



# Rotational Wear and Friction of Ti-6Al-4V and CoCrMo against Polyethylene and Polycarbonate Urethane

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## ABSTRACT

Total joint replacement (TJR) is a successful procedure for millions of patients each year. Optimizing mechanical properties of bearing couples is important to increase implant longevity and improve patient outcomes. Softer viscoelastic materials offer a potential solution by more closely replicating the mechanical properties and lubrication regime of a native joint, but their wear properties are relatively unknown compared to the wealth of knowledge about polyethylene. In this study, the utility of an experimental set-up not widely used in wear testing was investigated through the evaluation of the mechanical characteristics of four bearing couples often used in TJR. A flat-on-flat rotational test evaluating wear through a change in height of the upper sample introduced several variables that are thought to alter the mechanical properties of compliant bearing materials. The wear properties and coefficient of friction (COF) of two polymer surfaces, ultra-high molecular weight polyethylene (UHMWPE) and polycarbonate urethane (PCU) were directly compared as they articulated against both CoCrMo and Ti-6Al-4V at contact stresses of 3.46, 2.60, and 1.73 MPa. Wear rate was influenced by both polymer surface and normal force while independent of metal counter bearing, with increased wear of couples containing PCU, and at higher forces. Increased COF was seen with PCU, but was independent of other variables. This study elucidated several factors present with this experimental set-up that may contribute to an inadequate lubrication regime and subsequently increased wear and friction of PCU. These are important considerations to maximize the mechanical properties and longevity of implants.

## 1. Introduction

Total joint replacement (TJR) is considered one of the more reliable, cost-effective and successful health interventions in modern medicine [1,2]. The incidence of these operations is expected to continue to rise significantly in coming years due to aging populations and increasing rates of obesity and osteoarthritis [3]. In the United States alone from 2005 to 2030, total knee replacements (TKA) are expected to increase 673% to 3.5 million, with total hip replacements (THA) growing 174% to 572,000 [4].

Once reserved for older patients, TJRs are also increasingly being performed in younger patients due to the excellent functional outcomes, expansion of indications, and increasing prevalence of obesity [5,6]. It is projected that by 2030 52% of THAs and 55% of TKAs will occur in patients younger than 65 [7]. The increased functional demand and lifetime of the younger patients have exceeded initial design constraints

for TJR and have resulted in an increased rate of revision surgery [8–11]. Failure mechanisms for TJR include osteolysis and aseptic loosening due to polyethylene wear debris, infection, periprosthetic fracture and dislocation [12–15]. There is an increasing need to maximize the longevity of joint replacements in order to reduce revision rates, minimize complications and conserve healthcare resources as TJRs continue to rise. Moreover, current total joints are comprised of relatively stiff metals and polymers resulting in little shock absorption capacity and a deviation from the mechanical properties of native joints.

Metal-on-polyethylene (MoP) bearing couples have been around for decades and remain the gold standard for hip, knee, shoulder, elbow and ankle replacements today due to advancements in both polyethylene and metallic bearing components [15–21]. Attempts to reduce polyethylene wear and failure of the implant briefly saw the introduction of metal-on-metal implants, which fell out of favor due to detrimental local and systemic effects from metallic debris [22–28]. Cobalt-

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chrome-molybdenum alloys (CoCrMo) are the preferential metallic counter bearing surface in MoP implants, as their superior hardness and resistance to both corrosion and wear allows for preferential long-term wear and fretting behavior. Titanium alloys (Ti-6Al-4V) and stainless steel are the next most commonly used metals used in TJR, with stainless steel remaining available in some European countries [21,29].

Recently, innovations in bearing surfaces have returned to compliant material, attempting to replicate the mechanical properties of native cartilage. Polycarbonate-urethane (PCU) is a subset of a larger class of polyurethanes (PUs) and has shown promising results in lowering friction and wear rates when compared to ultra-high molecular weight polyethylene (UHMWPE) [30–32]. Much of the beneficial wear properties are dependent on the ability of PUs to form a thick fluid-film regime, similar to that of a native joint. This allows for the separation of components and for much of the load to be carried across a fluid film, reducing wear of bearing surfaces [30,33]. In contrast, joint replacements utilizing UHMWPE create a mixed or boundary lubrication regime, without full separation of components and partial load bearing provided by the articulating surfaces [30,33–35]. This asperity contact leads to increased wear and production of UHMWPE debris, contributing to osteolysis and aseptic loosening of the implant. While PUs are a promising alternative to UHMWPE in some situations, more research is needed to fully elucidate the mechanical properties of compliant materials for use in TJRs under all loading conditions expected in the body. There has been concern over a lack of long-term data for PCU use, as well as studies noting higher pain scores, increased cup dislocation and back-sided wear, and allowance of femoral head penetration and creep which may disrupt the adequate formation of the lubrication regime and contribute to high start-up friction [30,36–38].

The wear properties of material pairings considered for use in TJRs undergo several rounds of characterization before use in clinical trials. Initial testing often uses simplified wear paths and contact geometries to directly compare trends between candidate material couples. Common initial wear tests for metal on polymer pairings include linear reciprocating, pin-on-disc, and ball-cup test set-ups, with mass or volume loss of polymer representing wear rate. After initial testing, results should be confirmed with use of prototype prostheses in a joint simulator to more accurately replicate in-vivo conditions prior to implantation in patients in any clinical trial [39].

