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Using a patterned microtexture to reduce polyethylene wear in metal-on-polyethylene prosthetic bearing couples

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ABSTRACT

The longevity of metal-on-polyethylene prosthetic hip joint bearings, in which a CoCrMo femoral head articulates with a polyethylene liner, is often limited by polyethylene wear and osteolysis caused by polyethylene wear particles. Current approaches to reduce polyethylene wear include improving the mechanical properties of the polyethylene liner, and/or manufacturing ultra-smooth articulating surfaces. In contrast, this experimental work shows that adding a patterned microtexture of concave "dimples" to a polished CoCrMo surface significantly reduces polyethylene wear by promoting the formation of an elastohydrodynamic lubricant film, which reduces contact between the CoCrMo and polyethylene bearing surfaces. Using a gravimetric method to measure polyethylene pin wear during pin-on-disc experiments, it was demonstrated that microtextured CoCrMo caused reduced polyethylene wear compared to polished CoCrMo surfaces. Wear was quantified for different polyethylene materials currently used in commercial prosthetic hip joint bearings, and for several microtexture geometries. It was also documented by correlating polyethylene wear with surface topography measurements that the patterned microtexture reduced contact between the articulating bearing surfaces.

1. Introduction

More than 300,000 total hip replacement (THR) surgeries are performed in the United States each year to treat degenerative joint diseases that cause pain and disability (2015 data) [1]. The most common type of prosthetic hip joint consists of a metal femoral head typically made from a cobalt chromium molybdenum (CoCrMo) alloy, articulating with a polyethylene acetabular liner consisting of (vitamin-E infused/cross-linked) ultra-high molecular weight polyethylene (UHMWPE). It is well-documented that the survivorship of these metal-on-polyethylene (MOP) prosthetic hip joints declines significantly after 15–20 years of use [1,2] due in part to adhesive, and/or abrasive wear of the acetabular liner that articulates with the femoral head [3–6], and adverse immunological reaction to microscopic wear debris that causes inflammation and osteolysis [7–10], which weakens the implant to bone interface and may cause mechanical instability [11]. Increasing longevity of prosthetic hip joints will reduce the need for complicated revision surgeries to replace implants [3,12,13] or surgery postponement, which leaves the patient in pain and disability.

Research to increase longevity of prosthetic hip joints by reducing wear can be categorized into improving the mechanical properties of the polyethylene liner or improving the design of the femoral head/liner pairs. For example, the introduction of highly cross-linked polyethylene (HXPE), and subsequently the addition of anti-oxidant materials such as vitamin E to UHMWPE, has substantially reduced polyethylene wear [14–19]. Alternatively, improvements in the design of the femoral head/liner pairs have focused on employing new materials [20–24] and manufacturing ultra-smooth bearing surfaces, as indicated by the increased interest in ceramic-on-polyethylene (COP) and ceramic-on-ceramic (COC) prosthetic hip joints [25,26]. Hard ceramic bearing surfaces can be polished to an average surface roughness that is an order of magnitude smaller than that of metal femoral heads, which may enable them to operate in the (elasto)hydrodynamic lubrication regime during a portion of the gait cycle, thus reducing friction and polyethylene wear. Ceramic materials are also less susceptible to abrasion and they exhibit improved hydrophilicity compared to CoCrMo and are biologically inert. As such, materials such as zirconia gain popularity [20,22,24] but despite their attractive tribological properties, reports of in-vivo early osteolysis with a zirconia (ceramic) on polyethylene bearing have been documented [27].

In contrast with this existing research, reducing polyethylene wear by adding a patterned microtexture to polished CoCrMo material was investigated, in a CoCrMo/polyethylene bearing couple analogous to that used in MOP prosthetic hip joint bearings. The patterned

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microtexture forms a dense array of concave “dimples,” creating microhydrodynamic bearings that pressurize the joint fluid and increase the separation between the CoCrMo and polyethylene surfaces during articulation, thus reducing contact, friction, and polyethylene wear.

