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Visualization of lubricating films between artificial head and cup with respect to real geometry

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ABSTRACT

The aim of this study is to propose a novel experimental approach enabling in-situ observation of film formation within hip joint replacements with respect to real geometry (including radial clearance) of rubbing surfaces. A pendulum hip joint simulator in combination with thin film colorimetric interferometry was employed for film thickness evaluation between metal femoral head and glass acetabular cup lubricated by bovine serum solution. Glass acetabulum was developed according to dimensions of artificial cup so the real radial clearance between components was considered. The pendulum, deflected at an initial position, was released and allowed to oscillate freely in the flexion–extension plane; therefore the transient character of motion was considered. Maximum central film thickness of 232 nm was measured at the beginning of the experiment. After a short time it decreased and became quite stable (around 90 nm) until the end of the measurement. The preliminary results shown that novel experimental approach seems to be a very powerful tool for studying lubrication processes within artificial hip joints while considering different loading and kinematic conditions, influence of geometry, clearance and material combination of contact pairs.

1. Introduction

In recent years, an extensive research has been conducted to clarify interfacial lubrication processes within hip joint replacements. Lubricant film thickness between rubbing surfaces influences friction, wear and therefore the service life of artificial joints. However, in vivo measurement is not suitable in this case; the artificial joint is surrounded by human tissues, which disables usage of conventional experimental methods, and also ethical consideration must be taken into account.

In general, two different approaches can be applied while studying lubricant film thickness; numerical simulations and experimental measurements. Several attempts have been made to predict film thickness numerically [1–3]. However, it is well known that a synovial fluid is a non-Newtonian liquid and corresponds to shear thinning behaviour [4,5]. This makes numerical predictions to be extremely complicated. Furthermore, protein adsorption, whose simulation is particularly difficult, significantly affects film thickness [6] and tribochemical layers [7].

In terms of experimental validation, electrical and optical methods represent two groups of routine techniques. The first experimental study about lubricant film within artificial hip joint using electrical resistivity method was given by Dowson et al. [8]. The aim of this study was to detect the gap between metallic head and cup during whole walking cycle. Achieved results were only qualitative in this case. The same method was applied by Smith et al. [9] while studying the surface separation of ceramic components during walking cycle. Since ceramic is non-conducting material, rubbing surfaces were coated with thin titanium nitride layer to allow the application of the resistivity technique. However, electrical methods usually suffer from very high sensitivity and, in addition, do not allow observing lubricant film formation directly, so that any information about physical or chemical processes is missing.

Mavraki and Cann [4,10] employed optical interferometry while studying lubricant film thickness within the model of hip joint replacements. They focused on the influence of mean speed and different model fluids on central film thickness. These articles were followed by Myant and Cann [5]; Myant et al. [11] where the influence of load was also introduced [11]. Although these articles brought a lot of important information about the fundamentals of protein film formation, lubricant film thickness was studied in classical ball-on-disc EHL simulator where the contact of non-conformal bodies occurs.

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From the literature review it can be assumed that the conformity of rubbing surfaces and therefore the radial clearance can substantially influence film thickness [12–14]. In our previous studies, we have applied two experimental configurations to verify this hypothesis [15, 16]. As was shown by Vrbka et al. [16], changing the experimental setup from ball-on-disc to more conformal ball-on-lens configuration led to significant differences in film thickness measurements. But even in this case, the diametral clearance was still quite high (about 3.2 mm), which does not correspond to real situation (0.04–0.2 mm).

The above information indicates that so far there has not been in vitro study about film thickness determination respecting the real geometry of head and cup. The aim of this study is to introduce a novel experimental approach, which enables to evaluate the film thickness inside the contact of artificial joints with respect to real geometry of both parts, including the radial clearance. For this purpose, an optical interferometry measurement method was combined with a pendulum hip joint simulator to enable the evaluation of film thickness and the observation of protein film formation.

2. Materials and methods

An experimental apparatus, employed in the present study, consists of a pendulum hip joint simulator and optical imaging system. The simulator, originally designed by Stanton [17], is composed of two main parts; a base frame with acetabular cup and pendulum with femoral head. The optical imaging system includes the episcopic microscope, halogen illuminator, CMOS digital camera and PC, while the microscope and camera are mounted in an inverted position, as can be seen in Fig. 1. For observation of film formation inside the contact, the acetabular cup was transparent.

