Spatial geometric effects on the friction coefficients of UHMWPe

Alison C. Dunn, Jason G. Steffens, David L. Burris, Scott A. Banks, W. Gregory Sawyer

Abstract

Multi-directional wear of ultra-high molecular weight polyethylene (UHMWPe) is of particular interest due to its wide-spread use as a bearing component polymer in orthopedic implants. To date, attempts to quantify wear mechanisms have depended greatly upon material orientation theories and average wear values over long periods in specific motions. This study introduces spatially resolved \textit{in situ} friction coefficient measurements over relevant motion paths with a tribometer that provides uniform pressure and velocity under the pin. Normal and friction forces were measured simultaneously under dry and lubricated conditions during curvature-modulated paths. Spatially resolved friction coefficients increased with decreasing radius of curvature, which is consistent with the hypothesis that molecular chain alignment during unidirectional sliding is disrupted in multi-directional sliding.

1. Introduction

Orthopedic joint implants are increasingly used in younger and more active patients. Finite wear lives of these joints require multiple surgeries to carry these patients through long life. The state of the art bearing material, ultra-high molecular weight polyethylene (UHMWPe), has been the focus of significant efforts to improve wear performance in these implants. Creep, counterface roughness, third body wear and sensitivity of the material to multi-directional motion paths have all been cited as primary contributors to bearing failures in UHMWPe implants. This paper intends to address the friction trace of multi-directional motion paths and contextualize the results within current wear models.

Many authors have observed a directional dependence on wear rate of UHWMPe, which does not typically form transfer films in the presence of consistent lubrication. They have shown that wear rate, \( k \) (mm\(^3\)/Nm), typically increases 10–1000 times with a deviation from linear pin-on-disk sliding. Laurent \textit{et al.} \cite{1} and Bragdon \textit{et al.} \cite{2} have shown that cumulative wear during walking gait cycles in the medial compartment of knee implants, where the directionality of sliding is greater, is over 100% higher than in the lateral compartment. This apparent multi-directional sensitivity emphasizes the need for extensive multi-directional testing of UHMWPe (Table 1). Turell \textit{et al.} \cite{3,4} and Muratoglu \textit{et al.} \cite{5} have investigated wear of UHMWPe in a rectangular wear pattern to simulate total hip replacement (THR). They relate an aspect ratio of the pattern to the wear factor \( k \) and surmise that orientation or texturing of the UHMWPe in one direction will affect wear in multiple directions. Saikko \textit{et al.} \cite{6} determined that the wear factor \( k \) showed a strong power relationship with the aspect ratio, \( AR \), of oval-shaped paths of the form \( k \propto 1/\sqrt{AR} \). Gevaert \textit{et al.} \cite{7} performed multi-directional wear tests with a motion path composed of a five-pointed star with five crossing points. They conclude that there is a direct and quantitative relationship between the measurements of cross-shear angle and damage, and that the ratio of those measurements is indicative of a material’s ability to resist wear in a cross-shearing configuration.

Hamilton \textit{et al.} \cite{8} proposed a geometrical/statistical parameter to describe wear damage to UHMWPe, assuming a probable orientation direction of the material and its subsequent changes...
in motion direction. This is compared to clinical tibial component wear in a total knee replacement (TKR) in which there is a multi-directional sliding motion path with a high aspect ratio. Wang [9] proposed a unified theory of wear for UHMWPe in multi-directional sliding using experiments with a rotating pin in unidirectional sliding. This theory considers two components of work dissipation: \( W_x \) is defined as the frictional work in the predominant direction of sliding. This component is assumed to contribute negligibly to wear; rather, it acts to orient and elongate fibrils that lead to low friction and wear. \( W_y \) is the component perpendicular to the predominant sliding direction. This component is hypothesized to dominate wear by rupturing crosslinks, and in general, preventing the formation of a stable sliding interface. \( W \) is the total work done. The work components are given in Eqs. (1)–(3), where they differ in their dependence on \( \alpha \), the cross shear angle (Fig. 1). It is defined for these equations as the angle between the velocity vector of a differential surface element and the predominant sliding direction. Other variables are as follows: \( \mu \) is the friction coefficient from linear sliding with \( \alpha = 0 \), \( P \) the contact pressure, \( v \) the linear reciprocating velocity and \( \omega \) is the angular velocity. Linear and angular velocities are decoupled because the tribometer used for that paper by Wang provides linear motion to the plate and angular velocity to the pin.

\[
\Delta W_x = \frac{2 \mu P v}{\omega} (\alpha + \sin(2\alpha) \) \tag{1}
\]

\[
\Delta W_y = \frac{2 \mu P v}{\omega} (\alpha - \sin(2\alpha) \) \tag{2}
\]

\[
\Delta W = \Delta W_x + \Delta W_y \tag{3}
\]

The governing parameter in this wear model is the cross shear angle. Changing friction coefficient was not addressed in this model, but based on the assumptions made for wear one would expect the friction coefficient to vary with varying motion paths.

