavior parameters depending on the friction pair. Knowing the extent of the performance qualities of endoprosthesis moving parts enables prediction of the total kinematic balance and streamlines valid selection of arthroplasty method based on studying the adhesive interactions of friction pairs, which is probably one of the key factors of extending a structure's lifespan.

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