Surface texturing has been successfully used in a myriad of applications, resulting in a substantial reduction of friction and wear of bearing surfaces [28]. A few researchers have experimentally studied the effect of surface texturing on prosthetic joint bearings to reduce friction and wear. Ito et al. [29] used concave circular dimples (0.5 mm diameter, 0.1 mm depth, and 1.2 mm pitch) on a CoCrMo femoral head in a hip simulator, and reported that the friction coefficient and the UHMWPE wear was reduced by 36.2% and 69%, respectively, compared to using a smooth femoral head, in a 60 degree swing motion test (0.33 Hz, 1 million cycles). Sawano et al. [30] performed pin-on-disc (POD) experiments to evaluate wear of UHMWPE pins articulating against textured CoCrMo alloy discs (0.3–4 µm diameter, 0.25–4.40 µm depth, and 0.1 mm pitch). They demonstrated that a 1 µm deep dimple reduced the UHMWPE wear by up to 61% compared to a smooth CoCrMo surface, and attributed this to wear particles being trapped within the dimples. Roy et al. [31] performed POD experiments with a UHMWPE pin articulating with a textured CoCrMo disc, and found that circular dimples with 400 µm diameter, 30 µm depth, and 15% texture density reduced the friction coefficient and UHMWPE wear by 22% and 53%, respectively, compared to articulating with a smooth CoCrMo surface. However, testing was performed at 5–20 Hz, which exceeds the approximately 1 Hz gait frequency. Cho et al. [32] evaluated steel surfaces textured with circular dimples of 75 µm diameter, depth ranging between 20 and 75 µm, and texture density between 5% and 25% in a POD test with UHMWPE pins, and found a reduction of the friction coefficient between the textured discs and the UHMWPE pins independent of the dimple geometry. Chyr et al. [33] used cylindrical surrogate CoCrMo femoral heads articulating with a cylindrical UHMWPE liner. They used a numerical lubrication model to optimize the microtexture geometry and density in terms of maximum lubricant film thickness, and then selected four candidate microtexture designs from the numerical results to use in experiments. Using a custom testing apparatus that implemented the primary kinematic and loading components of a hip, and with a reciprocating sliding motion to mimic gait, they found that adding the optimized microtexture designs to the smooth femoral head reduced friction drastically over almost the entire kinematic cycle.

While several researchers have reported reduced friction and wear for a textured CoCrMo surface articulating with a smooth UHMWPE specimen, no systematic study is available that quantifies the polyethylene wear rate as a function of microtexture parameters. Such results are critical for translation to the clinic. Hence, the objective of this paper is to experimentally quantify wear between UHMWPE pins and smooth and microtextured CoCrMo discs, the same materials used in commercial prosthetic hip joints. Different microtexture designs and different types of polyethylene were evaluated, currently used in prosthetic hip joints, to evaluate the effect of bearing surface texture parameters on polyethylene wear. It is noted that pin-on-disc testing does not provide the same wear rates and mechanisms as implant simulator testing, but it is typically used as a comparative screening test.

2. Materials and methods

2.1. Specimens

Laser surface texturing (LST) with a femtosecond laser ablation process was employed to manufacture five different patterned microtexture designs, selected based on our previous numerical optimization work [34] on smooth CoCrMo (ASTMF1537-08 [35]) discs polished to $R_a < 50$ nm, identical to the surface quality of femoral heads of commercial MOP prosthetic hip joints. Table 1 identifies the different microtexture designs used in terms of the texture density S_p, which represents the fraction of the bearing surface covered by the microtexture features, and the texture aspect ratio ε, which is the ratio of depth and diameter of the spherical texture features. In addition, Table 1 shows a smooth non-textured CoCrMo disc used as benchmark specimen. An optical microscopy image, a white light interferometry image, and a cross-sectional view of the latter to illustrate the geometry of the

Table 1
CoCrMo discs with different microtexture geometry designs, identified by their texture density S_p and texture aspect ratio ε. Optical microscopy and white light interferometry (with cross-sectional profile) images are also provided for each.

Disc 1	Disc 2	Disc 3	Disc 4	Disc 5	Disc 6
smooth non-textured	$Sp = 0.05$, $\varepsilon = 0.02$	$Sp = 0.2$, $\varepsilon = 0.02$	$Sp = 0.1$, $\varepsilon = 0.01$	$Sp = 0.2$, $\varepsilon = 0.01$	$Sp = 0.3$, $\varepsilon = 0.04$

