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BIOMECHANICAL JOINTS AS TRIBOLGY SYSTEM

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Abstract

This study gives the definition of the tribology system of hip joint prosthesis. The aim of the study was to examine the nature of damages occurring on the joint surfaces. The analysis was performed using a Ring's total prosthesis. Out of two terminal types (kinds) of motion, torsional swinging motion of the acetabular prosthetic component was examined in relation to the femoral component. The testing device was adapted to suit this special purpose: a four-part mechanism was added for real motion simulation. Changes of roughness and friction moment in time were measured for the input parameters of loading, velocity flow and roughness. The obtained values show that real radius of friction does not correspond to the theoretical one and that out of overall frictional surface only a small portion is realized, which may account for the damage of the frictional surfaces and loosening and migration of the hip prosthesis.

Key words: *Biomechanical Joints, Tribology, Wear, Friction*

1. INTRODUCTION

Tribology is a science that studies surfaces in contact in relation to relative motion as well as the associated phenomena (friction, wear and the like). Both human and artificial hip prosthesis are typical examples of these phenomena that lead to function failures.

Each relative change in the position of two objects in contact is not possible without a force necessary to overcome the resistance to mutual motion. The force resisting this relative change of position is called frictional force. The effects of frictional forces are losses of energy spent on friction and wear of the material that occur with dynamic friction.

According to the majority of the existing theories, forces producing friction can be adhesional and deformational or have both adhesional and deformational properties (the intermediary case). Assuming that there is no interaction between these two cases we can write the following formula (1) [7]:

$$\mu = \frac{F_t}{N} = \frac{(F_{ad} + F_{def})}{N} = \mu_{ad} + \mu_{def} . \tag{1}$$

Where F_t is the overall fractional force, N is normal force, F_{ad} is adhesional portion of the frictional force, F_{def} is deformational portion of the frictional force, and μ is corresponding coefficient of friction.

In case of dry friction of two rough metallic surfaces it has been proven that adhesion is twice as large as deformation. This holds true for metallic implants. However, for thermoplas tic and other non-metallic materials these ratios are quite different. This is also true for the combination of metallic and thermoplastic (non-metallic) materials.

The friction surfaces, that compose the human hip joint, are coated with cartilage on the all parts where friction of bones takes place. The whole tribosystem is full of synovial (natural) fluid (Fig. 2).

As friction causes loss of energy, it is essential to reduce the coefficient of friction. Therefore, contact surfaces are separated by adequate media whenever possible. The application of lubricating media significantly reduces the coefficient of friction between contact surfaces as compared to direct surface contact.

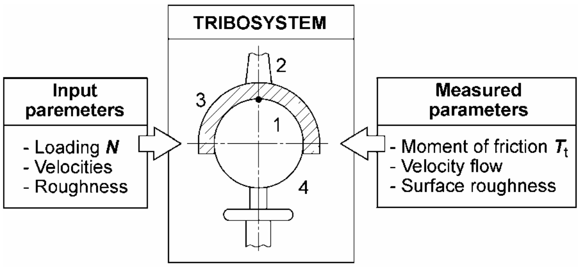

Fig. 1: *Tribosystem of the hip prosthesis (1 - femoral component, 2 - acetabular component, 3 – lubricant, 4 – environment)*

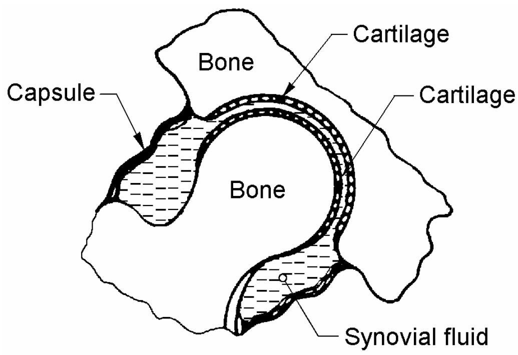

Fig. 2: *The section of human hip joint*

The medium can have various states of matter, including mixed states as well. In the presence of media between contact surfaces three completely different states of lubrication can be differentiated:

- Boundary lubrication, with thin layers of lubricant on contact surfaces that can be removed only with chemical agents. This lubricant layer is attached to the metallic surface by strong molecular forces and cannot be removed mechanically. A typical example for this is greasy surfaces or cases where the remaining lubricant has been squeezed out (great loading, the moment of resuming movement). With regard to the molecular thickness of the boundary lubricant layer, the coefficient of friction depends not only upon the properties of the applied lubricant but also upon the quality of contact surfaces, Hydrodynamic (fluid) lubrication, where contact surfaces are separated by a boundary layer and a layer of fluid lubricant thicker than the height of the rough surface.

