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Estimation of Appropriate Lubricating Film Thickness in Ceramic-on-Ceramic Hip Prostheses

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Abstract. Artificial hip prostheses, consisting of femoral head and acetabular cup are widely used and have affected the lives of many people.However, the primary issue associated with the long term performance of hip prostheses is loosening induced by excessive wear during daily activity. Therefore, an effective lubrication is necessary to significantly decrease the wear. To help understand the lubricating performance of such typical hip joint prostheses, in the present paper a hydrodynamic lubrication model based on Reynolds equationwas introduced. The material pairs of ceramic acetabular cup against ceramic femoral head was investegated.The main aim of this study is to investigate of the effect of loading on the formation of lubricating film thickness.The model of a ball-in-socket configuration was considered assuming that the cup was stationary while the ball was to rotate at a steady angular velocityvarying loads.Based on simulation result, it was found that to promote fluid film lubrication and prevent the contacting components leading to wear, the film thickness of lubricant should be determined carefully based on the load applied. This finding may have useful implication in predicting the failure of lubricating synovial fluid film and wear generation in hip prostheses.

INTRODUCTION

Hip joint is a spherical joint between the acetabular and the femoral head in the pelvis. Hip joint can accommodate a wide range of movements and load transmission due to the ball-in-socket geometry. Joint deseases, sport injuries and trauma cause damage the joint and disability. As one of the solutions, hip prostheses have been introduced and implemented to replace the damaged parts.

Total hip prostheses usually made of an ultra high molecular weight polyethylene (UHMWPE) against a metallic or ceramic femoral head, are widely used. All materials used are biocompatible. However, daily activities significantly can affect the longevity of the hip prosthesis. The crucial issue associated with the long term performance of hip prostheses is loosening induced by excessive wear due to the pressure distribution of the contact area of hip prostheses during daily activities [1-4]. According to this, due to the complexity of the geometry and the amount of forces which is often impossible to be investigated experimentally, computer models can be a very useful way to solve some of these issues.

As previously mentioned, the hip prostheses problems are very complex that need to be deeply explored. Most studies just present the contact analysis of the femoral or acetabular component by neglecting the presence of natural lubricant effect. Therefore there is lack of information about the consensual boundary conditions used in modeling the hip prostheses. Only a few studies have been performed regarding with this issues [5-6]. It is interesting to note that in order to minimize wear it is necessary to support as much load as possible by fluid film lubrication.

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The present work intends to investigate with numerical models the hip prostheses in terms of lubrication. Numerically, the effect of the significant design parameters, i.e. the load and the femoral head radius on the formation of lubricating film thickness is assessed. This finding can provide detailed information about how operating conditions affect the lubrication performance and thus it is imperative for further insights into the failure of lubricating film.

LUBRICATION MODEL

In this work, a hydrodynamic lubrication analysis for the ball-on-plane model representing the ball-in-socket configuration shown in Fig. 1 isassumed to analyze the formation of the lubricant film in hip prostheses.The assumption of the hydrodynamic lubrication for the analysis is acceptable, because in practice the ceramic is quite rigid in preventing the occurrence of elastic deformation of the surface.In addition, from tribological point of view, it should be pointed out that because of better wear resistance, ceramics are considered as good alternative to metal as bearing couple materials. Therefore, the Reynolds equation (Eq. 1) is used as the governing equation for the pressure generation under steady-state condition for the present lubrication problem.

$$\frac{\partial}{\partial x}\left(h^3 \frac{\partial p}{\partial x}\right) = 6\mu u \frac{\partial h}{\partial x} \tag{1}$$

where h is the film thickness, p is the hydrodynamic pressure, μ is the dynamic viscosity, u is the velocity. The synovial lubricant is assumed to be isoviscous, incompressible and Newtonian [7].

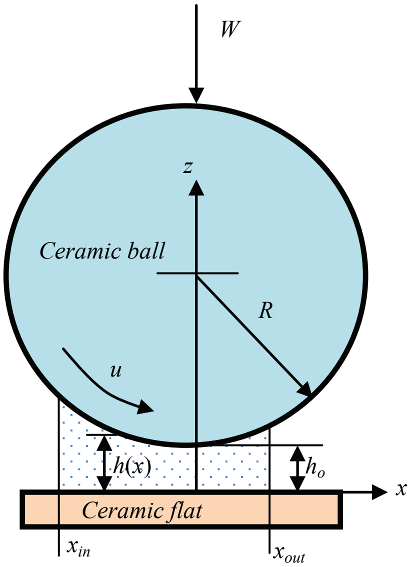

FIGURE 1. Schematic of equivalent ball-on-plane configuration of hip prostheses lubrication

The film thickness (h), as shown in Fig. 1 consisting of the gap, can be written approximately as [8]

$$h(x) = h_o + x^2 / 2R \tag{2}$$

whereh_o is the minimum film thickness at $x = 0$ and R is the radius of the ceamic ball. In the numerical simulations the following parameters are used: $x_{in}/R = -0.2$, and $x_{out}/R = 0.1$. Thepressure boundary condition at the inlet is $p = 0$ at $x_{in}/R = -0.2$. At the outlet, the free boundary pressure condition of Reynolds is applied, i.e. $p = 0$ and $\partial p / \partial x = 0$. Finite volume method and tri-diagonal-matrix-algorithm [9, 10] are used in the numerical solution.Table

1 shows the parameters used for the analysis.A hydrodynamic lubrication was performed under variations of load (*W*) and femoral head radius (ceramic ball), see Fig. 1.Different loads ranging between 2000 to 3000 Nare applied[11–13].

