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Tribological investigation of ultra-high molecular weight polyethylene against advanced ceramic surfaces in total hip joint replacement

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Abstract

The aim of the study was to investigate whether a modified ceramic head surface could reduce the friction and wear rate of simulated ceramic-on-polyethylene hip joints. To address this aim, ultra-high molecular weight polyethylene (UHMWPE) was made to slide on aluminium oxide (Al_2O_3), dimpled Al_2O_3, diamond-like carbon (DLC) coated and DLC-coated dimpled substrates. The experiment condition was replicated to simulate artificial hip joints in terms of contact pressure, speed and temperature. UHMWPE on non-dimpled Al_2O_3 showed lower friction coefficient and wear rate compared to other advanced surfaces. Lower wettability, and higher hardness and surface adhesion of DLC resulted in increased friction and wear. The high difference in modulus of elasticity and hardness between UHMWPE and both, Al_2O_3 and DLC, reduced the effectiveness of textured surface techniques in friction and wear reduction. Therefore, no tribological benefit was found by fabricating either DLC coating or surface texturing on hard surface when rubbed against softer UHMWPE.

Keywords

Ceramic on polyethylene, diamond-like carbon, micro-dimpled surface, friction coefficient, wear, tribology, textured surface, prosthesis design

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Introduction

Total hip replacement is one of the most successful achievements in orthopaedic surgery. Since successful introduction of hip replacement operation in the 1960s, the procedure has been increasing at a rate of 10% every year.[1,2] Successful hip replacements restore patients' mobility, enabling them to have a comfortable and independent life. However, there are still major challenges that need to be overcome, including implant durability and the biological response from joint-induced wear debris,[3,4] both associated with wear rate, as well as other material- and patient-related factors. A reduction of wear rate, not only increases the durability of the reconstructed joint, but also reduces the risk of biological response, which is dependent on the dose level (concentration) and sizes of wear debris.[5]

Polyethylene cups, combined with hard metallic or ceramic spheres, are widely used in artificial bearing surfaces because of their excellent tribological characteristics and elastic property, which helps reduce stress shielding. Following its initial success as cup material in total hip replacement for 30 years, ultra-high molecular weight polyethylene (UHMWPE) has been the dominant orthopaedic material in total joint replacements (TJRs).[6] However, their wear rate is still high (4–10 µm per million motion cycles[7]) and the revision rate of a metal or ceramic on UHMWPE is as high as 10% after 10 to 15 years of joint

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replacement.[8] High wear rate results in high dose of wear debris, a major influencing factor on biological response.[5]

It is therefore important to reduce wear rate for increased durability and effective performance of hip implants. Polyethylene, being relatively softer than their counterface materials, contributes to most of the wear. Attempts to reduce the friction and wear rate of polyethylene include improving its material properties (cross-link UHMWPE)[9,10] and changing its surface properties (surface energy, wettability).[11] However, failure still occurs in highly cross-linked UHMWPE, in particular, an increase in rim fracture is caused by a decrease in fatigue resistance.[12]

Several studies have been conducted to reduce friction and polyethylene wear rate in artificial hip joints by applying surface texturing. For example, Ito et al.[13] and Swano et al.[14] fabricated micro-dimple surfaces on metallic femoral head and confirmed reduced friction and wear in their simulated joints. More recently, Sagbas et al.[15] found that a dimpled UHMWPE cup resulted in lower friction temperature compared to the non-dimpled UHMWPE. They also showed that, when blended with vitamin E, dimpled UHMWPE cups could further lower the rise in friction temperature. A rise in friction temperature influences the rate of wear, fatigue, creep and oxidative degradation of bearing materials. This can contribute to cup loosening by causing bone necrosis and surrounding tissue damage.[16–18]

Aluminium oxide (Al_2O_3)-based femoral head has a number of advantages compared to CrCoMo-based metallic head, including better mechanical properties, such as higher hardness, smother surface profile and, therefore, lower friction coefficient and wear. Urban et al.[19] monitored 64 ceramic-on-polyethylene (CoP) hip joints and reported lower and more consistent wear rates than previously reported metal-on-polyethylene (MoP) wear rates. Furthermore, the wettability of Al_2O_3 is higher than the CrCoMo; water contact angles on Al_2O_3 and CrCoMo are around 59° and 75°, respectively.[20,21] Therefore, Al_2O_3 attracts more water, thus ousts the protein towards the courterface substrate, which helps to reduce wear on the polyethylene surface.

