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The impact of surface and geometry on coefficient of friction of artificial hip joints

Dipankar Choudhury[a,b,*], Martin Vrbka[b,c], Azuddin Bin Mamat[d], Ian Stavness[e], Chanchal K. Roy[e], Rajshree Mootanah[f], Ivan Krupka[b,c]

[a] Department of Mechanical Engineering, University of Arkansas, Fayetteville, AR 72701, USA
[b] Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2, 616 69 Brno, Czech Republic
[c] CEITEC-Central European Institute of Technology, Brno University of Technology, Technicka 3058/10, 616 00 Brno, Czech Republic
[d] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[e] Department of Computer Science, University of Saskatchewan, 176 Thorvaldson Building, 110 Science Place, Saskatoon, SK, Canada S7N 5C9
[f] Faculty of Science and Technology, Anglia Ruskin University, Chelmsford, Essex CM1 1SQ, UK

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ABSTRACT

Coefficient of friction (COF) tests were conducted on 28-mm and 36-mm-diameter hip joint prostheses for four different material combinations, with or without the presence of Ultra High Molecular Weight Polyethylene (UHMWPE) particles using a novel pendulum hip simulator. The effects of three micro dimpled arrays on femoral head against a polyethylene and a metallic cup were also investigated. Clearance played a vital role in the COF of ceramic on polyethylene and ceramic on ceramic artificial hip joints. Micro dimpled metallic femoral heads yielded higher COF against a polyethylene cup; however, with metal on metal prostheses the dimpled arrays significantly reduced the COF. *In situ* images revealed evidence that the dimple arrays enhanced film formation, which was the main mechanism that contributed to reduced friction.

1. Introduction

The number of hip replacement procedures is more than 2 million per annum worldwide, which will increase twofold by 2020 because of increasing elderly population (Kurtz et al., 2007; Lysaght and O'Loughlin, 2000). According to the 2014 Canadian Joint Replacement Registry, the number of hip and knee replacements have increased by 16.5% and 21.5%, respectively, over the last five years (Canadian Joint Replacement Registry, 2014). The demographics of joint replacement patients include an increasing number of younger patients (45–64 years) and thus, prostheses are now required to function for over 30 years (Canadian Joint Replacement Registry, 2014; NJR 10th Annual Report, 2013; Rahman et al., 2013).

Orthopedics device manufacturing companies, equipped with advanced manufacturing facilities, are able to produce prostheses with high precision and very smooth surfaces (10–20 nm). Although ISO standard is followed during *in vitro* testing, revision rates of prostheses in clinical application are as high as 8–10%, within an average 15-year lifespan per device, according to the UK and Canadian national survey reports (Canadian Joint Replacement Registry, 2014; NJR 10th Annual Report, 2013). Surgical techniques and precision (Kennon et al., 2003), as well as physiology of synovial fluid (Ghosh et al., 2014) and activity levels (Wagner et al., 2016) are important factors that determine the survival rates of implanted hip or knee joints. In addition to these factors, excessive wear rate and its associated debris are the major drivers of revision surgery (Nine et al., 2014; Jämsen et al., 2014). Wear is a complex mechanism, and it can be influenced by lubrication and coefficient of friction (COF) (Di Puccio and Mattei, 2015; Zhou and Jin, 2015). Scholes et al., (2000) concluded that lower friction factors are associated with thicker lubrication film formation. It is noted that articular cartilage, along with synovial fluid, plays the key role in protecting the joint interface from mechanical wear and facilitating a smooth motion (COFs can reach as low as 0.001) (Ishihara, 2015). Thus COF, wear rate and associated wear debris are the main measurable outcomes for evaluating the functionality and durability of newly developed hip prostheses.

One of the widely-used methods for determining COF is based on a strain gauge, e.g. a pin-on-disk tribo-tester (Rabinowicz, 1965). Such tribo-testers however have non-conformal contact, whereas a hip joint is a ball-and-socket joint with conformal contact. Therefore, it is challenging to measure the COF and real-time wear rate of an artificial hip joint using a strain gauge. Thus, the measurable outcome from a hip

* Corresponding author at: Department of Mechanical Engineering, University of Arkansas, Fayetteville, AR 72701, USA.
E-mail address: dipankar.choudhury78@gmail.com (D. Choudhury).

