Predicting wear of UHMWPE: Decreasing wear rate following a change in direction
Matthew R. Dressler a,∗, Michael A. Strickland b, Mark Taylor b, Todd D. Render a, Craig N. Ernsberger a

a DePuy Orthopaedics, 700 Orthopaedic Drive, Warsaw, IN 46581, United States
b Bioengineering Sciences Research Group, School of Engineering Sciences, University of Southampton, Hampshire SO17 1BJ, UK

A R T I C L E   I N F O
Article history:
Received 5 November 2010
Received in revised form 4 May 2011
Accepted 6 June 2011
Available online 12 June 2011

Keywords:
Bio-tribology
Joint prostheses
Wear testing
Polymers
Non-ferrous metals
Sliding wear
Wear modeling

A B S T R A C T

Computational tools are emerging as design tools for the development of total joint replacement with improved wear performance. The current wear models of polyethylene assume that wear is linearly proportional to sliding distance; however, it is hypothesized that the wear rate varies and is higher near a change in direction, but diminishes with continued unidirectional sliding which eventually exhibits negligible wear. Our goals were to (1) reveal the presence of a variable wear rate in polyethylene; (2) identify the sliding distance required to reestablish unidirectional sliding subsequent to a change in sliding direction. The wear of polyethylene was evaluated in pin-on-disk testing for several different sliding distances (0 mm, 1 mm, 2 mm, 5 mm, 10 mm, and 100 mm) after a 90° change in direction. The results indicate the wear rate immediately following the change in direction is high, but with continued linear sliding the wear rate appears to drop to near zero—returning to the low wearing condition of unidirectional sliding. Furthermore, this transition appears to occur nonlinearly below 5 mm from the change in direction. While more studies are required to explore other paths and uncover the underlying mechanisms, these results should aid the development of computational tools for the design of advanced joint replacement.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Osteoarthritis, manifest by a loss of the articular cartilage that lines the bone of synovial joints, can result in pain that limits activities of daily living. It is estimated that 10% of the global population age 60 years and older experiences significant clinical problems due to osteoarthritis [1]. Total joint replacement has emerged as the standard treatment for advanced osteoarthritis achieving greater than 90% survivorship after 15 years or more [2,3]. Not surprisingly with this long-term clinical success, the frequency of this procedure has increased substantially in the United States and is expected to grow exponentially in the next decades [4,5]. In addition to the growing numbers of patients, expectations are growing with many younger and active patients expecting to return to their previous lifestyle after surgery [6–9], enjoying activities such as cycling, hiking, tennis, etc. [7]. Consequently, new products are emerging that have been designed to meet these increased performance demands.

In vitro wear simulations are often used to benchmark the wear performance of new products against clinically successful predicate devices. While invaluable, these in vitro tests are long, expensive, and can only be performed near the end of the design cycle. Computational modeling (both finite element and rigid body modeling) techniques have the potential to acquire insights into the wear behavior of new designs faster, cheaper, and earlier in the design process. Early studies, implementing Archard’s law, reported reasonable correlations with implant retrievals [10] and experimental data [11]. However, a more extensive study comparing multiple implant designs and kinematic conditions achieves good correlation in vitro wear results (R2 ≈ 0.6), restricting its use to qualitative comparisons rather than absolute quantitative wear values [12].

Further improvements in the predictive power of in silico wear simulation could be achieved by revisiting and refining the underlying wear model for ultrahigh molecular weight polyethylene (UHMWPE). The classic Archard relationship for abrasive wear, where wear is proportional to the contact pressure and the sliding distance [13], established a foundation for many computational studies in total joint replacement [14–17]. Further investigations into the fundamental wear behavior revealed accelerated wear of polyethylene when articulated with so-called crossing motions as compared to linear reciprocation [18–21]. Consequently, a cross-shear term was introduced to augment the original Archard relationship [19,22,23]. This greatly improved predictive power [12,24], but as mentioned previously, these models are best

∗ Corresponding author. Fax: +1 574 371 4880.
E-mail addresses: mdressle@its.jnj.com (M.R. Dressler),
ams05@alumni.soton.ac.uk (M.A. Strickland), m.taylor@soton.ac.uk (M. Taylor),
trender@its.jnj.com (T.D. Render), cernsber@its.jnj.com (C.N. Ernsberger).
0041–1648/5 – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2011.06.006
reserved for qualitative comparisons. Although there are several different cross-shear formulations, most are calculated post hoc from the aggregate motion rather than determined at each step in time from a time history of sliding events.

For example, square articulation paths will produce similar cross-shear regardless of their size and therefore the cumulative wear of square paths are solely dependent on the total sliding distance. This scale-independence assumes, perhaps erroneously, a constant wear rate along the sliding path. While the instantaneous wear rate in a region subsequent to a change in direction will be high, it is possible that a very large square will possess sides so long that the instantaneous wear rate will eventually drop to near zero similar to the behavior in unidirectional sliding (Fig. 1). To the authors’ knowledge, this variation in wear rate with sliding distance after a change in sliding direction has not been explored experimentally.