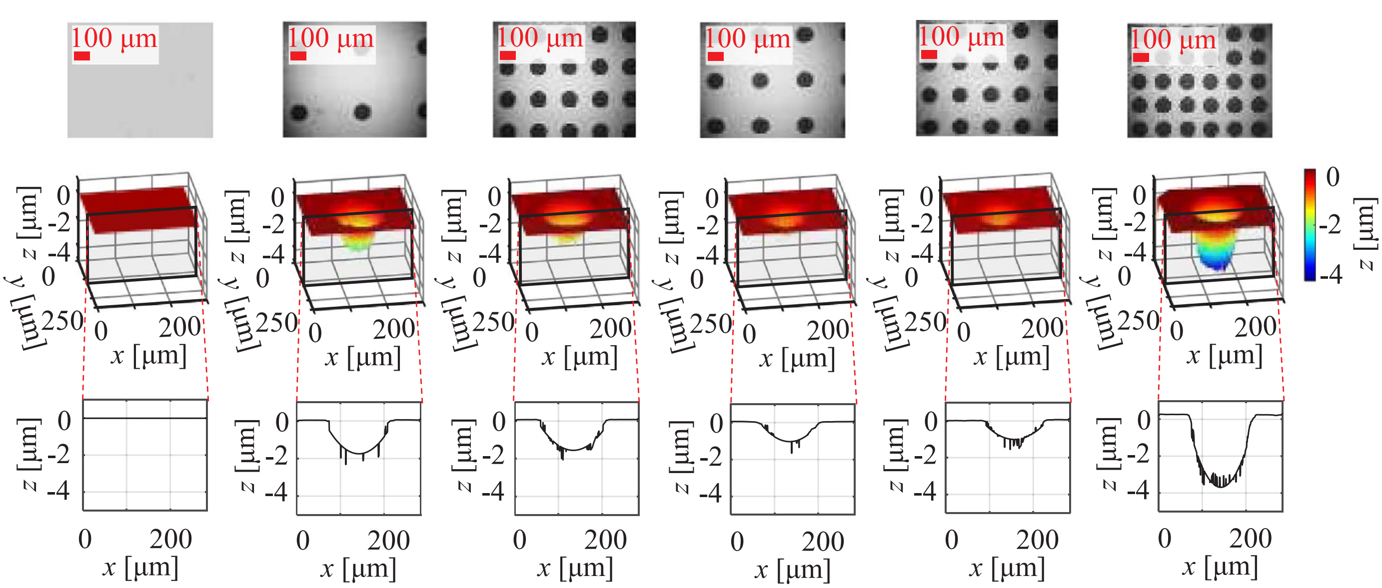
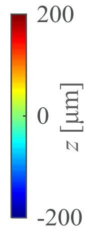
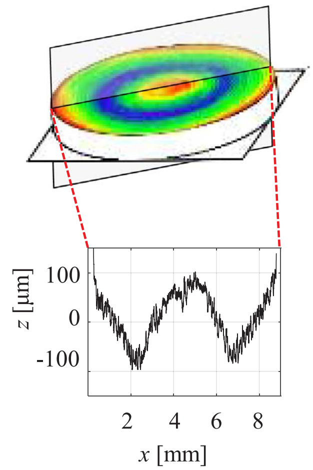
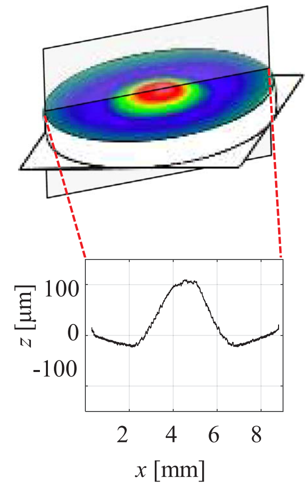
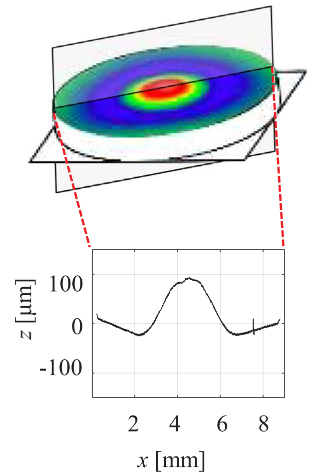


Table 2
White light interferometry image of the articulating surface of the UHMWPE pins, and average surface topography metrics of all pins.

Pin-type	UHMWPE GUR 1050	HXPE	VEXPE UHMWPE
 White light interferometry			
R_a [µm]	1.312	0.869	0.874
R_q [µm]	1.816	1.531	1.325
R_t [µm]	197.651	181.585	135.389
n_s [1/µm^2]	0.491	0.098	0.112
σ_s [µm]	1.265	0.909	0.934
R_s [µm]	0.277	0.732	0.440

microtexture feature and to demonstrate that the surface texturing does not affect the land area in between texture features, is shown for each CoCrMo disc.

