Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

The effect of lubricant constituents on lubrication mechanisms in hip joint replacements

*David Nečas**, *Martin Vrbka*, *Filip Urban*, *Ivan Křupka*, *Martin Hartl*

Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic

ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
2 November 2015
Accepted 9 November 2015
Available online 19 November 2015

Keywords:
Hip replacement
Fluorescent microscopy
Colorimetric interferometry
Albumin
γ-globulin
Lubricant film thickness

ABSTRACT

The aim of the present paper is to provide a novel experimental approach enabling to assess the thickness of lubricant film within hip prostheses in meaning of the contribution of particular proteins. Thin film colorimetric interferometry was combined with fluorescent microscopy finding that a combination of optical methods can help to better understand the interfacial lubrication processes in hip replacements. The contact of metal femoral head against a glass disc was investigated under various operating conditions. As a test lubricant, the saline solution containing the albumin and γ-globulin in a concentration 2:1 was employed. Two different mean speeds were applied, 5.7 and 22 mm/s, respectively. The measurements were carried out under pure rolling, partial negative and partial positive sliding conditions showing that kinematic conditions substantially affects the formation of protein film. Under pure rolling conditions, an increasing tendency of lubricant film independently on rolling speed was detected, while the total thickness of lubricant film can be attributed mainly to albumin. When the ball was faster than the disc (negative sliding), a very thin lubricant film was observed for lower speed with no significant effect of particular proteins. The increase in sliding speed led to the increase of film thickness mainly caused due to the presence of γ-globulin. On the contrary, when the disc was faster than the ball (positive sliding), the film formation was very complex and time dependent while both of the studied proteins have shown any qualitative change during the test, however the effect of albumin seems to be much more important. Since a very good agreement of the results was obtained, it can be concluded that the approach consisting of two optical methods can provide the fundamental information about the lubricant film formation in meaning of particular proteins while the simultaneous presence of other constituents in model synovial fluid.

*Corresponding author. Tel.: +420 541 143 227.
E-mail address: necas@fme.vutbr.cz (D. Nečas).

http://dx.doi.org/10.1016/j.jmbbm.2015.11.006
1751-6161/

1. Introduction

A total hip replacement is one of the most successful surgical treatments of modern medicine. In OECD countries, 160 operations per 100,000 inhabitants were conducted in 2011 as is reported in Health and Glance 2013: OECD indicators. Although there was a rapid improvement of applied materials during the last tens of years (Pramanik et al., 2005), artificial hip joints still suffer from limited longevity. The need of re-operations as the consequence of implant failure leads to deterioration of daily life, especially in case of younger patients (Adelani et al., 2013). The most common cause of this failure is aseptic loosening accompanied by osteolysis due to wear of rubbing surfaces (Joshi et al., 1993). Several authors focused on investigation of wear of rubbing surfaces under various operating conditions (Goldsmith et al., 2000; Smith et al., 2001a; Wang et al., 2004). However, little is yet known about interfacial lubrication processes in hip replacements, even though such a knowledge can help to reduce wear and therefore can eventually extend the implant longevity. The tribological performance of contact pair is substantially influenced by prevailing lubrication regime and material properties of the components. To ensure minimisation of wear, a complete separation of rubbing surfaces by fluid film is necessary. However, in case of hip implants, a boundary or mixed lubrication regime usually occur (Jin et al., 2006).