This study evaluated the effect of normal force, polymer and metallic component on wear rate and coefficient of friction (COF) of four bearing couples. Compliant surfaces, such as PUs are increasingly considered as an alternative to UHMWPE in TJRs in an attempt to improve the longevity of implants. PCU has been found to have preferable biostability and resistance to degradation when compared to the standard polyester urethanes, making it a promising candidate for an alternative material for TJRs [40,41]. Compared to the available literature on UHMWPE, there is a relative lack of knowledge on the mechanical behavior of PCU under various conditions. Additionally, this study utilizes a continuous rotational wear test set-up, which has not been widely used to evaluate performance of materials in consideration for articulating surfaces. While this experimental set-up does not allow for direct clinical interpretation of wear, it allowed for the comparison between material pairings and for the introduction of several factors that have previously been noted to have detrimental effects on the wear performance of compliant materials. It was hypothesized that these experimental conditions would affect the performance of PCU more so than UHMWPE. Results from this study could inform the value of this rotational test in elucidating material properties and trends for articulating components in worst case scenario situations, as well as further shed light on environmental factors affecting tribological performance of compliant materials.

## 2. Materials and Methods

### 2.1. Sample Preparation

#### 2.1.1. Ultra-High Molecular Weight Polyethylene (UHMWPE)

Ultra-high molecular weight polyethylene (UHMWPE) in compliance with ASTM F648 standards was obtained from Total Plastics International as a 0.75in x 0.75in (19.05 mm) bar stock, machined from a GUR1050 CM sheet. The bar stock was further machined to 5 mm wide cross sections. Each segment then underwent a washing procedure prior to use, as outlined in ASTM Practice F2025. Samples were not sterilized.

#### 2.1.2. Polycarbonate Urethane (PCU)

Pellets of physically crosslinked Carbothane AC-4095A were obtained from Lubrizol. These pellets were sent to Lansen Mold Co. Inc., and injected molded sheets 6 mm thick were prepared using the mold, nozzle, front, middle, and rear temperatures as provided by Lubrizol documentation (18 °C, 215 °C, 210 °C, 210 °C, 205 °C, respectively). Sheets were cut into 19 mm × 19 mm samples and washed according to ASTM Practice F2025 prior to use. Samples were not sterilized.

#### 2.1.3. Metal Counter Bearing Surface

Thirty cobalt chrome and thirty titanium pins were printed via a ProX DMP 320 (3D Systems) SLM printer with CoCrMo and Ti-6Al-4V ELI powder respectively. All Ti-6Al-4V pins underwent post-processing with HIP at 920 °C and 1000 bar for 120 min. All CoCrMo pins underwent stress relieving heat treatment at 1050 °C for 120 min. Pins had a 4.2 mm diameter and length of 40 mm. One flat cross-sectional end of each pin was mechanically polished to a Ra < 0.05 µm. A custom-made jig was used to polish samples with a polishing and lapping machine (Logitech PM5) with successively finer alumina final polishing abrasive (9 µm, 1 µm, 0.05 µm). Samples were finished with 1500 and 3000 grit sandpaper, and polished to a mirror finish with Diamond polishing paste. In an effort to eliminate raised outer rims on the flat polished samples that may lead to a cutting wear in subsequent tests, the outer rim was briefly polished with the final mirror finishing paste at an angle to create a minimal bevel. All metal pins were autoclaved at 121 °C on a Gravity cycle with 30-min sterilization and 20-min drying cycles.

### 2.2. Roughness Measurements

Surface roughness measurements were made using a 3D Optical Profiler (Zygo NewView 5000) at 25× magnification with a 40 µm scan path. Measurements were taken at 3 different locations on each sample and averaged. Surface roughness is reported as Ra, the arithmetical average of absolute values of profile heights over the evaluation length, RMS, the root mean square of the profile heights over the evaluation length, and PV, the distance between the highest and lowest points.

### 2.3. Scanning Electron Microscopy (SEM)

Samples were imaged on Tabletop Scanning Electron Microscope (Hitachi TM3030Plus) at 100× and 500× magnification and 15.0 kV.

### 2.4. Wear Testing

Continuous unidirectional rotational wear tests were performed with an Anton Paar MCR302 Rheometer fitted with an established tribology accessory produced by Anton Paar (SCF7). Four bearing couples were tested; CoCrMo against UHMWPE, Ti-6Al-4V against UHMWPE, CoCrMo against PCU and Ti-6Al-4V against PCU. For each sample, the metal pin (d = 4.2 mm) served as the rotating upper counter bearing sample, while the bottom sample consisted of a stationary square of UHMWPE or PCU, creating a flat-on-flat wear test.

Each of the four bearing couplings were evaluated under a constant vertical normal force of 48 N, 36 N and 24 N (n = 5). These forces

corresponded to contact stress of 3.46 MPa, 2.60 MPa, and 1.73 MPa respectively, all of which are within range of average contact stress in normal joints [42]. Each test began with a 300 s stationary pre-loading period and was run in lubricated conditions at room temperature with a maximum velocity of 132 mm/s for all tests. Tests against UHMWPE were run for 24 h at 10 Hz, corresponding to the outer circumference of the pin traveling a distance of 11.4 km. Tests with PCU as a counter bearing surface were run for 6 h at 10 Hz, corresponding to a maximal distance traveled of 2.85 km. Preliminary tests indicated that a minimum of 24 h was needed to demonstrate appreciable wear in the UHMWPE samples. In contrast, in some initial tests the metal pin was found to wear through the PCU sample within 8 h, and was thus reduced to 6 h to avoid damage to the rheometer. Continuous data was reported as the gap between upper and lower sensors located within the rheometer, as the upper sensor underwent downwards displacement to maintain normal force as wear occurred between samples. The Rheometer also provided measured normal force and frictional force throughout the wear test, allowing for calculation of a coefficient of friction (COF) for each sample.

