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A patterned microtexture to reduce friction and increase longevity of prosthetic hip joints

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ABSTRACT

More than 285,000 total hip replacement surgeries are performed in the US each year. Most prosthetic hip joints consist of a cobalt–chromium (CoCr) femoral head that articulates with a polyethylene acetabular component, lubricated with synovial fluid. The statistical survivorship of these metal-on-polyethylene prosthetic hip joints declines significantly after 10–15 years of use, primarily as a result of polyethylene wear and wear debris incited disease. The current engineering paradigm to increase the longevity of prosthetic hip joints is to improve the mechanical properties of the polyethylene component, and to manufacture ultra-smooth articulating surfaces. In contrast, we show that adding a patterned microtexture to the ultra-smooth CoCr femoral head reduces friction when articulating with the polyethylene acetabular liner. The microtexture increases the load-carrying capacity and the thickness of the joint lubricant film, which reduces contact between the articulating surfaces. As a result, friction and wear is reduced. We have used a lubrication model to design the geometry of the patterned microtexture, and experimentally demonstrate reduced friction for the microtextured compared to conventional smooth surrogate prosthetic hip joints.

1. Introduction

More than 285,000 total hip replacement (THR) surgeries are performed in the US each year to treat degenerative joint diseases that cause pain and disability [1]. Several bearing types for prosthetic hip joints exist: ceramic-on-ceramic (COC), ceramic-on-metal, ceramic-on-polyethylene (COP), metal-on-metal (MOM), and metal-on-polyethylene (MOP). This paper focuses on the MOP type because it is the most commonly used in the US. An MOP prosthetic hip joint consists of a femoral head, usually made of cobalt–chromium (CoCr), attached to the femur with a taper or stem. The head articulates with a polyethylene liner (usually ultra-high molecular weight polyethylene (UHMWPE) or (highly) cross-linked polyethylene (XL polyethylene)) fixed in an acetabular component that is anchored in the pelvis (see Fig. 1). The most common reasons for an MOP prosthetic hip joint to fail include [2]; (1) wear of the polyethylene liner as a result of articulation with the CoCr femoral component. Particles generated by adhesive wear, corrosive wear, and/or abrasive wear may act as abrasives and accelerate deterioration of the sliding interface [3,4]. (2) Adverse biological reaction to indigestible microscopic wear debris leads to periprosthetic osteolysis [5–7], which undermines the implant and causes mechanical loosening and instability. Even XL polyethylene, while reducing wear [8–11], has been observed to cause osteolysis [12]. Failure of a prosthetic hip joint may lead to a risky revision surgery [13,14]. Hence, it is important to reduce friction and wear of the articulating surfaces to increase the longevity of prosthetic hip joints.

The current engineering paradigm for combating implant wear is to improve the mechanical properties of the polyethylene component and to manufacture ultra-smooth bearing surfaces, as witnessed by the re-introduction of MOM [15] and the development of COP [16] and COC prosthetic hip joints [17]. For example, COC articulating surfaces are polished to an average surface roughness $R_a < 5$ nm, which enables them to operate in the (elasto)hydrodynamic lubrication regime, thus reducing friction and wear. Despite this advantage, COC prosthetic hip joints are prone to edge-loading wear that leads to squeaking, problems that MOP hips do not exhibit. To date, the potential of reducing friction and wear by increasing the load-carrying capacity of the

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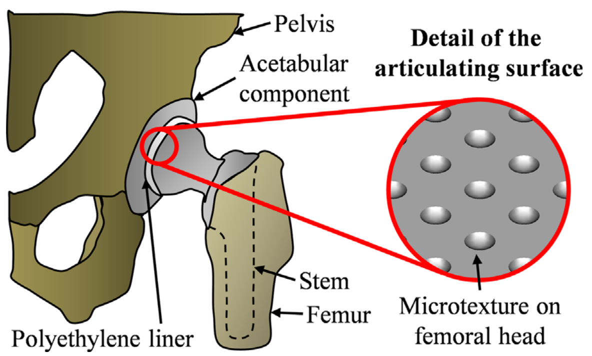

Fig. 1. Metal-on-polyethylene (MOP) prosthetic hip joint with a patterned microtexture on the CoCr femoral head.

lubricant film in MOP hips has been neglected, likely because the polymer bearing surface is compliant, prone to dimensional error, and not feasible to polish. In contrast to the existing knowledge, we attempt to decrease friction in MOP hip joints by adding a patterned microtexture to the ultra-smooth CoCr femoral head. The microtexture is implemented as an array of concave features ("dimples") and is well-known to increase the load-carrying capacity and lubricant film thickness in other man-made bearings [18], such as, for instance, magnetic tape drives [19,20], piston rings [21], and thrust bearings [22]. The dimples form an array of microhydrodynamic bearings that increase the load-carrying capacity of the lubricant film between two bearing surfaces in relative motion. This increases the lubricant film thickness and reduces contact, thereby reducing friction and potentially wear of the articulating surfaces.