Three types of medical grade UHMWPE pins were evaluated, machined from ram-extruded bar stock: (1) standard UHMWPE (GUR 1050-ASTM F648-14 [36]), (2) highly cross-linked polyethylene with 75 kGy gamma radiation (HXPE-ASTM F648-14), and (3) vitamin-E infused polyethylene highly cross-linked polyethylene with 75 kGy gamma radiation (VEXPE UHMWPE-ASTM F-2695 [37]). Six pins of 9 mm diameter and 15 mm length were machined of each material type, with one flat and one hemispherical end (ASTM F732 [38]). The hemispherical end seats in a conical pin holder and ensures self-alignment of the flat end of the pin, finished to $R_a < 1.5$ µm [38], with the disc surface. Table 2 shows the surface topography of the articulating flat surface of a representative polyethylene pin of each material type, obtained with white light interferometry (Zygo NewView 5000), which reveals a shallow raised area in the center of the pin and concentric machining marks. A trace along the diameter of the pin further illustrates the scale of the surface topography. Table 2 also shows the average values for all six pins of each material type, of R_a, R_q, and R_t values, and the asperity density n_s, mean radius of asperity summits R_s, and the standard deviation of asperity heights σ_s, derived from the white light interferometry data of the articulating surface, using an 8-nearest neighbor scheme [39]. It was observed that the surface topography is almost independent of the material type, but that the articulating surfaces of the HXPE and VEXPE UHMWPE pins were slightly smoother than that of the regular UHMWPE surface, indicated by lower R_a, R_q, and R_t, and by lower n_s, σ_s and higher R_s values.

2.2. Wear testing apparatus

Fig. 1 shows a schematic of the five-station POD tester developed at the University of Utah, which was employed to measure wear of the polyethylene pins when articulating with the CoCrMo discs under circular motion and static loading. A POD tester enables fast evaluation of a large number of material pairs (pin and disc) as a function of operating and environmental conditions. It is a well-established and widely accepted method in testing biomaterials, because experimental data is available to potentially benchmark with new results. Each station of the POD tester consists of a shaft supported by two linear bearings, driven by a closed-loop, velocity-controlled motor and gear mechanism, and loaded with deadweights (13 kg) to provide the desired contact pressure between the pin and disc. The eccentricity e determines the radius

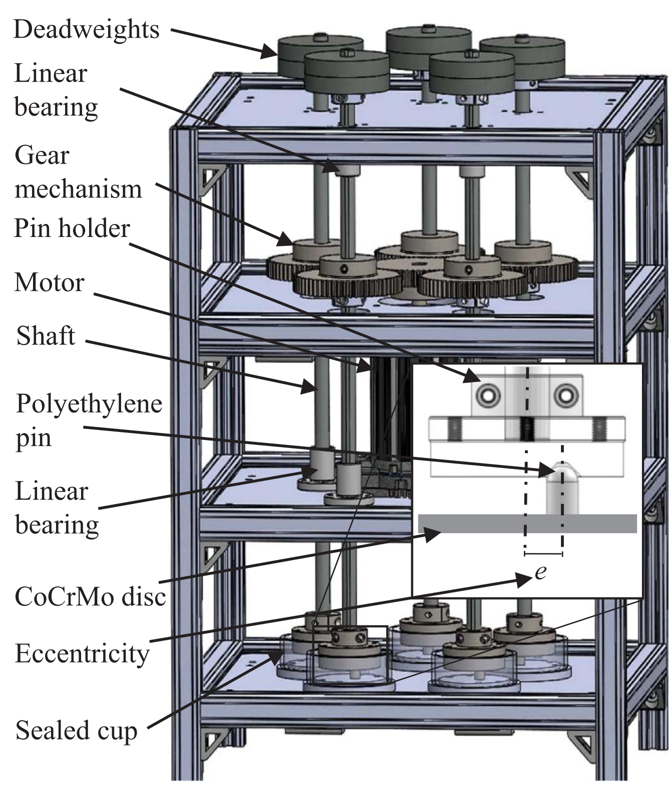


Fig. 1. Schematic of five-station pin-on-disc tester. Inset shows detail of polyethylene pin articulating with CoCrMo disc.