- Mixed-film lubrication that comprises both boundary and fluid lubrication. A typical example for this is friction during motion in the presence of a lubricant. At rest, there is only a boundary lubricant layer whereas the increase in relative speed of frictional surfaces results in fluid friction. A graphical representation of lubrication state is shown in diagram (Striebeck's diagram) in Fig. 3 (similar to the sliding bearing performance and types of lubrication related to the sliding bearing parameter). The zone next to the curve minimum represents heterogeneous/mixed friction. At this point, surfaces are separated and the coefficient of friction increases according to the laws of directly proportional growth of the fluid resistance and speed.

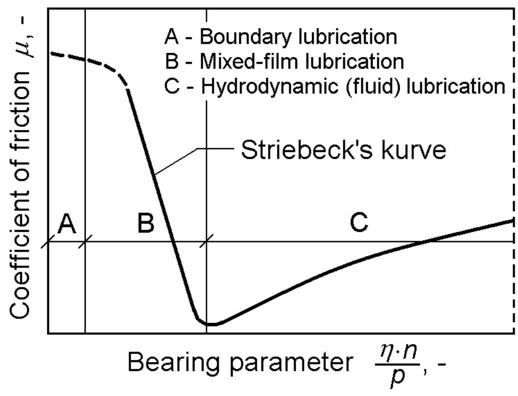

Fig. 3: *Striebeck's diagram*

Left to the point of minimum there is boundary friction at low speeds, whereas a partial separation of contact surfaces occurs at increased speeds resulting in mixed friction. This is the case especially in kinematic pairs with reversible motion at relatively small speeds, which are the subject of this study. Static friction appears at the moment of resuming movement when the speed is zero.

The tested prosthesis-loading and contact scheme with observed zones and pole distance shown in Fig. 4, and design of tested prosthesis shown in Fig. 5.

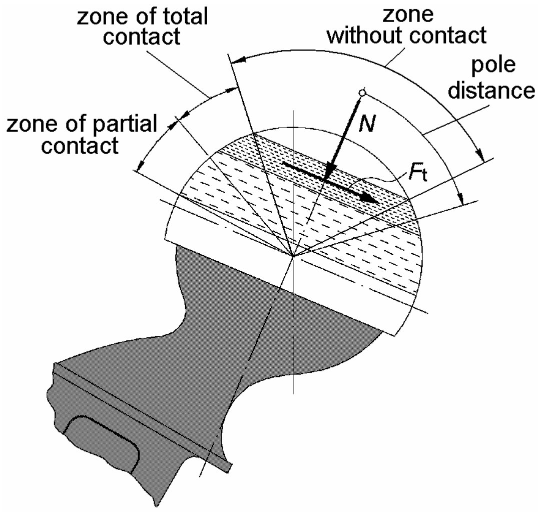

Fig. 4: *The tested prosthesis-loading and contact scheme*

Fig. 5: *The tested prosthesis*

2. DETERMINATION OF THE FRICTIONAL MOMENT AND SURFACE ROUGHNESS

Fig. 6 shows a schematic representation of the testing device [6].

Through fan-belt transmission and worm one-stage reducer, the electric motor (6) transmits the moment of motive power onto the four-part mechanism (8). The test joint (hip joint prosthesis) (1, 2) (Fig. 5) is attached to the driven part of the four-part mechanism (the oscillating part) with a tensometric measuring shaft (3). The test joint is loaded by the axial force F_a using staged oscillating static loading (G) with weights via a lever (5).

The frictional resistance in the joint during motion (momentum of friction) produces torsional deformations of the measuring shaft (3) and tensometric measuring tapes glued on it (10).

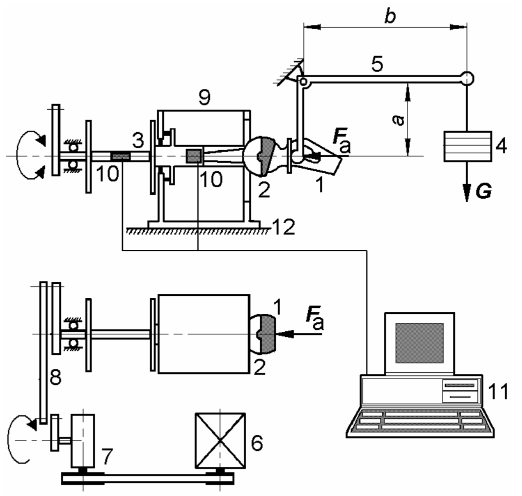

Fig. 6: *The testing device schema: 1 - the lower part of the prosthesis (femoral part), 2 - the upper part of the prosthesis (acetabular part), 3 - tensometric measuring shaft, 4 - loading weights, 5 - lever mechanism, 6 - propelling motor, 7 - gearing, 8 - mechanism for motive power, 9 - housing, 10 - tensometric tapes, 11 - measuring amplifier and computer.*

Tensometric measuring tapes are located within the massive Wheatstone bridge whose disbalance caused by the measuring shaft deformations is registered by the measuring amplifier (1).