Lubricant was composed of 25% FBS, 20 mM EDTA and 0.1%w/v sodium azide (Sigma Aldrich) and filtered through a sterile 0.2  $\mu\text{m}$  filter. A custom lubricant holder was printed from durable resin. This holder screwed into the bottom base of the MCR Rheometer, allowing the bottom sample to remain stationary and ensure lubrication of the wear surface throughout the duration of the test. To achieve this, the lubricant holder contained a recessed 19.5 mm  $\times$  19.5 mm area, allowing the wear surface to be the lowest point in the holder and the surface least affected by lubricant evaporation. A lid with a single opening providing the minimal space needed for free rotation of the upper metal pin was added to approximate a closed environment. Lubricant was replaced after each run, but not replaced during the study as this was found to significantly alter the continuous displacement output readings. Test set-up is depicted in Fig. 1.

### 2.5. Statistical Analysis

A three-way ANOVA test was performed to evaluate for statistically significant differences in wear rate and COF. Wear rate or COF served as dependent variables, with normal force, polymer, and metallic component each serving as independent variables. Statistical analysis was conducted in GraphPad Prism. Alpha was set at 0.05.

## 3. Results

Initial surface roughness measurements are shown in Table 1. Polished surfaces of CoCrMo pins had an average Ra of 33 nm, while that of Ti-6Al-4V had an average Ra of 47 nm. Both metal samples achieved a surface roughness in compliance with ASTM F732, which states that the

wear counter face for a polymer wear should be polished to 50 nm or smoother [43]. Ti-6Al-4V pins were more challenging to polish and required longer at each stage of polishing to achieve results similar to that of CoCrMo. Both materials had similarly minor increases in all roughness measurements following wear testing. The polymer counterfaces had more variability in initial roughness measurement. UHMWPE has a higher starting roughness due to inherent surface markings from the machining process required to create 5 mm samples. The post-wear samples of UHMWPE had a reduction in the prominence of these machined lines, and corresponding reduction in surface roughness. In contrast, the PCU samples began with an average initial surface roughness of 26 nm as they were obtained from an injection molded sheet. Final post-wear measurements of PCU samples are not recorded. Multiple of these samples had large areas of macroscopic wear that were not able to be accurately captured by the optical profiler and were therefore omitted to prevent misleading data.

Displacement curves for each UHMWPE sample coupled with CoCrMo and Ti-6Al-4V at 24 N, 36 N and 48 N over 24 h are depicted in Fig. 2. Continuous data is depicted as the displacement of upper sensor required to maintain the constant specified normal force. There was more variability in CoCrMo samples, particularly at the higher normal forces. Each curve depicted an initial non-linear segment representing increase rate of wear of specimens, followed by a more linear portion as the wear rate stabilized.

Displacement curves for each PCU sample coupled with CoCrMo and Ti-6Al-4V are shown in Fig. 3. Similar to the UHMWPE bearing couples, there was more variation seen in the CoCrMo pairing, most notably at 48 N. Tests with PCU were conducted for 6 h, and also depict a similar initial rapid decline indicating higher wear rate, followed by a more linear portion.

Fig. 4 illustrates the average wear rate of each of the four bearing couples at 24 N, 36 N and 48 N, which corresponds to stresses of 3.46, 2.60, and 1.73 MPa. Results are displayed as the absolute value of total displacement at the 6-h mark for PCU and UHMWPE samples. Trends depict greater wear with increasing normal force, as well as higher wear against PCU. A statistically significant difference in wear rate was seen dependent on polymer ( $p \leq 0.0001$ ) and normal force ( $p \leq 0.0001$ ), while metallic counter bearing did have a significant influence ( $p = 0.093$ ) in the range of parameters considered here. Averages of wear over 6 h with standard deviations are reported in Supplemental Table 1 for all four bearing couples.

Fig. 5 presents the coefficient of friction (COF) of samples for different metal and polymer material combinations and all three applied load levels. PCU bearing surfaces consistently demonstrated a high start-up coefficient of friction (COF) at 48 N and 36 N, while tests at 24 N were variable in whether or not start-up friction was present. COF in PCU samples fell rapidly after the initial peak and leveled off at a steady state which was consistently higher than the steady state of UHMWPE bearing