Liu et al.[22] reported that hard-coated surface, such as diamond-like carbon (DLC) or nitrogen ion-implanted CoCrMo, can increase the wear rate of UHMWPE, which has a much lower hardness. However a meta-analysis, conducted by Roy and Lee,[23] showed that DLC-coated femoral head against UHMWPE cup had impressive performance. In their review article, Love et al.[24] reported that wear rates produced between UHMWPE acetabular cups against DLC-coated metallic femoral heads were reduced by up to 14 times when the DLC coating materials were based on tetrahedral carbon (ta-C).

To our knowledge, no study has investigated the influence of ceramic femoral ball surface texture and coating, combined, on the tribological outcomes of CoP hip joints. A recent study[25] showed that a combination of dimple and DLC coating can significantly reduce friction and wear. However, the study was not performed in a biotribological environment. Therefore, the aim of the study is to compare the tribological performance of Al_2O_3, dimpled Al_2O_3, DLC coating and dimpled DLC against UHMWPE, using simulated hip joint conditions.

Material and methods

Specimen preparation

A 99% Al_2O_3 plate (AdValue Technology Tucson, USA) was trimmed into $15 \times 15 \times 6\,mm^3$ blocks, using a diamond cutter (IsoMet® 5000 Precisions Saws Buehler, China) to simulate the femoral head surface. The cup surface was represented by cylindrical pin UHMWPE (Goodfellow Cambridge Ltd, UK) of 6 mm diameter and 6 mm length ($n = 12$). The bulk surface roughness of Al_2O_3 and UHMWPE were relatively high (~1 µm). The Al_2O_3 blocks were processed in a number of polishing steps, including diamond grinding, using a 30 µm disc for initial polishing, followed by 9 µm, 6 µm, 1 µm and 0.05 µm diamond polycrystalline suspensions. Following the polishing steps, the Al_2O_3 surface profiles had a mirror finish (mean 0.1 µm). Surface polishing on the UHMWPE cylinders were not carried out to avoid any risk of misaligning of the line contact.

A CNC micro-machine (Mikrotools DT110, Singapore) was used to produce the micro-dimples on the Al_2O_3 samples ($n = 4$) (Figure 1). A set of diamond drill bit (M.A. Ford, USA) with diameter of 300 µm was used to create the dimples. In order to achieve effective machining, the spindle speed and feed rate were maintained at 55,000 r/min and 334 mm/min, respectively, as per manufacturer's recommendation. A new drill bit was used in each sample, as there was a visible sign of wear on the tip of the drill bit.

Following the surface finish and dimple fabrication procedures, a set of dimple ($n = 3$) and non-dimple ($n = 3$) block was sent to a specialised physical vapour deposit coating (PVD) company (Nocon Technology Limited, Malaysia) to produce a tetrahedral amorphous carbon (TA-C) coating. TA-C is one form of DLC which is considered to be one of the hardest form of DLC.[24] The experimental samples described are shown in Figure 1.

Mechanical and surface characterisation

The material and surface properties of the specimens were determined from the following tests:

Surface roughness. The sample surface roughness, Ra, was measured, using a surface profilometer