TABLE1.Simulated parameters

The viscosity of synovial lubricant	μ	0.005	Pa.s
The angular velocity	ω	1.5	µm
Femoral head radius	R	13 – 15	mm
External load	W	2000 – 3000	N

All equations above were discretised on the grid in terms of numerical solution. To this end, finite difference equations are obtained by means of the micro-control volume approach [9], on account of its advantages in analyzing a complex domain. For all derivatives the central difference is used except at the boundaries. Appropriate one-sided difference is used at the boundaries. The modified Reynolds equation is solved using TDMA (tri-diagonal matrix algorithm), [10]. In the present study, relatively to the finite volume analysis, grid convergence tests were conducted to select the adequate quantity of the mesh.

RESULTS AND DISCUSSION

The main components of the hip prostheses are femoral stem, femoral head, femoral neck and acetabular cup (embedded in the pelvis). The output results from the present hydrodynamic lubrication analysis include the pressure profiles and the film thickness. In the present study, the prediction of film thickness is based upon the assumption of smooth surfaces. Fig. 2 shows the effect of the load on the predicted minimum film thickness. The femoral head radius of 13 mm is assumed for the analysis based on the geometry model of the unipolar artificial hip joint proposed by Eko*et al.* [14].It is clearlynoticed that an increase in the load leads to a decrease in the predicted film thickness. This is as expected because the lubricant cannot withstand a significant load. This shows that the lubricant cannot develop a high enough pressure profile to counteract the load during the activity. The predicted lubricating film thickness touches approximately 0.057 µm where the load is 3000 N.

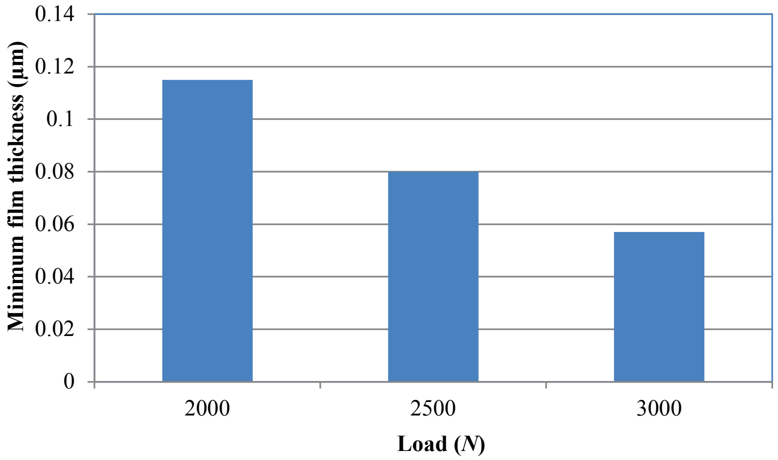

FIGURE 2. Effect of the load on the predicted film thickness with femoral head radius of 13 mm

Figure 3 shows the effect of the femoral head radius on the predicted minimum film thickness at load of 2000 N. Here, the nominal load was chosen to be 2000 N (approximately three times body weight), which represents the peak contact hip force during the stance phase of a gait cycle [12].It can be shown that the variation of the predicted film thickness is relatively large for small range of femoral head radius considered. The lubricating film thickness is strongly dependent on the femoral head radius. It is evident that an increase in the femoral head radius results in an increase in the minimum film thickness. A most possible explanation is the fact that increasing the femoral head radius leads to an increase the entraining velocity and consequently lubricant film thickness.

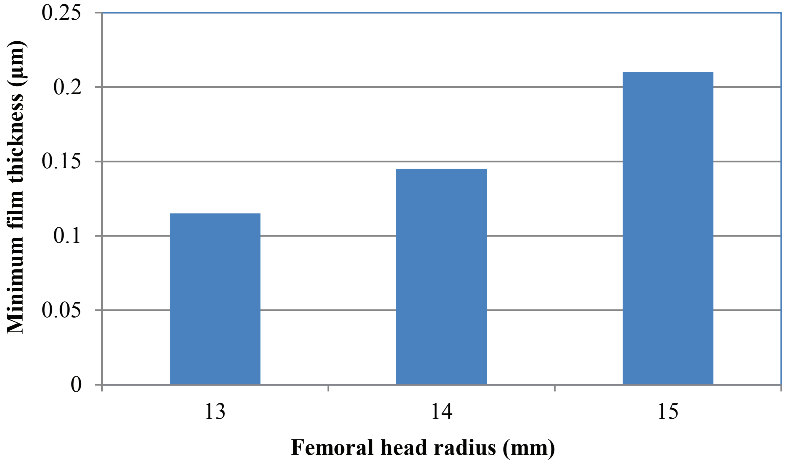

FIGURE 3. Effect of the femoral head radius on the predicted film thickness at load of 2000 N

CONCLUSIONS

An investigation into the prediction of film thickness in hip prosthesis was conducted. The principal aim of this study was to explore the role of the loading and the femoral head radius on the promotion of the fluid film lubricant. It was concluded that the development of hydrodynamic lubrication in ceramic-on-ceramic hip prosthesis with respect to the lubricating film thickness depends on the loading and the femoral head radius significantly.As a consequence,the load and the femoral head radiusshould be determined carefully.

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