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Short Communication

The lubrication performance of the ceramic-on-ceramic hip implant under starved conditions

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ABSTRACT

Lubrication plays an important role in the clinical performance of the ceramic-on-ceramic (CoC) hip implant in terms of reducing wear and avoiding squeaking. All the previous lubrication analyses of CoC hip implants assumed that synovial fluid was sufficiently supplied to the contact area. The aim of this study was to investigate the lubrication performance of the CoC hip implant under starved conditions. A starved lubrication model was presented for the CoC hip implant. The model was solved using multi-grid techniques. Results showed that the fluid film thickness of the CoC hip implant was affected by fluid supply conditions: with the increase in the supplied fluid layer, the lubrication film thickness approached to that of the fully blooded solution; when the available fluid layer reduced to some level, the fluid film thickness considerably decreased with the supplying condition. The above finding provides new insights into the lubrication performance of hip implants.

1. Introduction

Hip arthroplasty has shown excellent outcomes in decreasing pain and restoring function in patients with degenerative hip joint diseases. The ceramic-on-ceramic (CoC) hip implant is increasingly used due to its outstanding tribological and biocompatible properties. Lubrication plays an important role in the clinical performance of the CoC hip implant. First, poor lubrication is one potential reason of squeaking noise, which is an audible phenomenon receiving increasing concerns (Jarrett et al., 2009), of CoC hip implants (Chevillotte et al., 2010). Second, under deprived lubrication conditions, such as edge loading that occurs when the contact patch between the acetabular and femoral components extends over the rim of the cup, wear of CoC hip bearings significantly increases (Al-Hajjar et al., 2013). In return, third body particles can disrupt lubrication and cause higher friction and squeaking (Sariali et al., 2010). Additionally, poor lubrication increases friction of hip implants which itself can cause loosening (Bishop et al., 2013). Therefore, understanding the lubrication mechanism of CoC hip implants is extremely important.

However, all the previous lubrication analyses of CoC hip bearings were based on an assumption that synovial fluid is sufficiently supplied to the lubricated contact area (Jin et al.,

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1997; Mabuchi et al., 2004; Meng et al., 2013). This is not always true since realistic conditions may limit the amount of synovial fluid supplied to the contact area of the implant. For example, it has been reported that the volume of the synovial fluid varies much between individuals, ranging from 0.7 to 11.6 mL (Moss et al., 1998). Then it is possible that the available amount of the synovial fluid itself is not sufficient to build up the fluid film. Moreover, under some adverse conditions, such as the edge loading, the inlet distance of fluid may be considerably reduced, which in return will cause starvation. Furthermore, under normal walking or running, hip replacements experience continuously reciprocating motion. Such a repeated reciprocation changes the inlet and outlet of the lubricated contact of hip replacements. Since the film thickness at the outlet of lubricated contact tends to be very small (similar to that in the contact area), when the outlet becomes the inlet, starvation may occur. However, the lubrication performance of CoC hip bearings under starved conditions has not been studied and is thereby still not clear. Therefore, the aim of this study was to investigate the lubrication performance of the CoC hip implant under starved conditions.

2. Materials, model and methods

2.1. Materials

A typical CoC total hip replacement bearing, which consists of three components, a titanium acetabular shell, a ceramic insert and a ceramic head, was considered. The ceramic insert is normally fixed in the titanium acetabular shell using a taper locking mechanism. The initial stability of the acetabular shell is achieved using either cemented or uncemented methods while the long term fixation is reached by the in-growth of bone onto and around the porous-coated shell surface. The spherical ceramic head articulates against the hemi-spherical inner surface of the ceramic insert to form a joint. In the present study, the insert was assumed to be securely fixed to the shell. A uniform thickness of 10 mm and 4 mm was adopted for the ceramic insert and the titanium shell, respectively. The bone and the fixation of the shell were represented by an equivalent support layer with a thickness of 2 mm and appropriate material properties (Jagatia and Jin, 2001). Such a CoC hip bearing configuration is shown in Fig. 1. All the materials of the implant were assumed to be homogeneous and linear elastic. The material properties adopted in the present study are summarized in Table 1. The radius of the head was 14 mm. To achieve a good convergence, the radial clearance was assumed to be 10 μm, which is the lower limit of the radial clearance used for CoC hip bearings (Di Puccio and Mattei, 2015).