In order to determine the frictional moment in the test joint based on the measurement registered by the measuring amplifier and printer, it was necessary to calibrate the tensometric measuring shaft with the measuring amplifier and printer. Following the procedure (performed statically without shaft movements) the shaft drive is switched on and the force F_a is imposed onto the test site using a weight G. The ratio between forces G and F_a is expressed by the equation (see the schematic description):

$$G \cdot b = F_a \cdot a \quad (2)$$

or $$F_a = G \cdot \frac{b}{a}. \quad (3)$$

Where b/a is the lever ratio during transmission, which was kept constant during the whole period of testing and was equal to 12,2.

During one motion cycle (oscillation) of the driven element ranging from $\Phi = 0°$ to $\Phi = 110°$ and back to $\Phi = 0°$ and with certain combination of joint lubrication, by change in the magnitude of frictional moment during a certain period of time was noted a computer.

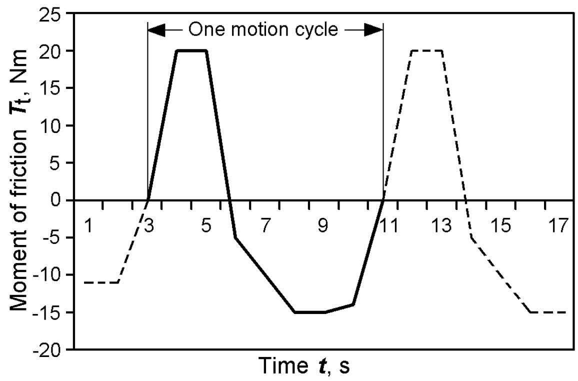

Fig. 7: *The variation in the friction moment T_t for one motion cycle*

At rest points (Φ = 0° and Φ = 110° the magnitude of frictional moment measures $T_t = 0$ (intersection of the printed curve and the x-axis), which is shown in the diagram, Fig. 7 (start and end points of one motion cycle).

The maximum frictional moment values during one cycle were calculated from the registered frictional moment flow, whereas real values of the frictional moment within the joint were calculated using the calibrated diagram.

The analysis was conducted in combination with 7 various loads and 4 types of lubrication: dry, water, plasma and light oil (for the purpose of comparison) (Fig. 9) [4].

Combinations of loads and lubrication as well as the obtained results are shown in diagrams in Fig. 8 [4].

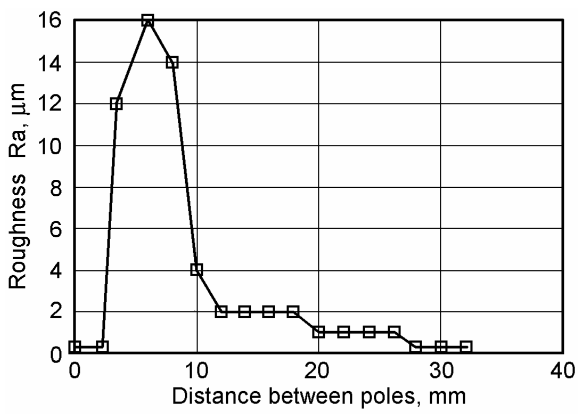

Fig. 8: *Results of measuring the surface roughness*

In relation to the achieved speed levels (low speeds), i.e. impossibility to obtain hydrodynamic friction, the following relation between the frictional moment, force, frictional radius and coefficient of friction can be established:

$$T_t = F_a \cdot \rho \cdot \mu \tag{4}$$

For axial sliding bearings the radius of friction is

$$\rho = \frac{2}{3} \cdot R \, . \tag{5}$$

Where are T_t - the frictional moment of the hip joint prosthesis in Nm, R - the radius of prosthetic head in m, F_a - the force loading a prosthetic implant in N, ρ - radius of friction for axial sliding bearing in m, μ - coefficient of friction.

Now the equation for the frictional moment can be written as follows:

$$T_t = F_a \cdot \frac{2}{3} \cdot R \cdot \mu \tag{6}$$

Based on this equation, the coefficient of friction can be expressed as follows:

$$\mu = \frac{3 \cdot T_t}{2 \cdot R \cdot F_a} \tag{7}$$

The values of obtained coefficients of friction based on this calculation are presented in Fig. 9 along with the mentioned combinations of loads and lubricants.