To date, most models of the tribological behavior of UHMWPe have been based on gross empirical observations of wear as a function of shape parameters. Unfortunately, measurements of UHMWPe wear are inherently insensitive, generally requiring weeks to months of continuous sliding under relevant conditions to obtain a wear rate. These measurements represent average behavior over the entire motion path and do not probe the fundamental mechanisms specific to the tribological system. The primary aim of this study is to measure changes in friction coefficient of UHMWPe over a multi-directional motion using an apparatus designed to capture complicated friction traces. The secondary aim of this study is to identify trends in friction coefficient as a function of curvature intensity, as well as identify ramifications of these changes for specific current wear theories. It is hypothesized that friction coefficient is higher at location of more intense curvature or curvature changes due to the theories of surface orientation, which must inherently have a rate. Friction coefficient has not been widely studied or included in wear models or predictions because it is considered to be of secondary importance to wear in orthopedic bearing design. This study investigates these fundamental mechanisms in UHMWPe by synchronously measuring friction coefficient and position along relevant multi-directional motion paths. This type of \textit{in situ} measurement may provide a basis for improved models and bearing designs.

2. Materials and methods

In order to quantify friction changes over multi-directional motion paths, a variety of spatially resolved wear paths were tested, beginning with a simple straight line. More complex paths included a circle, a lemniscate, and linked Fermat spirals (for continuity). The most complex path was a curvature-modulated “chirp,” comprised of six lemniscates of the same path length but varying aspect ratios superimposed at \( \pi/6 \)-radian angles. This particular motion path provided a variety of curvatures and curvature rates, with the aspect ratio of individual lemniscates varying from 2:1 to 14:1. Although those paths provide a wide range of radii of curvature, they are continuously increasing and decreasing. A final motion path, the Archimedes’ spiral, was devised to isolate the monotonically increasing or decreasing radius of curvature. These paths are shown to scale in Fig. 2. The radius of curvature, \( \rho \), was used to parameterize the motion paths, giving defined limits from \( \rho = 0 \) (a corner) to \( \rho = \infty \) (a

<table>
<thead>
<tr>
<th>shape</th>
<th>functionality</th>
<th>plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>line</td>
<td>( \alpha = 0 )</td>
<td>( \alpha )</td>
</tr>
<tr>
<td>circle</td>
<td>( \alpha = C )</td>
<td>( \alpha )</td>
</tr>
<tr>
<td>Archimedes spiral</td>
<td>( \alpha = f(r) ), ( r &gt; C )</td>
<td>( \alpha )</td>
</tr>
<tr>
<td>lemniscate</td>
<td>( \alpha = f(r) ), ( r = C )</td>
<td>( \alpha )</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic of orientation effects on the wear of UHMWPe in multi-directional sliding and the shape parameters for various paths examined in this study. Terms are as follows: \( \alpha \) is the angle of motion change, which affects shearing directions under the pin. \( C \) is an arbitrary constant, \( r \) the radial coordinate of the polar equation of each motion path, \( \theta \) the angular coordinate of the polar equation of each motion path and \( s \) is a motion path length parameter.
Fig. 2. A plot of selected motion paths: curvature-modulated chirps, double Fermat’s spiral, and Archimedes spiral with return leg. All paths are drawn to scale, and all dimensions are in millimeters. The pin diameter is noted on the upper left of the figure.

Fig. 3. Schematic and photograph of the multi-directional tribometer setup showing polymer sample on a polished counterface under a liquid lubricant. The UHMWPe sample is attached to the load cell to reduce the experimental uncertainty in the friction coefficient measurements.

straight line). The changes in friction will be observed by plotting friction traces along each motion path.

The experimental apparatus used to achieve those motion paths was a multi-directional pin-on-disk tribometer (Fig. 3), located on an optical table in a class 10,000 clean room. Two linear stages driven by ball screw motors were mounted orthogonally to provide in-plane motion. The positions of both stages were continuously measured by LVDTs. In an effort to minimize experimental uncertainty with friction coefficient measurements [10], the pin was mounted directly below a six-channel load cell, assuring that the only force path from the contact to ground was through the load cell. The cell reacted forces in the x–y plane and continuously measured the applied normal force. The lubricant bath covered the contact of the pin and was maintained about 5 mm above the contact. The bath was heated to body temperature (37 °C) using a tape heater around the perimeter of the bath with a temperature controller and type K thermocouple. The lubricant was emptied and replaced between each friction test.