In relation to lubrication mechanisms, determination of lubricant film thickness seems to be a crucial task. A mathematical model for film thickness estimation in metal-on-metal joints was pronounced several times (Dowson, 2006; Dowson and Jin, 2006; Jalali-Vahid et al., 2006). The analysis usually comes from the classical elastohydrodynamic lubrication (EHL) theory assuming that the lubricant film is affected by elastic deformation of contact surfaces in combination with fluid entrainment. It should be considered that both natural and artificial joints are not lubricated by simple Newtonian fluids. Human synovial fluid (SF), as well as bovine serum (BS), which is often used as its model (Essner et al., 2005), exhibit non-Newtonian and shear thinning behaviour (Mavraki and Cann, 2011). Moreover, it was proved that protein adsorption on rubbing surfaces significantly influences the lubricant film (Parkes et al., 2014; Scholes and Unsworth, 2006) and tribochemical layers (Wimmer et al., 2003). Because of the above information, numerical predictions in biological systems are particularly complicated. An experimental approach for film thickness evaluation based on the change of electrical resistivity was introduced by Dowson et al. (2000). The authors focused on the qualitative analysis of the gap between metallic components of artificial joint during the walking cycle. This study was followed by Smith et al. (2001b) who applied the same method on a ceramic pair. Although the electrical method can provide the information about the qualitative change of lubricant film between articulating surfaces, it does not allow observing the contact in situ; therefore it is quite demanding to describe the changes in terms of lubricant film formation.

In recent years, extensive research has been conducted into lubricating film formation within hip joints replacements. The pilot study was provided by Mavraki and Cann (2009), who focused on the fundamentals associated with SF lubrication. Different protein solutions were employed to model healthy and periprosthetic SF. In addition, the experiments were also carried out with BS. Friction measurements were realized on the commercial Mini Tractione Machine (MTM) apparatus finding that at low speeds (<20 mm/s) a boundary lubrication regime is typical for all applied lubricants reducing the friction. Film thickness was evaluated by using a ball-on-disc tribometer in combination with optical interferometry method. The experiments were performed under pure rolling conditions, constant load equal to 5 N, and room temperature. For BS, film thickness gradually increased with increasing rolling speed. During a subsequent decrease of speed back to initial value, the film was time independent with just a little tendency to increase (up to 28 nm at 5 mm/s). At the end of the experiment, the residual film thinner than 20 nm was detected suggesting the importance of adsorbed protein layer. The authors concluded that both friction and film thickness measurements were time dependent.

The following reference, given by the same authors (Mavraki and Cann, 2011), extended the previous study by investigating the influence of various loading and kinematic conditions on film thickness in the contact lubricated by BS. The effect of high (ball-on-disc) and low (lens-on-disc) contact pressure as well as the influence of BS concentration was examined. In a ball-on-disc configuration, the experiments were realized under pure rolling and pure sliding conditions. Under pure rolling, the film thickness increased with increasing speed from 5 to 50 nm with no significant effect of subsequent speed sweep. At the end of the experiment, a thin lubricant film in a range from 9 to 19 nm attributed to protein adsorption was detected. Under pure sliding, a substantial drop (around 70%) in lubricant film was observed. Low contact pressure generally led to a thicker film (60–80 nm), especially at lower speeds. A significant scatter in results was explained by inherent nature of applied fluid.

The effect of proteins in model fluid on film formation was analysed by Fan et al. (2011) who firstly employed a real metal femoral component. The CoCrMo ball was stationary while the glass disc was sliding as a counterface. Film thickness was evaluated in a range of speeds from 2 to 60 mm/s for simple protein solutions and compared with BS results. It was concluded that protein containing solutions form a thicker film than BS and show a complex time-dependent behaviour. The thicknesses of adsorbed film after a few minutes of sliding were in a good agreement with previous papers (Mavraki and Cann, 2009; Mavraki and Cann, 2011). The thickness of the layer was augmented by hydrodynamic effect especially at low speeds. Deposited films of 20–50 nm were measured at the end of the test. In author's opinion, this was due to molecule aggregations in the inlet zone creating a reservoir of high-viscosity material periodically passing through the contact and forming a much thicker film.

Myant et al. (2012) evaluated the film thickness between the glass disc sliding against the CoCrMo ball as a function of time and mean speed. The effect of variable load was also investigated. A series of BS and simple saline protein solutions were used as test lubricants. Static test under zero speed was conducted to provide the influence of test fluid on