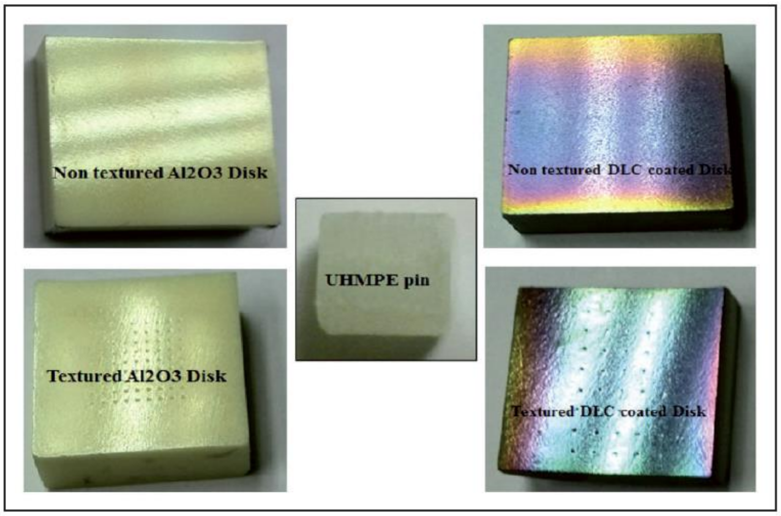

Figure 1. Experimental specimen: disc ($15 \times 15 \times 6\,mm^3$) and pin ($\varnothing\ 6 \times 6\,mm^2$).
UHMWPE: ultra-high molecular weight polyethylene; DLC: diamond-like carbon.

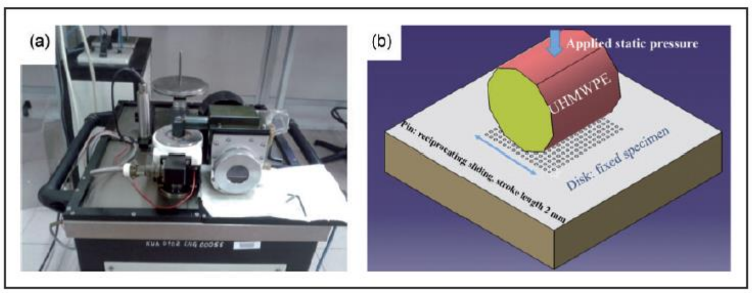

Figure 2. (a) Tribometer experimental set-up and (b) schematic diagram of the specimen.

(Mitutoyosj210, USA), at random locations across the surface (5 times in parallel, and 5 times transversely along 4.5 mm spans).

Surface profiles. A number of mechanical testing was performed to determine the dimpled and coating properties. The dimpled properties[26] included diameter, depth and distance measurements. The surface profiles (Figure 1) were inspected before and after the tests, using a field emission scanning electron microscopy (FESEM, AURIGA, Zeiss, Singapore).

Hardness, elasticity and wettability. Nano-indentation (DUH-211/DUH-211S Dynamic Ultra Micro Hardness Tester, Shimadzu, Japan) technique was used to measure the hardness and elasticity of each sample. A 150 µN load was applied to each of the sample for 15 s. The hardness and elasticity tests were conducted at three random locations on every sample. UHMWPE pin hardness was taken from the supplied material specification. The contact angle was measured, using a contact angle analyser (OCA15EC, Dataphysics Instruments, Germany). To increase accuracy, five resultant-water-contact-angle readings were taken for each specimen and the mean values were used.

Details of experiment

A tribometer (TR 283 Series, DUCOM, Bangalore, India), suitable for low frequency, was employed to simulated hip joints in terms of contact pressure, speed and temperature. Figure 2 shows the tribometer experimental set-up and the schematic diagram of the specimen. To simulate a human medium walking speed of 10 mm/s, the stroke length was set at 2 mm and the frequency at 5 Hz. Extracted bovine serum (50% with distilled water) was used as lubricant and temperature was maintained at 37 °C to simulate body temperature. Three sets of static loads of 10, 15 and

20 N were applied, which were equivalent to 17.86, 21.419, 24.733 MPa Hertz Pressure to UHMWPE/ Al_2O_3 interfaces and 15.486, 18.967, 21.901 MPa Hertz Pressure to UHMWPE/DLC interfaces. The three contact pressures refer to normal weight, overweight and obese patients. The experimental conditions are summarised in Table 1.