The synovial fluid in artificial hip joints behaves as a powerful non-Newtonian fluid under relatively low shear rates. However, under higher shear rates likely to be experienced in the hip joint (10^5/s), it was reasonable to assume the synovial fluid as Newtonian, isoviscous and incompressible (Cooke et al., 1978; Jin, 2006; Wang et al., 2008; Yao et al., 2003). A realistic viscosity of 0.0025 Pa s was adopted for the synovial fluid in the present study (Yao et al., 2003).

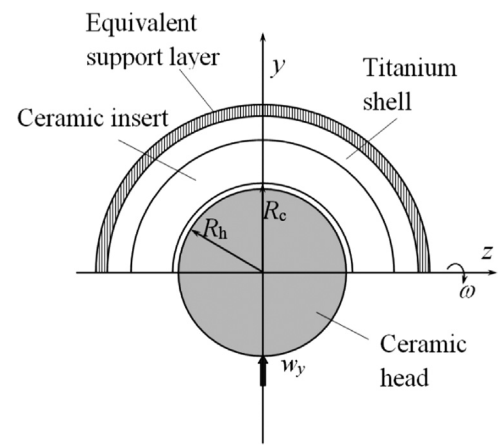

Fig. 1 – A ball-in-socket configuration for the starved lubrication analysis of the CoC hip implant.

2.2. Model

As the first step attempting to investigate the lubrication performance of the CoC hip implant under starved conditions, only the stead-state condition was considered in the present study. The hip joint is generally subjected to three-directional dynamic load and speed during walking. However, the major load and motion components are in the vertical and flexion/extension direction, respectively. Therefore, only the vertical load and the flexion/extension rotation were considered in the present study. The flexion/extension velocity and vertical load were chosen as 2 rad/s and 1500 N, respectively. Both were approximately the average values during a gait (Jin, 2006). Following the previous starved lubrication studies on circular or elliptical contacts (Chevalier et al., 1998; Wijnant, 1998; Yin et al., 2009), it was assumed that a layer of synovial fluid was supplied in the inlet region. The fluid supply condition was represented by the thickness of this inlet fluid layer.

The governing equations of the lubrication model were established in spherical coordinates (Meng, 2013). The starved lubrication was described using a modified Reynolds equation (Meng, 2013; Wijnant, 1998):

$$\sin\theta\frac{\partial}{\partial\theta}\left(h^3\sin\theta\frac{\partial p}{\partial\theta}\right)+\frac{\partial}{\partial\varphi}\left(h^3\frac{\partial p}{\partial\varphi}\right)=6\eta R_h^2\omega\sin^2\theta\frac{\partial(\theta_f h)}{\partial\varphi} \quad (1)$$

where p is film pressure; h is film thickness; R_h is the radius of the head; η is the viscosity of the periprosthetic synovial fluid; ω is the angular velocity of the femoral head; ϕ and θ are the spherical coordinates (Meng et al., 2010; Meng et al., 2013), and θ_f is fractional film content. The fractional film content was defined as the ratio between the thickness of the fluid layer (h_{fluid}) and the gap height (h) (Wijnant, 1998):

$$\theta_f(\varphi,\theta)=\frac{h_{fluid}(\varphi,\theta)}{h(\varphi,\theta)} \quad (2)$$

Hence, if the lubricant only partly fills the gap (i.e. the starved region), $0<\theta_f<1$; whereas if it completely fills the gap (i.e. the pressurized region), $\theta_f=1$.

Besides the boundary conditions similar to the fully flooded lubrication (Meng, 2013):

$$p(0,\theta)=p(\pi,\theta)=p(\varphi,0)=p(\varphi,\pi)=0$$
$$p(\varphi,\theta)\geq 0, 0<\varphi<\pi, 0<\theta<\pi \quad (3)$$