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simulator are generally focused on the evaluation of wear rate only, which does not include COF values (Medley et al., 1996; Bragdon et al., 2003). Scholes et al., (2000) evaluated the friction factor of hip prostheses using a simple harmonic oscillatory motion of amplitude 24° applied to the femoral head in the flexion extension plane. It is noted that the friction factor is different than the COF since the friction factor is influenced by the pressure distribution over the head. In this regard, the pendulum hip simulator is a novel device that can be used to obtain real-time velocity profile and estimated frictional coefficient data of a hip prosthesis, while accurately maintaining specific configurations of prosthesis geometry, such clearance and size. Furthermore, by substituting Cr coated glass used as a acetabulum cup, the simulator is capable of viewing the lubricating films between artificial head and cup with respect to real geometry (Vrbka et al., 2015).

Prosthesis size and clearance are important selection criteria for hip joint replacement (Gandhe and Grover, 2008; Dowson et al., 2004). A 28 mm-diameter (Ø) hip prosthesis is widely used (Bragdon et al., 2007), while a 36 mm-diameter (Ø) MoM hip prosthesis are considered to be potential in terms of lowering linear wear rate and stability. Few studies (Scholes et al., 2000; Dowson et al., 2004) have shown that hip joint prostheses with a larger diameter have lower linear wear rate, nevertheless their fundamental tribological behavior and lubrication viscous effects were not clearly understood. Similarly, no single study has investigated the effect of size and clearance on the COF with all of the common material pairs, such as metal-on-metal (MoM), ceramic-on-ceramic (CoC), metal-on-polyethylene (MoP) and ceramic-on-polyethylene (CoP) prostheses. In addition, a few articles have mentioned the effect of wear debris in the third body abrasive wear mechanism and it's possible reduction by surface modification (Sawano et al., 2009; Chyr et al., 2014), however their effect on COF is unknown. Micro-dimpling is a method of surface modification used in many engineering applications, such as in engine cylinders (Usman and Park, 2016; Hua et al., 2016) and ball and rolling bearings (Ali et al., 2013; Křupka and Hartl, 2007), which has potential to be utilized in orthopedic implants (Roy et al., 2014; Qiu et al., 2014). Micro-dimpling can increase hydrodynamic pressure by enhancing film formation. Dimples can also act as reservoirs, which increase lubrication and entrap debris.

A number of articles have been published investigating the effect of surface texturing on orthopedic implants such as 'MoP' (Sawano et al., 2009; Chyr et al., 2014; Qiu et al., 2014; Choudhury et al., 2014; Ito et al., 2000; Zhou et al., 2012), 'CoC' (Roy et al., 2014) and 'MoM' implants (Choudhury et al., 2013a; Choudhury et al., 2013b; Gao et al., 2010a; Gao et al., 2010b); Four patents have been granted based on these studies (Salahshoor and Guo, 2014; Puppulin et al., 2016; Wood, 2007; U.S.Patent6,045,581, 2010). The dimple parameters utilized were diverse, and most of them demonstrated that a micro-dimpled surface reduced friction and wear without providing any evidence of lubrication film formation. Therefore, a micro dimple surface technique has yet to be investigated in metal-on-metal hip joints, particularly in terms of friction coefficient and lubrication film formation.

In this study, three types of COF experiments were conducted, including 1) a 28-mm Ø and a 36-mm Ø prosthesis with four material combinations (MoM, MoP, CoC and CoP); 2) the impact of polyethylene particles in the MoP hip joints interface; and 3) the effect of three micro dimple arrays on friction coefficient and lubricating film thickness of MoP and MoM prostheses.