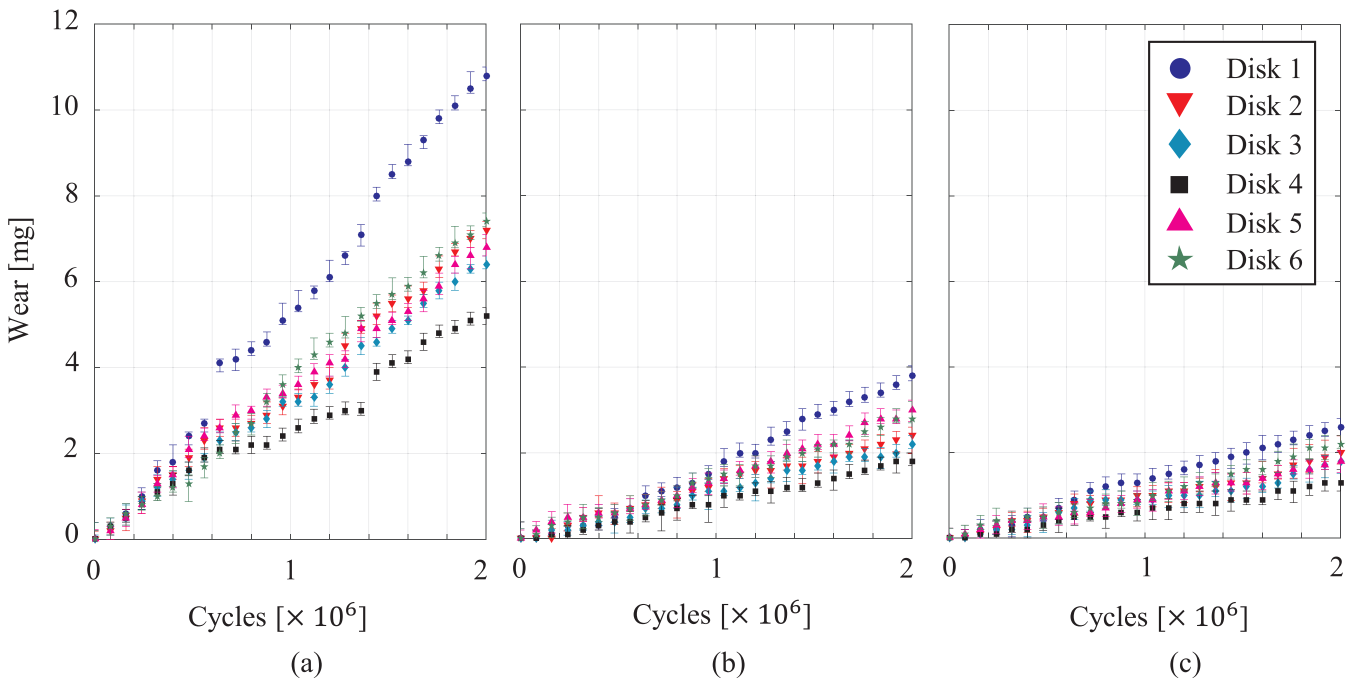


Fig. 2. Polyethylene wear as a function of number of cycles for (a) UHMWPE GUR 1050, (b) HXPE, and (c) VEXPE UHMWPE, articulating with microtextured and polished CoCrMo discs. The data points show the average of ten wear measurements, whereas the error bars show the extreme wear measurement results.

of the circular wear path. A sealed cup around each disc allows for lubrication during testing.

2.3. Testing procedure

The ASTM F732 standard [38] was followed for wear testing, using a 10 mm diameter circular wear path of a polyethylene pin on a stationary CoCrMo disc. This results in a sliding distance of 31.4 mm per cycle, which falls within the in-vivo sliding distance that ranges between 8.6 and 33.6 mm measured for hips [40]. Two million wear cycles were performed at a frequency of 1 Hz to approximate the frequency of human walking gait [41], a contact area of 63.6 mm^2, and contact pressure of 2.0 MPa (ASTM F732). This contact area is much smaller than the physiological contact area in prosthetic hips, which ranges between 320 and 960 mm^2 [42]. Saikko et al. [43] suggested that contact pressure should not exceed 2.0 MPa in POD wear tests of prosthetic joint materials to best mimic in-vivo wear, although in-vivo contact pressure may be higher than 2 MPa. Filter-sterilized (1 μm) bovine calf serum (Hyclone, Logan, UT) with 20 mg/ml protein concentration [44] was used as lubricant, and the sliding interface between