Friction coefficient was computed from the applied load and friction force data, which were measured 6000 times per minute on the tribology machine. The average friction coefficient was calculated for every 6000 data. Since the experiment was run for 30 min, a total of 30 average friction coefficient data were obtained for each sample and used in Figure 3. Wear rate was calculated by measuring the weight of UHMWPE pin before and after the test. Before measuring weight of the pin after the test, an ultrasonic cleaning was performed to wash out the generated wear debris. Following the cleaning process, we dried the sample by flowing hot air of about 25 °C for 15 min to eliminate any weight gain from the lubricant contamination. A digital weighing scale of 0.01-mg accuracy was used to record the change in weight. The disc wear rates of the Al_2O_3 and DLC discs were not measured as they were much harder than UHMWPE and were expected to produce negligible wear.

Table 1. Experimental parameters of wear tests.

Items		Description
Specification of pin		6×6.35 mm^2 (Ø)
Specification of block		$15 \times 15 \times 6$ mm^3
Lubricant		Bovine synovial fluid
Speed		10 mm/s
Hertz pressure	UHMWPE/Al_2O_3	17.86, 21.419, 24.733 MPa
	UHMWPE/DLC	15.486, 18.967, 21.901 MPa
Temperature		37°C

UHMWPE: ultra-high molecular weight polyethylene; DLC: diamond-like carbon.

Statistical analysis. The IBM SPSS statistics 21 software was used to perform statistical analysis to determine whether there was any significant difference in friction coefficient value between the applied loads. Single factor analyses were performed to check there was no significant difference between the testing results of same sample and under same loads. In that case, p-value was greater than 0.05 in 95% confidence level interval (CI), suggesting no significant difference between the testing results of same sample and under same load. A Tukey post hoc analysis was then conducted for multiple comparisons between the different samples under the different loads.

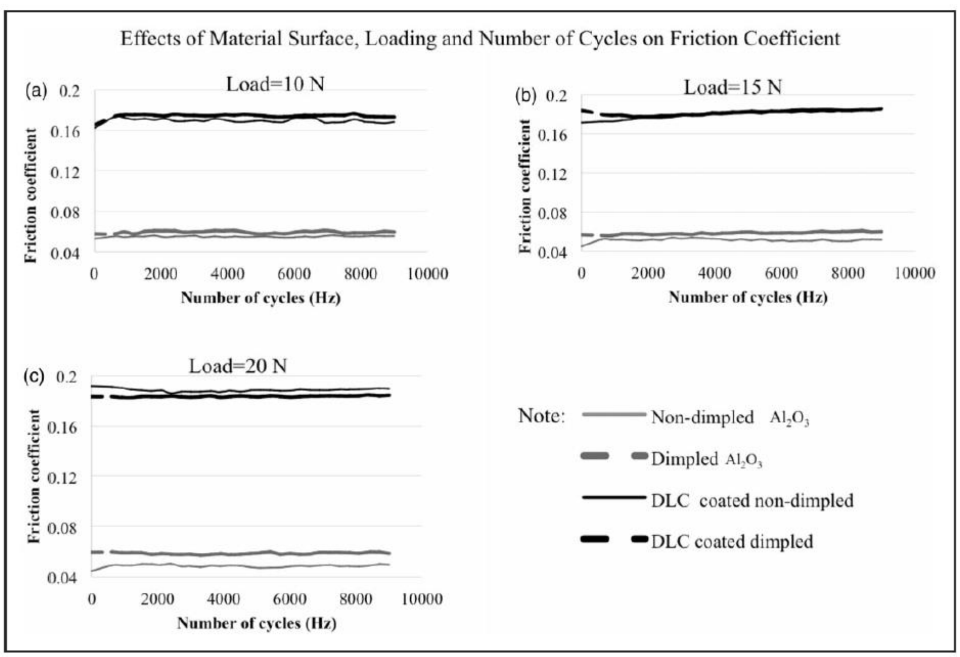

Figure 3. Friction coefficient profiles under: (a) 10 N, (b) 15 N and (c) 20 N loads.
DLC: diamond-like carbon.

In this case, the p-value was less than 0.05 in 95% CI, suggesting a significant difference between the different samples under different loads.