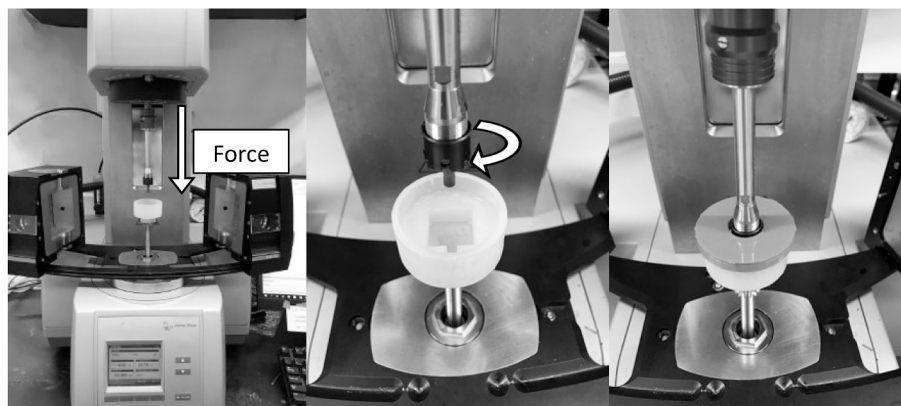
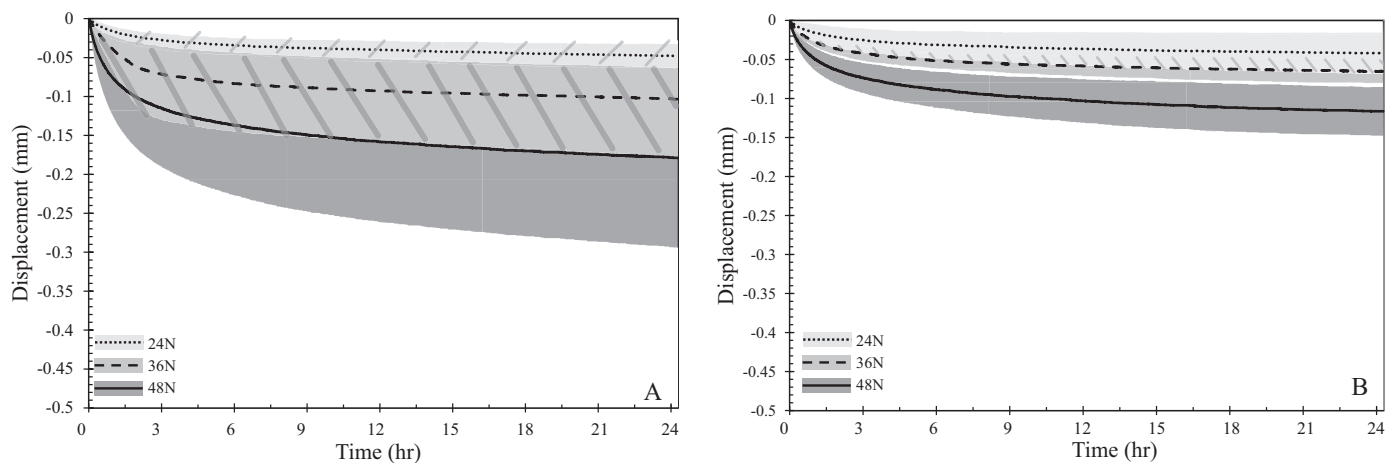


Fig. 1. MCR Rheometer test set-up with tribology accessory, bottom lubricant holder for polymer material and upper rotating metal pin.

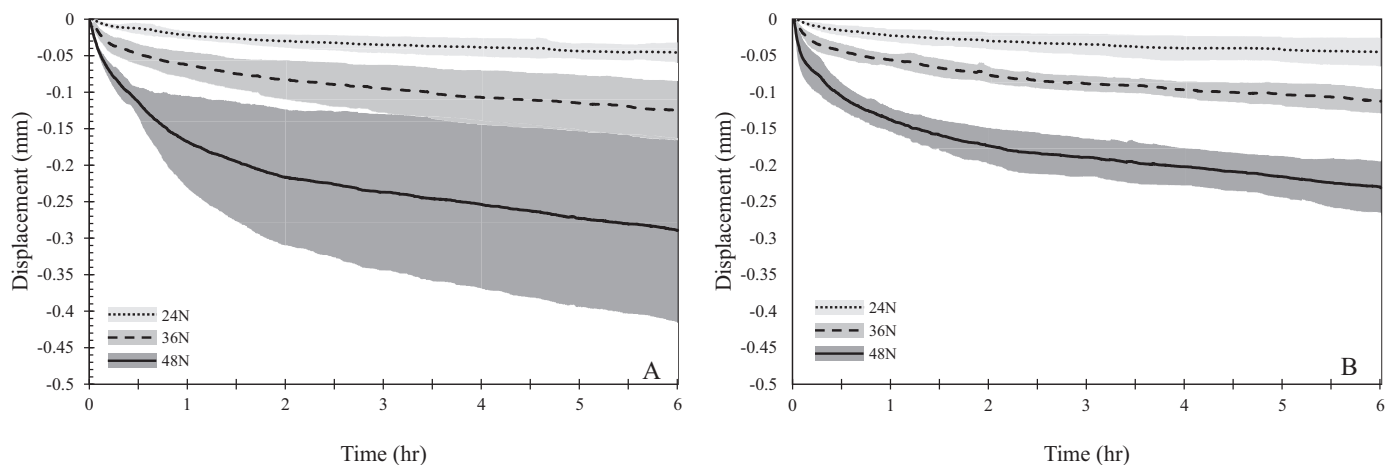
**Table 1**

Summary of roughness measurements of polished surface of CoCrMo and Ti-6Al-4V pins, and UHMWPE and PCU polymer counterfaces prior to and following wear tests.

	Pre-Wear			Post-Wear			Percent Change
	PV	RMS	Ra	PV	RMS	Ra	Ra (%)
CoCrMo	1275 ± 389	46 ± 9.8	33 ± 7.1	1895 ± 816	88 ± 37	61 ± 26	133%
Ti-6Al-4V	1651 ± 445	63 ± 10	47 ± 8.2	2048 ± 700	86 ± 28	65 ± 26	138%
UHMWPE	13,670 ± 200	2596 ± 376	2198 ± 342	12,650 ± 2830	1997 ± 4982	1638 ± 438	74.5%
PCU	1221 ± 485	41 ± 17	26 ± 7	N/A	N/A	N/A	N/A



**Fig. 2.** Mean displacement of A) CoCrMo and B) Ti-6Al-4V pins against UHMWPE wear surface at 48 N, 36 N and 24 N. Shaded areas represent one standard deviation in either direction, with striped areas indicating overlap in shaded regions.



**Fig. 3.** Mean displacement of A) CoCrMo and B) Ti-6Al-4V pins against PCU wear surface at 48 N, 36 N, and 24 N. Shaded areas represent one standard deviation in either direction.

couples. In contrast, UHMWPE did not have this initial elevated COF at start-up, maintaining a fairly level COF throughout all cycles (Fig. 5). PCU samples run at 24 N against both CoCrMo and Ti-6Al-4V appeared to display an all-or-nothing approach to increased start-up friction. Some samples at 24 N demonstrated an initial peak in COF, while others run under the same conditions stayed at a steady state COF for the duration of the test. (Supplemental Fig. 1).