2. Material and methods

2.1. Materials

Hip joint prostheses with diameters of 28 mm and 36 mm and in four material combinations, including MoM, MoP, CoC and CoP, as detailed in Table 1, were obtained from University Hospital Olomouc, Czech Republic. The UHMWPE cups were made with RCH-1000 Chirulen (Quadrant PHS Deutschland GmbH, Vreden, Germany) according to International Organization for Standardization (ISO: 5834-2) and American Society for Testing and Materials (ASTM: F648). The UHMWPE liner was γ-radiation sterilized (cobalt-60) while sealed in a threefold pouch in nitrogen atmosphere. The dose adopted was between a minimum of 25 kilogray (kGy) and a maximum of 37 kGy. The 36-mm Ø MoM had the largest clearance (609 µm) and the 28 mm Ø MoM had the lowest clearance (274 µm). The clearance and contact surfaces were measured, using a 3D optical scanner active fringe projection (GOM ATOS Triple Scan, GOM mbH, Germany). The accuracy of the measuring system is justified according to the acceptance test (VDI/VDE 2634 - Part 3) whereas the probing error size is ± 0.005 mm. Post-processing performed with the ATOS software was used to calculate the diameters of the spherical surface of the prostheses. The exact diameter of the contact surface of the artificial glass cups were 28.08 and 38.08 mm. Artificial femoral heads (details in the Table 1) were delivered in the original package from the manufacturer and the exact diameter after scanning was 27.988 and 35.299 mm.

Table 1
The geometrical descriptions of prosthesis head and cup.

Prosthesis head	Acetabulum cup	Diameter	Clearance
Biolox Delta, Zimmer (ceramic)	Biolox Delta, Zimmer (ceramic)	28 mm	363 µm
		36 mm	562 µm
Metasul, Zimmer (Metal)	Metasul, Zimmer (Metal)	28 mm	274 µm
		36 mm	609 µm
Biolox forte, Aesculap, B. Braun (ceramic)	UHMWPE-XE	28 mm	302 µm
		36 mm	412 µm
Isodur, Aesculap, B. Braun (metal)	UHMWPE-XE	28 mm	295 µm
		36 mm	453 µm

In order to evaluate the influence of debris on COF trends, the UHMWPE powders ET306010 (Goodfellow Cambridge Ltd, Huntingdon, UK) were purchased and used to test. To identify an average circumference value of these particles (initial grain sizes), we selected 5 random UHMWPE particles, and made 3 measurements of each of the particles. The images were captured from different slide orientations and analyzed, using a 3D optical microscopy device (Contour GT-I, Bruker, Italy). The average equivalent circumferences of the particles were 150 µm (standard deviation100 µm).

Three types of micro dimple arrays (square, triangular and circular) were fabricated on the 28 Ø Aesculap, Isodur (metal) prosthesis heads. Indentation techniques (Křupka and Hartl, 2007) were used to fabricate the square and triangle arrays (Fig. 1- a & b), and micro drilling (Choudhury et al., 2015a) was used to fabricate circular dimple arrays (Fig. 1-c). In the indentation process, a 3-axis rotation device was used to fabricate dimples on the spherical shaped prosthesis heads. The indentation has one axis of rotation (Z) and two axes of planar movement, which allowed the fabrication of the square and triangular micro dimple arrays on the top 6×6 mm^2 area of the prosthesis. The outer ring dimples were unavoidably slightly tilted from the perpendicular position. The tip of the indenter was tilted at an angle of 15° from the vertical axis. The CNC micro drilling machine, having three rotational axes, enabled fabricating the circular shape dimples perpendicular to the prosthesis head. A tungsten carbide WC drill bit of 200 µm Ø was used to produce the circular dimple arrays. The dimple parameters are presented in Table 2, and the 3D images are shown in Fig. 1. The images and their roughness profile were captured and evaluated, using a 3D optical microscopy device (Contour GT-I, Bruker, Italy). The images showed presence of protuberance formations around the dimples, which were removed by a further surface finishing, using 0.5 µm diamond paste. The dimple roughness profiles before and after polishing are shown in Fig. 2.

2.2. Friction test

Tribology tests were performed, using a novel pendulum hip joint