Results and analysis

Mechanical properties and experimental conditions

Results of the mechanical tests are presented in Table 2. Al_2O_3 is considered to be one of the hardest material, but the hardness of DLC (TA-C) is 53% higher. Moreover, the modulus of elasticity of DLC is 30% lower than that of Al_2O_3, indicating that DLC has a higher flexibility. However, the wettability of Al_2O_3 is higher than that of DLC. The presence of dimples increases the wettability of both of the substrates. The dimple parameters were precisely defined and were similar for both the Al_2O_3 and DLC substrates. The selection of dimple parameter was based on our previous study.[26]

Friction coefficient

The comparison of friction coefficient for each sample and loading conditions is presented in Figure 3 and Table 3. For every loading condition (10, 15 and 20 N), the non-dimpled Al_2O_3 surface generated lower friction coefficients (0.055, 0.050 and 0.049, respectively) compared to the other surface profiles. Friction coefficients were much higher for the DLC-coated surfaces, ranging from 0.170 to 0.184. A general decrease in friction coefficient was observed with increasing load for the dimpled and non-dimpled non-coated Al_2O_3 surfaces. The reverse was true for the dimpled and non-dimpled DLC-coated surfaces.

For the lower 10 N loading condition, both the Al_2O_3 and DLC non-dimpled surfaces produced lower friction coefficients compared to the corresponding dimpled surfaces. In both cases, the differences between dimpled and non-dimpled were similar (0.0044) (Figure 3(a)). For the 15 N loading condition, the non-dimpled Al_2O_3 surface produced a lower friction coefficient than the dimpled Al_2O_3 surface and the difference between the two increased to 0.008. However the friction coefficient profile for the DLC-coated non-dimpled and dimpled surfaces almost overlapped each other, the difference in friction coefficients being only 0.002 (Figure 3(b)). Under the 20 N loading condition, the non-dimpled Al_2O_3 surface still produced a lower friction coefficient than the dimpled Al_2O_3 surface and the difference between the two had further increased to 0.012. The DLC-coated non-dimpled surface exhibited a higher friction coefficient than the dimpled DLC-coated surface (Figure 3(c)).

Therefore, it can be deduced from the results that, with increasing loading, the dimpled surface became increasingly effective for the DLC-coated surfaces (decreasing friction coefficient compared to corresponding non-dimpled surface), but not for the

Table 2. Mechanical and surface properties of test specimens.

	Mechanical properties		Surface properties				
					Dimple profile (μm)		
Samples	Hardness (GPa)	Elasticity (GPa)	Roughness (μm)	Water contact angle	Diameter	Depth	Distance
UHMWPE (pin)	0.02	0.69	1 ± 0.5	–	–	–	–
Al_2O_3	5.2 ± 0.5	370 ± 3	0.12 ± 0.01	77	–	–	–
Dimpled Al_2O_3	5.2 ± 0.5	370 ± 3	0.12 ± 0.01	61	300	20	950
Non-dimpled DLC	8. ± 0.5	260 ± 5	0.29 ± 0.1	88	–	–	–
Dimpled DLC	8.1 ± 0.5	260 ± 5	0.29 ± 0.05	83.5	300	20	950

UHMWPE: ultra-high molecular weight polyethylene; DLC: diamond-like carbon.

Table 3. Mean friction coefficient of different material combinations at different loading conditions.

	Mean coefficient of friction			
Loads	UHMWPE/ Non-dimpled Al_2O_3	UHMWPE/ dimpled Al_2O_3	UHMWPE/ Non-dimpled DLC	UHMWPE/ dimpled DLC
10 N	0.055 ± 0.07%	0.059 ± 0.12%	0.170 ± 0.22%	0.174 ± 0.19%
15 N	0.051 ± 0.16%	0.058 ± 0.12%	0.179 ± 0.39%	0.181 ± 0.27%
20 N	0.049 ± 0.11%	0.059 ± 0.07%	0.188 ± 0.12%	0.183 ± 0.06%

UHMWPE: ultra-high molecular weight polyethylene; DLC: diamond-like carbon.

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