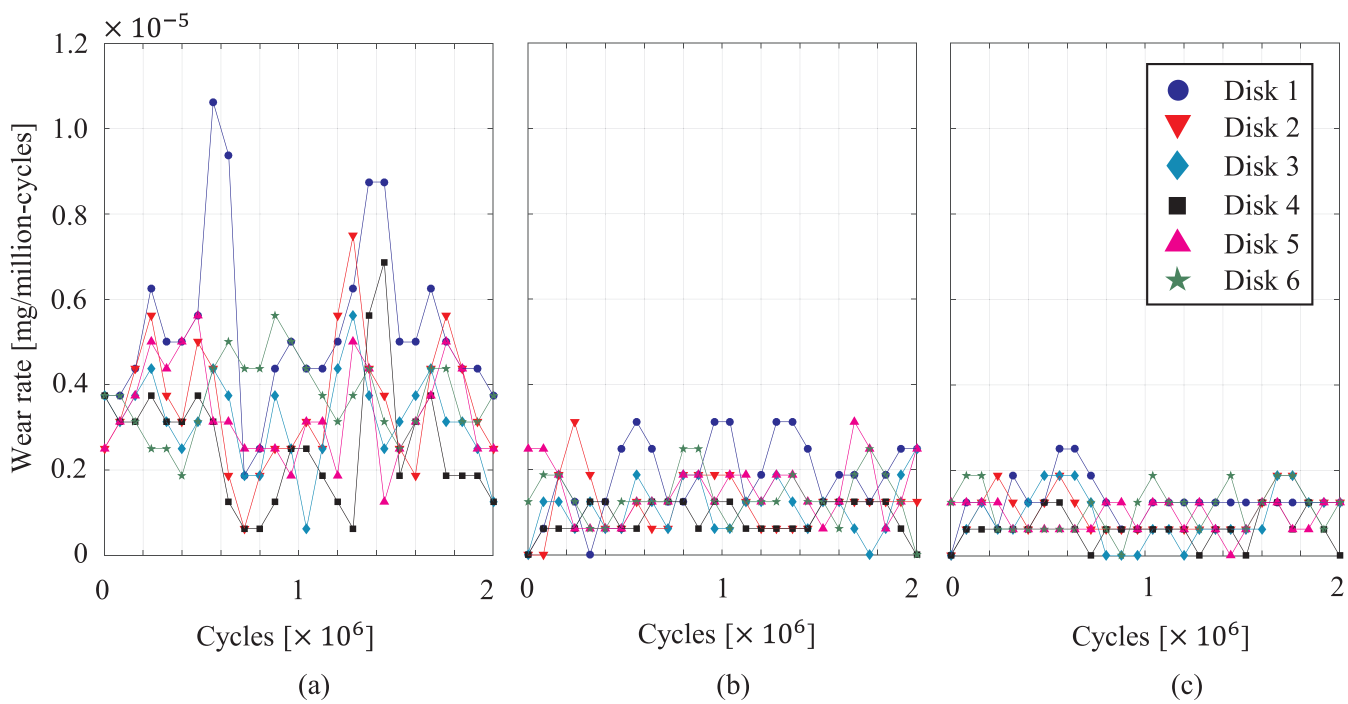


Fig. 3. Polyethylene wear rate as a function of number of cycles for (a) UHMWPE GUR 1050, (b) HXPE, and (c) VEXPE UHMWPE, articulating with microtextured and polished CoCrMo discs.

pin and disc is submerged at all time during the experiment. All polyethylene pins are pre-soaked for two weeks in the lubricant to reduce the fluid-sorption effect prior to testing, and one soak-control specimen is maintained for each experiment. Gravimetric methods were employed per ASTM F2025 [45] to quantify polyethylene wear, at 80,000 cycle intervals, when all testing chambers were thoroughly cleaned and the lubricant was replaced. Weight measurements were repeated for each pin ten times using an analytical balance (Mettler Toledo ML 204, resolution = 0.1 mg, repeatability = 0.1 mg) and the average was reported. Wear debris size and shape was not analyzed in this work. All experiments were performed at room temperature.

2.4. Data analysis

A 3 × 6 (polyethylene material by disc microtexture) full factorial design was used to measure wear of all possible bearing pairs (different polyethylene materials and microtextured versus polished CoCrMo discs). To analyze the effect of each independent variable, results were grouped based on the polyethylene material and based on the disc microtexture. The null hypothesis defined that neither polyethylene material nor disc microtexture affected polyethylene wear and all bearing pairs wore at the same rate. To test this null hypothesis a student's *t*-test was performed for two-tailed distributions with unequal variance between the groups. A p-value of 0.05 was considered statistically significant, as commonly used in other experimental studies of polyethylene wear of orthopedic materials [46]. However, we report the actual p-values in the results and discussion section. Linear regression analysis was conducted to assess the relationship between the pin's wear rate and average surface roughness of the pin's bearing surface (R_a).

3. Results and discussion

Fig. 2 shows polyethylene wear as a function of the number of wear cycles for UHMWPE GUR 1050 (Fig. 2(a)), HXPE (Fig. 2(b)), and VEXPE UHMWPE (Fig. 2(c)) articulating with smooth (Disc 1) and microtextured (Disc 2–6) CoCrMo discs. The results show that the polished disc always causes higher polyethylene wear than the microtextured discs, independent of the polyethylene type. The microtexture creates microhydrodynamic bearings, which compress the lubricant between the pin and disc, slightly increasing the lubricant film thickness for a constant bearing load. Hence, the increased lubricant film thickness reduces contact between the pin and disc, which in turn reduces friction and wear, as our research group has shown previously [33,34,47,48]. Specifically, it was observed that Disc 4 (S_p = 0.1, ε = 0.01) consistently yields the lowest polyethylene wear, which indicates that this microtexture design is the most optimal for wear reduction in this work. Consequently, since the smooth CoCrMo discs (Disc 1) do not have microhydrodynamic bearings, they result in higher polyethylene wear. Furthermore, it is noted that UHMWPE GUR 1050 polyethylene wears almost three times as much as the cross-linked polyethylene material, as expected [46], independent of the CoCrMo disc used.