If the contact of metal femoral head and glass acetabular cup is illuminated, then colour Newton rings can be observed. Thin film colorimetric interferometry, presented by Hartl et al. [18] was used for film thickness evaluation. Authors focused on ball-on-disc configuration and applied two different approaches [18]. Firstly, the glass disc was coated by chromium layer only. Secondly, the disc was, moreover, coated by silicon dioxide "spacer" layer. It was clearly proved that there is no influence of spacer layer on measured film thickness. In our case, the contact surface of glass cup is coated only with semi-reflective chromium layer to increase the contrast of interference fringes. The evaluation of the film thickness is based on three steps:

1. The calibration curves are obtained from an interferogram of a lightly loaded static contact, which is matched with measured contact profile. Therefore, information about the dependence between the colour and the film thickness is given.
2. Interferograms of fully loaded contact during the swinging motion of pendulum are captured via a high-speed camera.
3. Captured interferograms are matched with calibration curves, so the thickness at arbitrary location of the contact can be determined.

In our study, femoral head Aesculap NK430K (CoCr29Mo, ISO 5832-12) and optical glass (BK7) acetabular cup were investigated. By using the optical scanning method (GOM ATOS Triple Scan) it was found that the actual diameters of head and cup were 27.988 mm and 28.080 mm, respectively. Therefore, the rubbing surfaces have shown the diametral clearance of 92 μm. Initial surface topography of metal head was analysed in greater detail using the optical measurement method based on phase shifting interferometry (Bruker Contour GT X8). Evaluated average surface roughness *Ra* was 3.8 nm. The contact surface of glass cup was considered to be optically smooth.

For the purpose of this study, a human synovial fluid was substituted by a 25% bovine serum (BS) solution (Sigma-Aldrich B9433) in deionized water. Total protein concentration was 22.4 mg/ml and the lubricant was prepared in volumes of 12 ml and immediately stored in a freezer at −22 °C. The solution was taken out from the freezer 2 h before testing to thaw naturally and then supplied to the glass cup; thereby a vicinity of the contact pair was fully bathed. All components, which were in contact with BS, were cleaned in 1% sodium dodecyl sulphate solution, rinsed in distilled water, and then washed in an isopropyl alcohol before assembly.

Test conditions of all experiments were as follows. Applied load, achieved by putting the weights on the pendulum arms, was 532 N, while the resulting maximum contact pressure reached 28.7 MPa (contact zone diameter was approximately 6 mm). As can be seen in Fig. 1, the acetabular cup can be tempered by heating cartridges, so all the measurements were carried out under body temperature of 37 °C. BS solution was also heated just before the test. The pendulum was deflected at an initial offset angle of 16°, released, and allowed to oscillate freely in the flexion–extension plane.

3. Results and discussion

Previously, the majority of authors have applied simplified unidirectional pure sliding or rolling/sliding conditions while studying lubrication processes within artificial hip joints [4,5,10,11,15,16]. Although it was declared that this approach can provide important information about the fundamentals of protein film formation, in real situation kinematic and loading conditions are transient. In hip joints, there are three types of motions; flexion/extension, abduction/adduction and inward/outward rotation, while the flexion/extension is a dominant during the gait cycle.

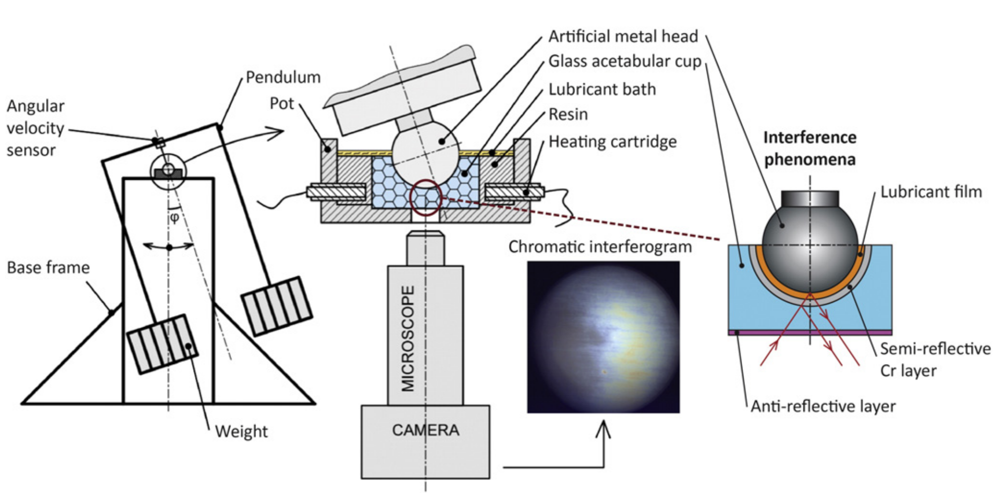

Fig. 1. Observation of lubricant film using optical test device — a pendulum hip joint simulator.