A few researchers have experimentally attempted to improve the durability of MOP prosthetic hip joints by using surface texture or increasing the surface roughness of the femoral head. Ito et al. [23] manufactured circular dimples of 0.5 mm in diameter and 0.1 mm deep, with a 1.2 mm pitch on a CoCr femoral head. They observed a 17% friction reduction and a 36% reduction in polyethylene wear, and hypothesized that this may be the result of the abrasive wear particles being trapped in the dimples and lubricant being accumulated and subsequently dispensed from the dimples during lubricant starvation conditions. Sawano et al. [24] used a waterjet to machine 0.25 μm to 4.4 μm deep channels, spaced 10 μm apart and running perpendicular to the direction of articulation, into a CoCrMo plate. A modest reduction in polyethylene wear was measured in a pin-on-disc experiment, which was attributed to the channels trapping wear particles. Zhou et al. [25] used a diamond indenter to manufacture spherical dimples of 1 mm in diameter and 2 μm deep into stainless steel plates. They conducted a pin-on-disc experiment with a UHMWPE pin (GUR 1020) and the textured stainless steel plates, and concluded that microtexture does not improve lubrication, but instead increases the surface roughness and subsequently wear. However, tall ridges were observed around the contour of the microtexture features, which may have increased friction in the bearing.

This work aims to improve the longevity of prosthetic hip joints by adding a well-defined patterned microtexture to the smooth femoral head, as illustrated in Fig. 1. The approach is opposite to the current engineering paradigm of improving prosthetic hip joint longevity by improving the mechanical properties of the polyethylene to increase wear resistance, and by manufacturing smoother articulating surfaces. It is also different from earlier research that attempted to improve longevity by using texture as lubricant reservoirs or wear particle traps.

We experimentally demonstrate reduced friction between the articulating surfaces of a textured surrogate prosthetic hip compared to a smooth one, using the exact same material pair and surface properties of commercial prosthetic hip joints. We have used a simplified steady-state lubrication model to design the patterned microtexture geometry in terms of maximum bearing load-carrying capacity. From these results, we have selected four microtexture designs that are manufactured on convex CoCr specimens. We find that the friction coefficient between a convex CoCr specimen articulating with a concave UHMWPE specimen is reduced significantly by adding a patterned microtexture to the CoCr specimen.

2. Patterned microtexture design

2.1. Model

We use a simple steady-state lubrication model, shown in Fig. 2, to design the geometry of the patterned microtexture, in support of the experiments described in Section 3. The microtextured femoral head is represented by a column of $N=7$ dimples and moves relative to the smooth acetabular liner. Since the curvatures of the femoral head and acetabular liner are almost identical, and much larger than the dimensions of the dimple, the bearing can be approximated as a parallel slider bearing.

The following assumptions are made: (1) each dimple has an identical spherical shape and is positioned in the center of a square unit cell of width $2r_1$ (see Fig. 2(b)). (2) While it is well-known that synovial fluid is shear-thinning, its shear rate dependence is much smaller in prosthetic joints than in natural joints [26]. Hence, we model synovial fluid as a Newtonian fluid with viscosity of water at room temperature [27,28], which is a conservative assumption. The viscosity of synovial fluid (and bovine serum) is typically larger, which would increase the hydrodynamic pressure in our model. (3) Inertial forces are neglected because they are at least two orders of magnitude smaller than the viscous forces. (4) The minimum spacing c between the bearing surfaces is sufficient to avoid asperity contact and, thus, hydrodynamic lubrication is maintained assuming abundant lubricant supply. (5) No slip is assumed at the solid boundaries. Thus, the relationship between bearing spacing and pressure is governed by the steady-state two-dimensional incompressible Reynolds equation, given in dimensional form as [29]

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

where x and y are Cartesian coordinates as indicated in Fig. 2, $p(x,y)$ is the local bearing pressure, $h(x,y)$ is the local bearing spacing, μ is the dynamic viscosity of the lubricant, and U is the relative sliding

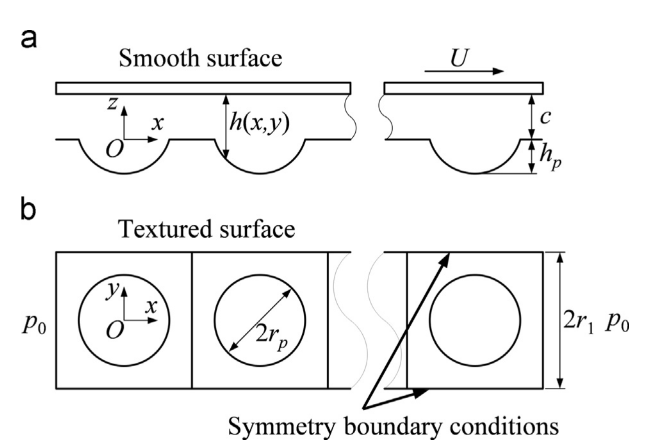

Fig. 2. Schematic of the lubrication model showing (a) cross-sectional view and (b) top view.