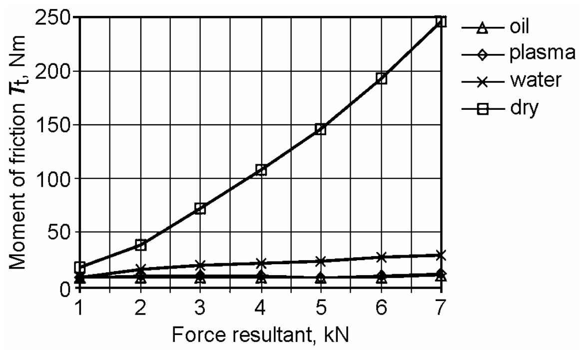

Fig. 9: *Friction moment dependency upon the lubrication method and loading*

3. CONCLUSION

The values of frictional moment obtained in an experimental study showed a large range depending upon the applied lubricant and loading. A significant deviation of the real radius from the theoretical one shows the possible effect of design precision on the magnitude of torsional moment. An especially unfavourable influence occurs in case of contact of spherical surfaces against each other at a certain point (possiblly due to functional clearence in the joint). Although such a positioning of spherical surfaces is rather rare, it should be pointed out that in such a case the torsional moment can be enlarged by several times.

The control of surface roughness preceding and following the experiment showed that certain parts of the spherical surface were not involved in the process of friction despite excessively large loading. This can be explained by incorrectness as well as intentional deviations of geometry in order to improve the conditions of lubrication. Based on the obtained results it is possible to analyse the effects of torsional loading on the loosening within the "prosthesis-cement-bone" system.

In all testing combinations, the picture of bearing, i.e. the zone of contact is much smaller than it is theoretically possible, even with maximum loading (Fig. 1 and Fig. 4). It could be assumed that the zone of contact will become enlarged parallel to the increased loading, but this did not occur. In fact, the largest part of loading was transmitted only to the 8 mm wide spherical zone (Fig. 4 and Fig. 10). This may be convenient only for a small distance between poles when a point contact is avoided, which increases torsional moments.

Fig. 10: *The largest part of loading was transmitted only to the 8 mm wide spherical zone.*

In view of this, the flow of changes in roughness seems to be logical. In zones without contact roughness rose quickly up to approx. Ra = 16 µm and remained high (polar distance form 3 - 10 mm). This increase was caused by the disruption of contact surfaces in the presence of large frictional forces and was visible to the naked eye. However, based on the measurements of the roughness, another zone of contact was found. It could be named a zone of partial contact as it is obvious that it was taking over a part of loading so that roughness was several times smaller. This zone extended from the preceding zone up to the polar distance of 25 mm.

4. REFERENCES

[1] Dumbleton, J. H.: *Tribology of Natural and Artifical Joints*, Tribology Series 3, Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York 1981.

[2] Nikolić, V.; Hudec, M.: *Principi i elementi biomehanike*, Školska knjiga, Zagreb 1988.

[3] Ivušić, V.: *Tribologija*, HDMT, Zagreb 1998.

[4] Dovžak, I.; Opalić, M.; Lederer, D.: *On Measurement of Friction in Biomechanical Joints,* International Design Conference Design '98 Dubrovnik, May 19 - 22, 1998.

[5] Goltner, G.H.: Einfürung in die Schmiertechnik, KM Verlag, Düsseldorf 1961.

[6] Opalic,M.;Rakamaric,P.: *Statička antifrikciona svojstva nekih plastomera,* Zbornik radova FSB, Liber, Zagreb 1982.

[7] Ruszkovski, I.; Orlic, D.; Muftic, O.: *Endo-proteza zgloba kuka*, Medicinski fakultet, Zagreb 1984.

[8] Horvat, Z.:*O trenju u sfernim zglobovima*, Disertacija, Zagreb 1984.

[9] Witt, H.; Rettig, H.; Schlegel, K.; Hupfauer, W.: *Allgemeine Orthopedie*, Georg Thieme Verlag, Stuttgart-New York 1984.

LIST OF CHARACTERISTICS AND UNITS

F_t - overall fractional force, N
N - normal force, N
F_{ad} - adhesional portion of the frictional force, N
F_{def} - deformational portion of the frictional force, N
μ - corresponding coefficient of friction, -
η - viscosity, N·s/m^2
n - rotational speed, s^{-1}
p - pressure, N/m^2
F_a - axial force (the force loading a prosthetic implant), N
G - weight, N
b/a - lever ratio during transmission, -
T_t - frictional moment of the hip joint prosthesis, Nm
R - radius of prosthetic head, m
ρ - radius of friction for axial sliding bearing, m