Fig. 3 shows polyethylene wear rate as a function of the number of wear cycles for UHMWPE GUR 1050 (Fig. 3(a)), HXPE (Fig. 3(b)), and VEXPE UHMWPE (Fig. 3(c)) articulating with smooth (Disc 1) and microtextured (Disc 2–6) CoCrMo discs. From Fig. 3(a) break-in period was observed during which an elevated polyethylene wear rate occurs until approximately 600,000 wear cycles, after which the wear rate decreases, shown by changing slopes of the wear measurements documented in Fig. 2. This is likely due to machining marks or surface roughness peaks on the articulating surface of the polyethylene pin that are removed during the first thousands of wear cycles articulating with the CoCrMo disc. Also, it was observed that the wear rate of UHMWPE GUR 1050 increases after approximately 1.4 million wear cycles, likely due to the fatigue wear, based on the discontinuous wear versus number of cycles results shown in Fig. 2. A sub-surface crack may form due to contact pressure between the pin and disc, grows under cyclic loading, and eventually a wear particle separates from the polyethylene pin, which is observed as a discontinuous wear rate. Discontinuous wear rate results were observed with HXPE also, but not with VEXPE UHMWPE, which is likely due to the higher fatigue resistance of VEXPE UHMWPE compared to UHMWPE GUR 1050 and HXPE [46].

Table 3
Average wear rate for each combination of polyethylene and CoCrMo disc in milligram per million cycles.

Pin	Average wear rate [mg/MC]					
	Disc 1	Disc 2	Disc 3	Disc 4	Disc 5	Disc 6
UHMWPE GUR 1050	5.4	3.6	3.2	2.6	3.4	3.7
HXPE	1.9	1.2	1.1	0.9	1.5	1.4
VEXPE UHMWPE	1.3	1.0	0.9	0.6	0.9	1.1

Table 3 lists the average wear rate in mg per million cycles (MC) for each combination of polyethylene and CoCrMo disc. The average wear of all experiments in this study with UHMWPE GUR 1050 is 3.65 mg/million-cycles after 2 million cycles (averaged over both smooth and textured discs), whereas the average wear for HXPE and VEXPE UHMWPE is 1.33 and 0.97 mg/million-cycles after 2 million cycles, respectively. Even though wear of HXPE and VEXPE UHMWPE is not significantly different (p = 0.059), the wear of UHMWPE GUR 1050 is significantly different from the other two materials (p = 0.001) for both UHMWPE GUR 1050 versus HXPE and versus VEXPE UHMWPE). HXPE and VEXPE UHMWPE wear significantly less than UHMWPE GUR 1050 pins due to their intrinsic resistance to shear stress resulting from cross-linking, which is well-known [46].

This result was also independently confirmed in a blind study performed at DePuy Synthes using an AMTI Orthopod test machine and a Paul loading curve per ISO 14242.

Wear results were correlated with the surface topography measurements of the polyethylene articulating surface to demonstrate the effectiveness of microtexture in creating microhydrodynamic bearings that increase lubricant film thickness for constant bearing load and, thus, to show how the texture features reduce contact and wear. Fig. 4 shows a typical example of the articulating surface of a UHMWPE GUR 1050 pin, before (Fig. 4(a)) and after the wear experiments with microtextured CoCrMo Disc 4 (Fig. 4(b)) and the polished CoCrMo Disc 1, respectively. These discs were chosen because they result in the lowest (Disc 4) and highest (Disc 1) polyethylene wear in our experiments. From Fig. 4 it was observed that the polyethylene surface that articulates with Disc 4 remains almost completely intact, apart from a few scratches, even still displaying the original machining marks after 2.0 million wear cycles. In contrast, the polyethylene surface that articulates with the polished Disc 1 displays two deep scratches on the surface and none of the original machining marks remain.

Surface topography of the articulating surface of the polyethylene pins was quantified before and after all wear experiments in this study. Fig. 5 shows the average surface roughness (R_a) for UHMWPE GUR

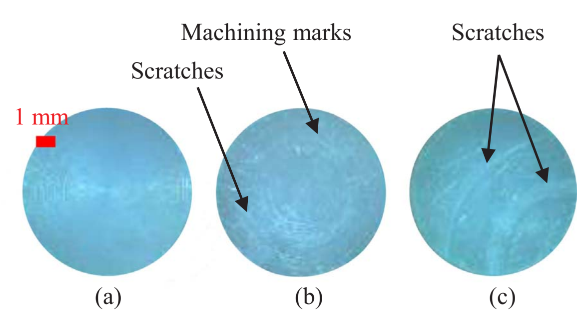


Fig. 4. Surface topography of UHMWPE GUR 1050 (a) before a wear experiment, (b) after wear experiment with Disc 4, and (c) with Disc 1.