The average steady state COF for each material pairing is displayed in Fig. 6. Overall, samples with PCU as a bearing surface demonstrated much higher variability in steady state COF than those with UHMWPE as bearing surface, regardless of metallic counter surface. Statistically significant differences in COF were seen dependent on polymer surface ( $p \leq 0.001$ ), while COF was not significantly affected by the metal

counter bearing surface ( $p = 0.064$ ) or normal force applied ( $p = 0.45$ ). Average values and standard deviation for COF of each test set-up is reported in Supplemental Table 2.

Wear surfaces of the metal pins were imaged with SEM before and after wear tests. (Fig. 7) Images prior to wear test depict well-polished surfaces with no major defects. After wear against UHMWPE for 24 h, both CoCrMo and Ti-6Al-4V pins demonstrated arcs of wear tracks, most prominent along the outer circumference of the pin. The metals pins after wear against PCU for 6 h had significant adhesive transfer of material, again in a circular pattern reflecting the motion of the wear test. Imaging of the post-wear surface of UHMWPE demonstrated a circular wear track with flattening of the machined lines that can be seen in the unworn areas of the sample. SEM images of the worn surface of PCU



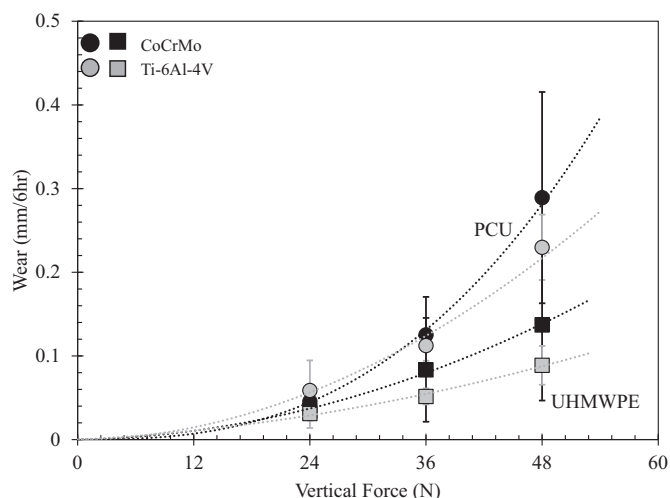


Fig. 4. Average wear of PCU and UHMWPE against CoCrMo and Ti-6Al-4V at 6 h. Results are reported as mean  $\pm$  standard deviation ( $n = 5$ ). Error bars represent one standard deviation in either direction.

similarly demonstrated a circular wear path. However, PCU samples often contained a central protrusion of material contributing to increased macroscopic roughness. This was likely due to the discrepancy in distance traveled at the outer edge of the pin versus that in the center of the wear track.

#### 4. Discussion

Thorough characterization of the mechanical properties of materials considered for bearing surfaces in TJRs is needed to maximize implant longevity and minimize complications. This study found that the metallic counter bearing material did not influence wear rate or COF of the bearing couple against the two polymers studied, under the normal force range and duration of test considered here. However, this study did show that the mechanical properties of the polymer are far more

influential than that of the metallic counter bearing surface, with compliant materials demonstrating significantly higher wear and COF than conventional UHMWPE.

Since wear was reported as displacement of the upper sensor to maintain a constant normal force, measurements represented wear of the both counterparts. This measurement was not able to differentiate between wear of polymer and metal surface; however, it was assumed to be attributable primarily to loss of the polymer surface. Wear of polymer is primarily dependent on inherent properties of the polymer itself, however it can also be influenced by the roughness and hardness of the articulating counter bearing surface [19,21]. When articulating against UHMWPE, it has been shown through SEM imaging that the metal surface of Ti-6Al-4V alloys experience greater wear than that of CoCrMo. Wear of the metallic component further influences total wear of the bearing couple by introducing abrasive third body wear of the polymer [21]. While there is the potential for the metal counter bearing surface to affect wear of the bearing couple, particularly in prolonged wear tests, results in this study showing are consistent with previous literature. A study by McKellop et al. [44] found no statistical difference in polyethylene wear when articulating against titanium, cobalt-chrome or stainless steel surfaces. Similarly, Peterson et al. [45] found no correlation between surface damage of the UHMWPE component and the metallic counter bearing surface in a wear simulation of 500,000 steps. Influence of metallic components on wear rate of the bearing couple may have been able to be identified over a longer duration of wear test allowing for greater development of abrasive third body wear and larger quantitative wear.

Significant differences in wear rate, as well as COF, were seen dependent on the polymer bearing surface, with greater wear in bearing couples containing PCU compared to UHMWPE. A significant peak in start-up friction was observed with PCU as an articulating surface under a normal vertical force of 36 N or 48 N, while variable appearance of this peak occurred at 24 N. In contrast, there was no observed peak in COF for UHMWPE. No test against UHMWPE demonstrated a startup similar peak in COF.