Computer control and acquisition (1 kHz) were phase-locked to table position. During a test, friction coefficient and transducer outputs were displayed in real time to monitor and ensure proper test performance. High acquisition rate data were saved at periodic intervals while lower-resolution average data were saved for each cycle. This allowed analysis of individual cycles at specified test times as well as overall trends. The average sliding speed for all tests was 50.8 mm/s, with test paths remaining within 25.4 mm of the center of the disk. The contact pressures were held constant by servo-controlled pneumatic thrusters at either 10 MPa (203 N) or 6 MPa (122 N), which lie in the middle of the in vivo bearing pressure range [8] and are common in in vitro experiments.

The material used was a reference UHMWPe obtained from the Hospital for Special Surgery in New York [11]. A large sample was machined into cylindrical pin samples 5 mm in diameter and 7.5 mm long, and the bearing surface was prepared with a razor blade. These pins were mounted into a rigid sample holder and rotation was prevented by a setscrew. Tribological experiments were conducted against a counter-surface of polished cobalt chrome (CoCr), over 60 mm in diameter and 6 mm thick (ASTM 1537). Lubricated tests utilized deionized water or a bovine serum solution constituted of Alpha Calf Fraction© from Hyclone diluted to 5 mg/mL protein and 0.3% disodium EDTA as a preservative. Dry-sliding tests were run in clean laboratory air, at about 45% RH and 26 °C.

3. Friction results

Average friction coefficients was inspected for cycle 100 of all tests, and these values correlate well to previously observed
Table 2
Average friction coefficient for various paths over 100 cycles

<table>
<thead>
<tr>
<th>Geometry of wear path</th>
<th>Path length (mm)</th>
<th>Lubricant</th>
<th>Friction coefficient (μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line</td>
<td>50.8</td>
<td>None</td>
<td>0.118</td>
</tr>
<tr>
<td>Reciprocating circle</td>
<td>50.8</td>
<td>None</td>
<td>0.204</td>
</tr>
<tr>
<td>Lemniscate</td>
<td>50.8</td>
<td>None</td>
<td>0.172</td>
</tr>
<tr>
<td>“Chirp”</td>
<td>50.8</td>
<td>None</td>
<td>0.270</td>
</tr>
<tr>
<td>Double Fermat spiral</td>
<td>50.8</td>
<td>None</td>
<td>0.223</td>
</tr>
<tr>
<td>Line</td>
<td>50.8</td>
<td>Bovine serum</td>
<td>0.053</td>
</tr>
<tr>
<td>Lemniscate</td>
<td>50.8</td>
<td>Bovine serum</td>
<td>0.087</td>
</tr>
<tr>
<td>“Chirp”</td>
<td>50.8</td>
<td>Bovine serum</td>
<td>0.077</td>
</tr>
<tr>
<td>Line</td>
<td>25.4</td>
<td>Water</td>
<td>0.034</td>
</tr>
<tr>
<td>Lemniscate</td>
<td>25.4</td>
<td>Water</td>
<td>0.043</td>
</tr>
<tr>
<td>“Chirp”</td>
<td>25.4</td>
<td>Water</td>
<td>0.047</td>
</tr>
<tr>
<td>Archimedes’ increasing radius</td>
<td>162.2</td>
<td>None</td>
<td>0.221</td>
</tr>
<tr>
<td>Archimedes’ decreasing radius</td>
<td>162.2</td>
<td>None</td>
<td>0.223</td>
</tr>
</tbody>
</table>

Fig. 4. Average friction coefficients for a variety of path geometries in dry and lubricated sliding. These values are averaged over the first 100 cycles of sliding. All tests were run on polished CoCr counterfaces dry or in DI-water as indicated. Applied normal load was 203 N.

values for UHMWPe (Table 2). Average friction also was inspected as a function of motion paths, and the more complex wear paths exhibited higher coefficients of friction than simple wear paths in dry and water-lubricated conditions (Fig. 4).

Three- or four-dimensional friction maps (two spatial dimensions plus time and friction coefficient coloration) were plotted to display friction coefficient with respect to spatial location on the various motion paths. This was done by taking the 3D plot of \( x \)-position, \( y \)-position, and friction coefficient, then mapping the latter axis down onto the \( x-y \) plane with different colors to indicate the value of friction coefficient measured (Fig. 5). The results from a single dry sliding curvature-modulated “chirp” cycle show that friction increases from the start point of the cycle (path length parameter; \( s \)), then fluctuates with each lemniscate loop before the end of the wear path. One trend is the increase in friction at the tip of each lemniscate leaf, specifically an increase in friction coefficient when entering the curve (\( dp/ds < 0 \)) and a subsequent decrease exiting the curve (\( dp/ds > 0 \)). This trend appears strongly on the lemniscates with higher aspect ratio, somewhat on the mid-range lemniscates, and least on the wider, shorter lemniscate. This is hypothesized to be due to the rate of change of the angular coordinate along a motion path. It follows that the time to reorient is greater for decreasing rate of change of radius of curvature than for increasing rate of change of curvature. Surface realignment cannot occur instantaneously, resulting in a resistance to sliding direction change, and higher measured friction.

