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On the observation of lubrication mechanisms within hip joint replacements. Part I: Hard-on-soft bearing pairs

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ABSTRACT

The present study describes the lubrication mechanisms within artificial hip joints considering real conformity of rubbing surfaces. Part I is focused on hard-on-soft material combination, introducing the fundamentals of lubrication performance. These pairs have not been explored in terms of in situ observation before. The contact of metal femoral component articulating with transparent polymer acetabular cup was studied using a hip joint simulator. The film formation was evaluated by fluorescent microscopy method. Various model synovial fluids were employed while the key constituents, i.e. albumin, γ-globulin, and hyaluronic acid were fluorescently stained to determine its role in film formation process. Two types of the tests were performed. The first dynamic test aimed on the development of film thickness under constant load during motor driven swinging motion mimicking flexion-extension. Subsequently, a combined test was designed consisting of the three phases; static part with loading/unloading phase (1), pendulum swinging till spontaneous damping of the motion due to friction (2), and static observation under the constant load (3). The results clearly confirmed that the interaction of constituents of synovial fluid plays a dominant role and substantially influences the lubrication conditions. In particular, the main finding coming from the present study is that γ-globulin together with hyaluronic acid form relatively thin stable boundary layer enabling the enhanced adsorption of albumin, thus increasing the lubricant film. Part II of the present study is focused on hard-on-hard pairs while the main differences in film formation process are highlighted among others.

1. Introduction

Total joint arthroplasty has become a routine surgical technique for patients suffering from joint diseases. With respect to the statistics, it is apparent that the replacements of hips and knees are dominant. Currently, various materials have been used. In general, joint implants can be divided into two groups. The first group, representing a major portion of implanted pairs, is known as hard-on-soft. In such a case, hard femoral head or knee femoral component made of metal or ceramic articulates with polyethylene (PE) acetabular cup or knee tibial plateau. These pairs are investigated within the Part I of the present study. Part II is focused on the second material combination known as hard-on-hard where both the implant components are made of metal or ceramic (Nečas et al., 2018a).

Although the amount of joint surgeries continuously increases, limited longevity of replacements persists as the main drawback. The implant is expected to fulfil its function for approximately 8–15 years which is limiting especially in the case of younger active patients (Huch, 2005; Unsworth, 1995). It must be taken into account that revision surgeries are more complicated and the associated costs are substantially higher. Implant failure is often accompanied by aseptic loosening as a consequence of osteolysis (Holzwarth and Cotogno, 2012); the process related to the interaction of hard and soft tissues with wear particles released during joint articulation. Indisputably, wear rate is associated with implant material. It was reported that the highest wear occurs in the case of metal-on-PE material combination while the amount of PE debris is of several orders of magnitude higher compared to metal-on-metal or ceramic-on-ceramic (Heisel et al., 2003).

Previously, an extensive research was carried out focusing on the determination of wear rate considering not only the implant material but also on its size (Goldsmith et al., 2006; Smith et al., 2001) or the size of the clearance between the rubbing surfaces (Brockett et al., 2008; Dowson et al., 2004). Focusing on hard-on-soft pairs, several in vitro studies were introduced, bringing an insight into wear mechanisms respecting the influence of synovial fluid. It was found that even a

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small amount of proteins leads to rapid increase of PE wear (Wang et al., 1998). The authors later reported that not only the total content of proteins in synovial fluid but also its ratio affects wear progression (Wang et al., 2004). The role of lipids in terms of wear of PE was later described by Sawae et al. (2008), who found that the effect of lipids is influenced by the total concentration of proteins. Considering low concentration, an increased amount of lipids led to a decrease of wear rate; however, opposite behaviour was observed when physiological protein concentration was considered. Assuming that wear is strongly affected by the overall tribological performance of the contact couple, friction and lubrication should be also taken into account when identifying the factors limiting the durability of implants (Wang et al., 1998).

Vrbka et al. (2015a) employed real implant components when determining the friction coefficient considering various material combinations. Using 25% bovine serum (BS) it was found that the friction between the head and the cup varies from 0.1 to 0.2 dependently on the head material. The effect of implant diameter was observed as well. Our previous paper was aimed on the deeper clarification of the effect of proteins on friction of metal-PE sliding pair, finding that simple saline solution ensures the lowest level of friction (Nečas et al., 2017a). Proteins added to the base lubricant led to immediate increase of friction which corresponds to elevated wear published elsewhere (Wang et al., 1998). It was also pointed out that the frictional behaviour is considerably influenced by the kinematic conditions while different film formation mechanisms could be observed under lower and higher sliding speed. Although the proteins are dominant components of synovial fluid (Galandáková et al., 2016), hyaluronic acid (HA) has to be also taken into account as it was previously shown that it leads to lowering of both the friction and wear (Sawae et al., 1998).