In this study, each wear test began with 300 s of static vertical loading. As data assumed downward displacement represented wear of

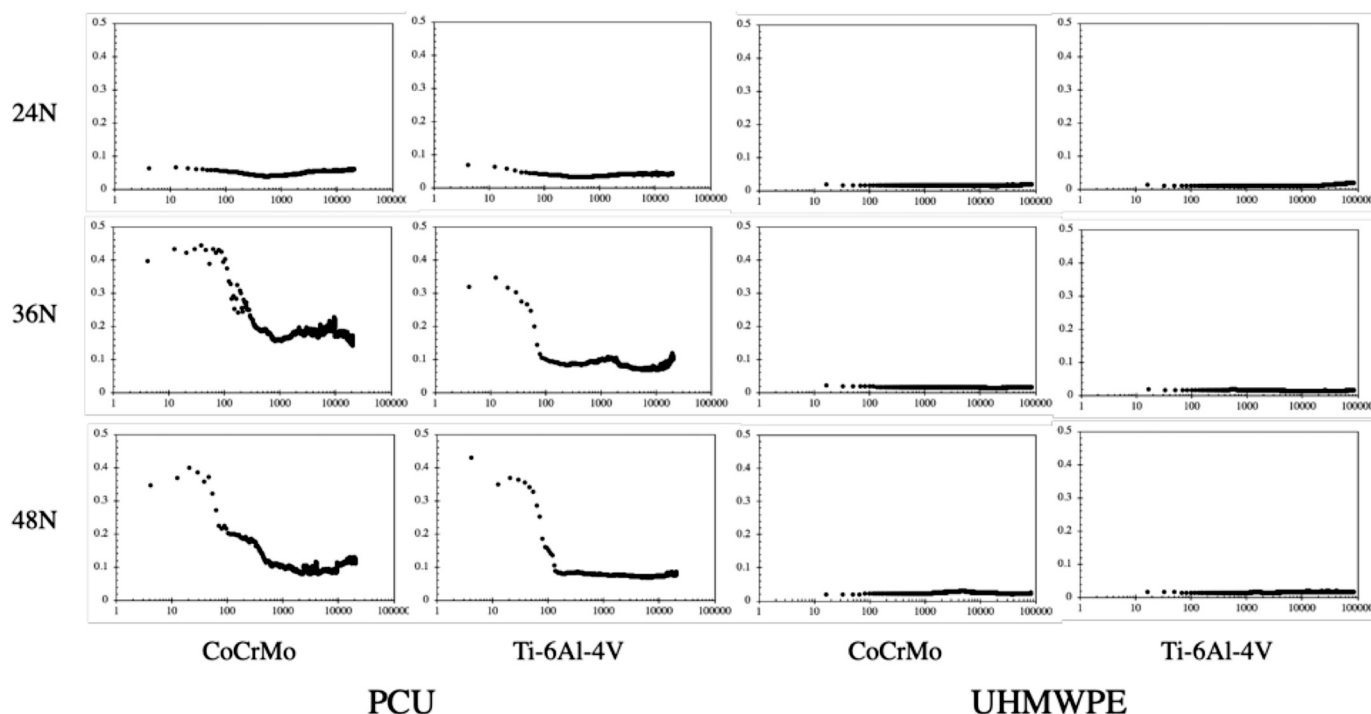


Fig. 5. Representative graphs of COF (y-axis) versus logarithmic scale of duration of wear test (x-axis) for each bearing couple.

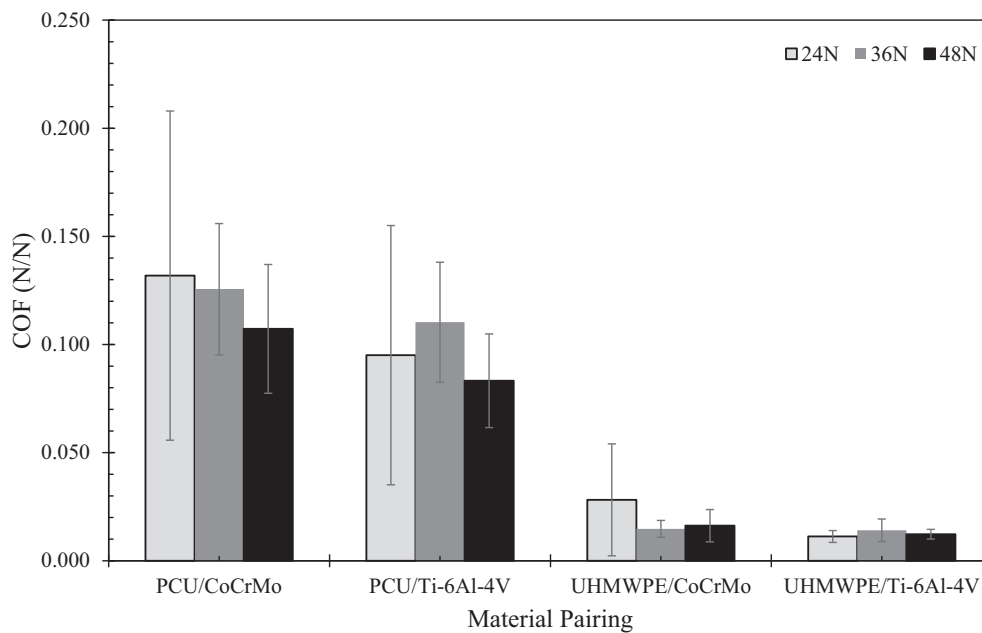


Fig. 6. Average Coefficient of Friction. Results are reported as mean  $\pm$  standard deviation ( $n = 5$ ). Error bars represent one standard deviation in either direction.