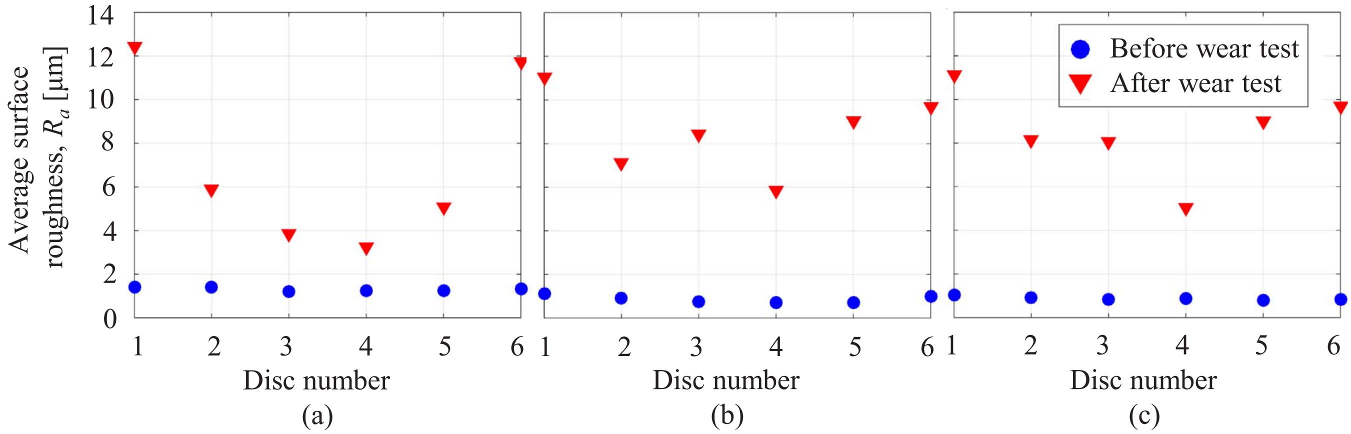


Fig. 5. Average surface roughness R_a before and after wear testing for (a) UHMWPE GUR 1050, (b) HXPE, and (c) VEXPE UHMWPE.

1050 ((Fig. 5(a)), HXPE (Fig. 5(b)), and VEXPE UHMWPE (Fig. 5(c)) pins articulating with polished and microtextured discs. The correlation coefficient *r* between the increase of R_a (after – before wear experiment) and the corresponding wear was determined to be to be 0.82 for UHMWPE GUR 1050, 0.90 for HXPE, and 0.92 for VEXPE UHMWPE, respectively. This result substantiates that wear particles break away from the articulating surface and increase wear and surface roughness of the articulating surface. In agreement with the wear measurements shown in Fig. 2, it was observed that the polyethylene material articulating against the smooth CoCrMo disc (Disc 1) always displays the highest increase of R_a, independent of the polyethylene type. Correspondingly, it was also observed that the pin articulating against Disc 4, which resulted in the lowest wear, displayed the lowest R_a increase independent of the polyethylene material.

The primary limitations of the wear experiments documented in this paper are intrinsic to POD testing, and have been documented by others [49]. Although POD testing enables quick evaluation of a large number of material pairs, the overly simplified flat-on-flat geometry does not represent the complex human joint geometry and articulation. Furthermore, the POD tester has a limited number of degrees-of-freedom (DOF) compared to the human joint, which affects the interface kinematics and how the material pair is loaded. For instance, the static loading implemented in this work neglects the dynamic in-vivo loading of the human joint. Also, the pin does not rotate about its own center axis and, thus, uni-directional sliding is used, as opposed to multi-directional sliding [50], which is generally considered to better mimic in-vivo kinematics. This work provides a relative comparison of polyethylene wear when articulating with microtextured and non-textured CoCrMo surfaces, without attempting to compare wear to previously published studies.

4. Conclusion

Polyethylene wear was reduced by adding a patterned microtexture of concave "dimples" to a polished CoCrMo disc, analogous to the surface finish and material of the femoral head of an MOP prosthetic hip bearing. Based on pin-on-disc wear measurements with a circularly rotating polyethylene pin on a CoCrMo disc, polyethylene wear was observed to be lower in all cases measured for microtextured compared to non-textured bearings. Combining wear with surface topography measurements demonstrated that the microtexture reduced wear by increasing the lubricant film thickness, which in turn decreased contact between the two articulating surfaces. Specifically, it was concluded that Disc 4 ($S_p = 0.1$, $\varepsilon = 0.01$) consistently yielded the lowest polyethylene wear, in-line with numerical optimization of the microtexture performed in earlier work.

Acknowledgments

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