Frictional behaviour of the contact is also influenced by the surface conditions. Widmer et al. (2001) focused on the ceramic-PE sliding pair concluding that oxygen-plasma treatment of PE caused enhanced adsorption ability of proteins, resulting to reduction of static and dynamic friction, thus affecting service-life of implants. The following paper aimed on the effect of conformational changes of BS albumin (BSA) on adsorption abilities (Heuberger et al., 2005). The authors concluded that the hydrophilic surfaces support the adsorption of proteins in a native state, forming thicker and denser film leading to reduced friction. Nevertheless, it should be pointed out that the surface properties of ceramic and metal are different (Nečas et al., 2017b) indicating that these findings should not be generalized. This statement is supported by later experimental observation focused on the adsorption of BSA (Serro et al., 2006). The results of pin-on-disc tests clearly showed that more pronounced adsorption occurred in the case of hydrophobic metal pin.

The above papers focused on the friction and wear providing a limited knowledge about lubrication. As the lubricating film apparently affects the joint conditions, a deeper understanding of lubrication mechanisms in hard-on-soft pairs should be of a greater interest. At this point, some limitations related to these bearing pairs should be highlighted. The fundamental point is the issue of material. Considering hard-on-hard pairs, optical glass is usually used as a substitution of one of the rubbing surfaces, allowing direct observation while keeping the rigid nature of the contact (Mavraki and Cann, 2011; Vrbka et al., 2014, 2015b). The authors often employed optical interferometry technique for film thickness investigation (Hartl et al., 2001). However, in the case of hard-on-soft pairs, mimicking the contact mechanics is much more complicated and the routine techniques usually fail. One of the pilot studies focused on the observation of lubrication mechanisms was given by Crockett et al. (2009) who enhanced the friction data by *ex situ* fluorescent observation of PE particles released during the sliding test. It was found that low friction is basically accompanied by relatively low amount of transferred wear particles. The authors also compared the effect of model fluid, finding that there was no significant difference considering saline solution and BS; however, BSA exhibited substantially higher friction.

Summarizing the literature review about the tribological behaviour of hard-on-soft bearing pairs, it can be concluded that some clear results have been published in relation to wear and friction mechanisms during the last three decades. However, so far, there is not a study examining the lubricant film formation based on in situ observation. The main reason is complicated modelling of contact mechanics together with limitations of the routine techniques used for film formation investigation. Therefore, the aim of the Part I of the present study is to clarify the lubrication mechanisms within hard-on-soft pairs with the use of direct contact observation. The main attention is paid to the effect of model synovial fluid composition, focusing on the determination of the mutual interaction of the constituents of model SF in relation to lubricant film formation. For this purpose, the fluorescent technique is a suitable tool since it is not dependent on the surface reflectivity nor conductivity (Myant et al., 2010; Fowell et al., 2014; Necas et al., 2018b). The technique was previously successfully employed when examining the lubrication considering both ceramic-on-glass (Nečas et al., 2016a) and metal-on-glass (Nečas et al., 2016b) material combinations; however, its use for soft-based joint replacements is presented for the first time. To be able to observe the contact in situ, the acetabular cup is made of transparent poly(methyl) methacrylate (PMMA) which exhibits similar mechanical properties like conventionally used PE.

2. Materials and methods

The measurements were realized utilizing pendulum hip joint simulator originally designed by Stanton (1923). Real geometrical ball-on-cup contact, mimicking the artificial hip joint is considered while the continuous swinging in flexion-extension plane may be applied. The range of swinging motion was set according to the standards together with the respect to actual motion range of hip joint published in literature. ISO 14242 provides the loading and displacement parameters for testing of hip implants, defining the range of flexion/extension from $+25°$ to $-18°$. However, it was found by Roaas and Andersson (2009) that actual extension angle is smaller; $-9.5° \pm 5.2°$ in particular. Additionally, it should be emphasized that the pendulum does not allow to apply asymmetric swinging; the maximum deflection has to be the same considering both ways (flexion vs. extension). Therefore, the conservative range of motion from $+16°$ to $-16°$ was applied.

The acetabular cup is fixed in the stainless steel pot using the resin and is mounted to the stationary frame of the simulator. The femoral head is attached to the cone and is inserted into the swinging pendulum arm. Some simulators exhibit the limitation associated with centring of the femoral component in the cup; however, in the case of pendulum, the contact is centred spontaneously as the swinging arm is released and the ball fits into the socket. The arm is then powered by electromagnetic motors while its bottom part flange moves within the rolling guide. Therefore, any undesirable rotation or deflection of the pendulum in transverse plane do not occur. The reverse arrangement of the contact allows direct observation using the imaging system (Vrbka et al., 2015b). For the first time, the use of fluorescent microscopy together with pendulum simulator is introduced in the present study. For this purpose, a tailor-developed optical module was implemented. The contact is illuminated by mercury lamp while the light passes through the assembly of optical filters. High speed scientific complementary metal-oxide semiconductor camera Andor Neo 5.5 is employed for data recording. A schematic sketch of the experimental methodology is displayed in Fig. 1.

The optical method based on the principle of fluorescence was used for the investigation of lubricant film formation. The fluorescence phenomenon is known to be a consequence of the following steps (Haugland et al., 1996; Lakowicz, 2006):

- **Excitation:** A photon is excited by the external light source being absorbed by the fluorophore contained in the lubricant.