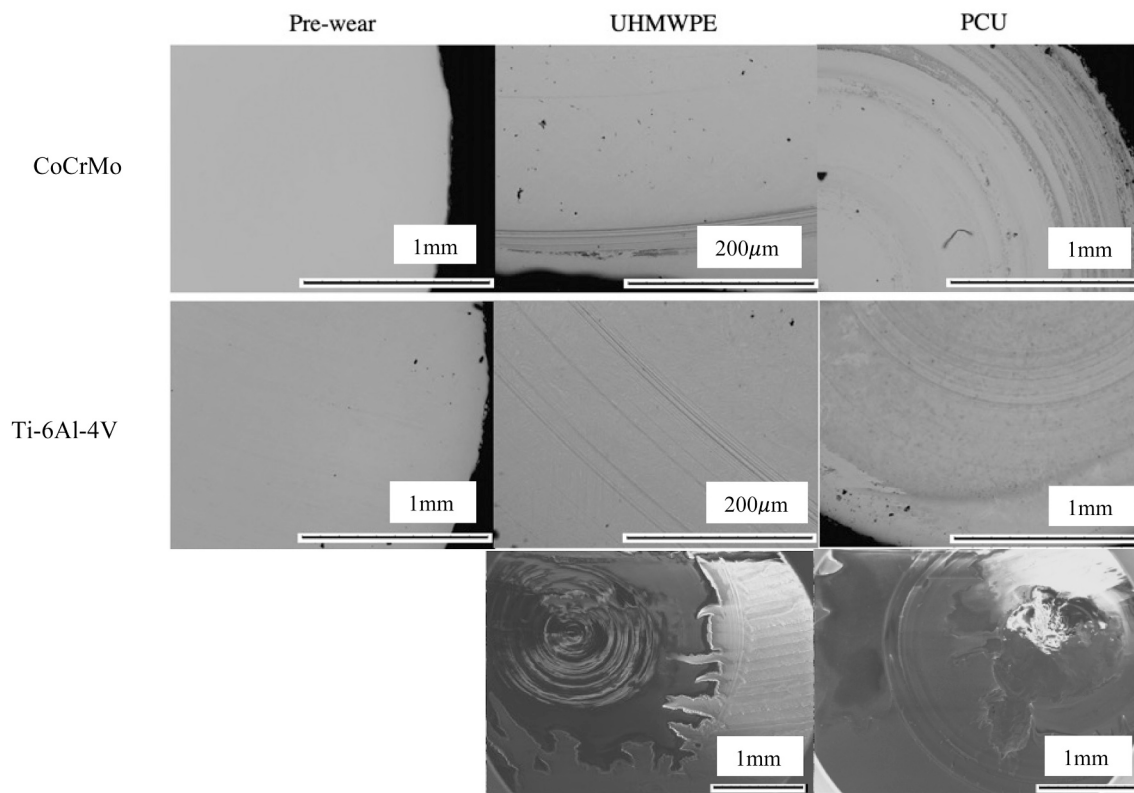


Fig. 7. SEM pictures of representative surfaces of CoCrMo and Ti-6Al-4V pins pre-wear, CoCrMo and Ti-6Al-4V pins after wear against UHMWPE and PCU surfaces, and polymer surfaces post-wear.

the samples, this step was important to minimize inflation the reported wear of more compliant materials with application of load. Previous studies have reported lubricant starvation of compliant materials after static loading displaying a COF for PU against metal in the same range as seen in dry conditions, 0.6–1.0 [46,47]. This is consistent with values of start-up friction seen in this study ranging from 0.4–0.7.

As seen in Fig. 6, the steady state COF of PCU samples demonstrated

greater variability than those with UHMWPE. This suggests inconsistent lubrication environments, which in part may be explained by variation in the ability of these samples to form an adequate lubrication regime with return of movement after static loading. Much of the reported superior wear properties of polyurethanes when compared to UHMWPE are dependent on their ability to form a thick fluid-film lubrication regime to minimize contact and wear of the two bearing surfaces. The

formation of this lubrication film with polyurethanes has been shown to be influenced by a number of factors including duration of static loading prior to movement, decreased stroke length, increased creep and geometry of the bearing couples [47].

TJRs frequently encounter rest under continued load that is concerning for inducing lubricant starvation, leading to a high start-up friction as the articulating surface is operating under dry conditions until the fluid-film lubrication is able to be restored with motion [47]. The torque generated with this high start-up friction is also transmitted to the implant fixation with concern for loosening and failure [47]. Caravia et al. [46] found that in PU layers, the start-up coefficient of friction (COF) was dependent on duration of static loading prior to sliding, with a sharp increase in COF until 80 s followed by a plateau ranging from 0.6–0.9 depending on surface roughness. They concluded that PU layers had favorable friction in good lubrication environments, however under heavy loading with static or low velocity movement the fluid film broke down, leading to contact of components and unacceptably high frictional forces and torque. It has been shown that thickness of the lubricating film is dependent on velocity of components sliding past each other, and that a decrease in stroke length can predispose to lubrication starvation [34,48]. With in-vivo conditions, as well as with wear tests utilizing a reciprocating sliding or pin on disc experimental set-ups, there is some amount of translational movement of the counter bearing surface with the contact area smaller than the wear path, providing adequate opportunity for formation of full thickness film. In this study a lack of translation and stroke length in the rotational wear test may have impeded formation of an adequate lubrication regime as the combination of creep and lack of translation may have sealed off the wear surface [49].

Finally, with compliant materials such as polyurethanes, geometry of the bearing couples can have more influence on lubrication environment. While this compliance has been shown to contribute to low wear rates by allowing the surface to conform to the counter bearing material and decrease contact pressure, there is concern for increased creep seen in more compliant materials, as was also seen in this experiment during the period of pre-loading. [30,50]. Smith et al. [30] found that creep of polyurethanes leads to pinching of the acetabular cup by the femoral head, sealing off the articulating space to fluid entry, causing lubricant starvation. This effect was eliminated by creating acetabular cups with flared outer edges. The outer edge geometry of the flat on flat design of bearing couples in this study may have further restricted fluid film entry [49].