Lubricated sliding produces a similar trend with overall lower friction coefficient (Fig. 6). Though the changes in friction coefficient due to changes in motion path are largely mitigated in the

Fig. 5. Friction coefficient as a function of wear track position for one cycle of the curvature-modulated “chirp” signal in dry sliding. Applied normal load was 203 N.
Fig. 6. Friction coefficients as a function of wear track position for one cycle of the curvature-modulated “chirp” signal for UHMWPe sliding against polished CoCr in bovine serum. Applied normal load was 203 N.

presence of bovine serum, the frictional mechanisms involved such as polymer chain motion are likely still present. The traction stresses are higher in dry sliding, which may cause the orientation rate and its effect on friction coefficient to be more pronounced.

4. Discussion

As a change in direction occurs (entering a tight curve), friction increases, and as the direction returns to the previous general direction, friction decreases. Because these are such short excursions from the general direction of each lemniscate \( (0, \pi/6, 2\pi/6, 3\pi/6, \ldots) \) it can be surmised that the probable orientation direction of a film or fibrils is the axis of that lemniscate. The wide change in energy dissipation between points on a motion path are thought to contribute to wear, and the locations of highest dissipation values may be the locations where wear is perpetuated at a higher rate than other locations.

Fig. 7. Friction coefficients in dry sliding as a function of wear track position for one cycle of the chirp, double Fermat’s spiral, and the Archimedes spiral. The friction coefficient for double Fermat’s spiral is noticeably lower than the others. Applied normal loads were 203 N; *applied normal load was 122 N.

Fig. 8. Friction coefficients vs. position for cycles \( 10^2, 10^3, \) and \( 10^4 \) of monotonically increasing or decreasing radii of curvature for Archimedes’ spirals. Tests were conducted on polished CoCr, dry. The sliding speeds were held constant at 50 mm/s except at the abrupt corners. Applied normal load was 122 N.
In comparing the double Fermat spiral to the other motion paths, it is apparent that the gradual and continuous change in curvature provides a reduced friction coefficient as opposed to the other paths that have locations of tight curvature. This is shown in Fig. 7. The extremes of friction coefficients from a single dry sliding cycle can be as low as 0.2 (broader curvature) and as high as 0.4 (tighter curvature). The extremes observed for lubricated sliding in a bovine serum solution were 0.025 to 0.10.

The ramifications of a variable friction coefficient has implications on current wear theories, changing energy dissipation from a dependence on angle to a dependence on the motion path in its entirety. For example, Wang [9] uses a constant coefficient of friction in his model of perpendicular work. If the regions of highest friction coefficient are also regions of greatest wear rate than the number of abrupt changes in sliding direction for a given path may be more important than the overall aspect ratio of the path. To demonstrate this, Archimedes’ spirals with monotonically increasing and decreasing radii of curvature were run in the same sliding conditions as the previous tests (Fig. 8). These paths have a continuously increasing friction coefficient with cycle number. Additionally, unlike the double Fermat spiral, the abrupt changes in sliding direction at the beginning and the end of the path are thought to be disruptive. It appears that there is some threshold rate of change of curvature that exceeds the reorientation rate of the polyethylene and gives rise to increased friction coefficient. The scaling parameters and values of this transition have not been identified or solved. Transfer film formation in the dry sliding friction of polymers such as UHMWPe may allow for low friction and wear in even a few sliding cycles. These low-shear running films may be present even though they were not visible in these short friction experiments.

This work has shown that friction coefficient measured in situ varies during multi-directional sliding. For a positive derivative of radius of curvature the steady-state friction is lower, and the opposite is true as well. It is possible that second derivatives play a role. This is consistent with the hypothesis that surface orientation of UHMWPe has a friction and wear anisotropy. Other authors have demonstrated that UHMWPe wears more when there are more abrupt motion path changes. Perhaps future wear models will take into consideration a variable friction coefficient.

5. Closure

A multi-directional tribometer with the capabilities of uniform-velocity and uniform-pressure motion paths has been designed and constructed. It has been used to run a variety of motion paths with the aim of analyzing the resulting friction with the path parameters such as changes in curvature. It has been shown that when all other parameters remain constant, friction coefficient of UHMWPe in multi-directional sliding is affected by changes of curvature in the motion path.

The chirp motion path with multiple passes of increasing and decreasing radius of curvature was run, and the highest friction is seen at times when the radius of curvature is decreasing (dp/ds < 0). Friction tends to increase with dp/ds < 0 and tends to decrease with dp/ds > 0.

Acknowledgements

The authors gratefully acknowledge the support for ACD from MAKO Surgical Corporation, DLB from W.L. Gore and Associates, and JGS from the Air Force Office of Scientific Research.

References