Multiple studies utilizing various iterations of joint simulators to evaluate the wear and friction of polyurethanes against CoCrMo or metallic counterparts have demonstrated that well lubricated compliant bearings typically have a steady state COF <0.01. In these studies, COF was typically calculated from the measured frictional torque, with normal loads ranging from 50 N to 2000 N [30,34,47,51]. In this study, COF for PCU bearing couples rapidly dropped after an initial peak to a steady state in the range of 0.03–0.17, indicating a mixed lubrication regime instead of the preferred full fluid film lubrication for polyurethanes. A loss of this lubrication boundary negates the favorable wear properties of polyurethanes and raises concern for high coefficients of friction damaging the articulating surfaces and resulting in high wear rates of compliant materials [34].

UHMWPE demonstrated more consistent COF with less variation between tests. In dry conditions, the COF for metal-PU pairings has been reported to be an order of magnitude higher than that of metal-UHMWPE pairing, as UHMWPE does not demonstrate such drastic changes in COF due to lubrication environments [52,53]. UHMWPE is less compliant than PCU, also reducing possibility of lubrication starvation due to creep and sealing off of wear surface by outer edge geometry. Results in this study demonstrated similar results, with no start-up peak in COF, as well as much less variability between test samples. The average steady state COFs for UHMWPE against metal in this study ranged from 0.01 to 0.03, which is within range of prior studies

reporting COF ranging from 0.017–0.042 [30,51]. Jin et al. [49] reported wear of PU against metal up to two orders of magnitude greater than that of UHMWPE in absence of a fluid film lubrication.

This study had a combination of significant static pre-loading, stationary rotational wear with minimal stroke length, and flat on flat contact of samples, which all contributed to predisposing the compliant PCU layers to non-optimal lubrication regimes and thus affecting the COF and wear rate. This effect was minimized in some samples at 24 N, as the contact pressure may not have been enough to lead to sealing off the wear surface from adequate lubrication formation.

This study was limited by a number of factors. Inherent to the rotational wear set-up, the outer circumference of the pin traveled significantly further than points towards the center of the pin, creating preferential wear at the points of contact of this outer circumference on the polymer. As this was inherent to the test and remained constant throughout all samples, trends in data were still able to be determined. Additionally, the metal pins were 3D printed to allow for control over specifications required for our experimental set-up and there remains the possibility that the mechanical properties of 3D printed metal parts vary from that of casted CoCrMo and Ti-6Al-4V. Although the fixed spinning pin approach has limitations it does serve as a good “worst case scenario” model where lubrication conditions are minimal, and surfaces do not have opportunity to translate.

Calculations of contact pressure assumed flat on flat surfaces were with 100% contact of the pin on the polymer. As measures of wear were on the order of micrometers, small deviations from parallel of either surface could have had significant effects on contact pressure and subsequent wear data. The greatest potential to introduce this bias occurred in the machining of the UHMWPE bar stock into 5 mm cross sections. As the PCU arrived in an injection molded sheet, no further processing was made to the plane of the wear surface. Additionally, PCU is more compliant and better able to conform to the pin surface and overcome any minor divergence from parallel of either surface. This rotational wear test did not simulate in-vivo conditions in wear motion, temperature or velocity, all of which could be adjusted in future studies. This study would need to be repeated in a joint simulator to more accurately address considerations of orthopaedic implants; however, this rotational wear test provides an efficient opportunity to evaluate trends between materials considered for articulating surfaces.

Future studies could further investigate the effect of load on start-up friction. At the lowest static load in this study, 24 N, some PCU samples demonstrated increased start-up friction while others did not. It is possible that this start-up friction is eliminated completely at a lower load. Lubrication starvation has also been reported at lower velocities and shorter wear paths [47]. Both of these variables could be altered along with contact pressure to better characterize situations in which PCU exhibits a peak in start-up friction. Finally, with this study, the measured outcome was total displacement, which was assumed to represent total wear of the bearing surfaces. There was not an ability to clearly differentiate contributions of wear of the metal pin from that of the bottom polymer surface from displacement alone. In the future, analyzing wear particles both quantitatively and qualitatively could provide insight into the potential for wear debris induced osteolysis and soft tissue reactions.

## 5. Conclusion

Improvements in materials currently used in total joint replacements can provide shock absorption and damping and potentially prolong the longevity of the implants, allowing for better outcomes for millions of patients as well as conservation of healthcare resources. While compliant materials show promise as an alternative to UHMWPE to more closely simulate the native joint, their superior mechanical properties are dependent on the development of a full fluid regime. While the experimental set-up in this study was not intended to simulate clinical wear, it did incorporate multiple variables including a period of static

loading prior to motion, outer pin geometry in a flat-on-flat set-up, and a pure rotational stroke path without any component of translation that contribute to the modeling of an inadequate lubrication environment. In these conditions, PCU demonstrated both increased wear and a higher steady state COF when compared to UHMWPE, as well as a high startup COF that was not seen in UHMWPE. Overall, UHMWPE had superior tribological characteristics that were not influenced by conditions that had led to suboptimal lubrication in their compliant counterparts. In future development of compliant implants and bearing components, it is essential they are designed in light of these limitations to ensure adequate lubrication.

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## Declaration of Competing Interest

Dr. Samuel B. Adams reports personal fees from Stryker, personal fees from Extremity Medical, personal fees from Conventus, personal fees from Orthofix, personal fees from Exactech, personal fees from Medshape, outside the submitted work.

All other authors declare that they have no conflicts of interest.

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## Appendix A. Supplementary Data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biotri.2021.100167>.

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