Using a novel experimental design for pin-on-disc testing, we combined reciprocating linear sliding with 90° rotations to investigate the fundamental wear behavior of two commercially available crosslinked polyethylenes used in orthopaedic joint replacement. Specifically our goals were to (1) reveal the presence of a variable wear rate; (2) identify the sliding distance required to reestablish unidirectional sliding subsequent to a change in sliding direction.

### 2. Methods

Wear was evaluated for similar articulation paths having six different sliding distances (0 mm, 1 mm, 2 mm, 5 mm, 10 mm, and 100 mm) using an OrthoPOD Wear Testing Machine (AMTI, Watertown, MA). Pins ($n = 3$) reciprocated in short segments (0 mm, 1 mm, 2 mm, or 5 mm) on a broad arc (radius = 52.4 mm) under a 330 N constant vertical load (∼4.7 MPa which is similar to mean pressures experienced in total knee and hip replacement [12,14] and is below the material yield strength) and constant sliding velocity (64 mm/s) until they achieved the target sliding distance per cycle (see Fig. 2 and Table 1 for summary of experimental conditions). The pins then stopped translating and rotated 90° about their own axis under a reduced vertical load of 30 N (∼0.4 MPa). The loading was restored to 330 N and sliding recommenced. A complete cycle included two sliding portions and two rotations of ±90°. For example, in the case of the 100 mm path, pins reciprocated 20 times in 5 mm increments, rotated 90°, slid 100 mm again, and then rotated back to 0°.

Two different polyethylene materials were evaluated. Both were comprised of GUR 1020 resin. One group (CVT™) was gamma irradiated to 40 kGy in a vacuum pouch. The other group (XLT™) was irradiated to 50 kGy and then remelted. The pins were machined from molded pucks to final dimensions of 17.8 mm (0.375 in.) diameter and 9.5 mm (0.38 in.) length.

Each pin articulated against a mirror polished wrought Co28Cr6Mo counterface. The disks, conforming to ASTM F1537 Alloy 2 (UNS 31538), were polished to an $R_{a}$ of less than 10 nm. No passivation treatment was applied prior to wear testing. The disks had a diameter of 38.1 mm (1.5 in.) and were 12.7 mm (0.5 in.) thick.

Testing was performed at 37 ± 1°C in 90% bovine serum (HyClone, Logan, UT) supplemented with 0.2% sodium azide and 20 mM EDTA to retard bacterial growth and calcium precipitation. The specimens articulated in the OrthoPOD for approximately 50 h and were then removed for analysis. All pins were then cleaned and weighed (similar to current ISO and ASTM standards [25,26]) using an analytical balance (AX205, Mettler Toledo, Columbus, OH). A “soak corrected wear” value was determined for each pin by summing the measured weight loss with the average weight gain of three soak specimens. A linear wear rate was then calculated using a

### Table 1

<table>
<thead>
<tr>
<th>Group</th>
<th>Reciprocations per cycle</th>
<th>Total turns</th>
<th>Total cycles</th>
<th>Total distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 mm</td>
<td>0 × 0 mm</td>
<td>0.60 M</td>
<td>0.30 M</td>
<td>0.0 km</td>
</tr>
<tr>
<td>1 mm</td>
<td>1 × 1 mm</td>
<td>1.62 M</td>
<td>0.81 M</td>
<td>1.6 km</td>
</tr>
<tr>
<td>2 mm</td>
<td>1 × 2 mm</td>
<td>1.56 M</td>
<td>0.78 M</td>
<td>3.1 km</td>
</tr>
<tr>
<td>5 mm</td>
<td>1 × 5 mm</td>
<td>1.44 M</td>
<td>0.72 M</td>
<td>7.2 km</td>
</tr>
<tr>
<td>10 mm</td>
<td>2 × 5 mm</td>
<td>1.20 M</td>
<td>0.60 M</td>
<td>12.0 km</td>
</tr>
<tr>
<td>100 mm</td>
<td>20 × 5 mm</td>
<td>0.48 M</td>
<td>0.24 M</td>
<td>48.0 km</td>
</tr>
</tbody>
</table>

Fig. 1. A linear wear path that undergoes a sudden change in direction will generate a high instantaneous wear rate initially and then will transition to a near zero instantaneous wear rate with continued sliding. The sliding distance required to achieve the reduced wear rate is unknown. 

Fig. 2. (a) Pins reciprocated in segments (1, 2, and 5 mm) under load until they achieved the target sliding distance (e.g. 5 mm × 20). (b) Pins stopped translating and rotated 90° under reduced load. (c) The loading was restored and sliding recommenced. (d) Pins rotated to 0° under reduced load.
best-fit linear regression through the soak corrected data, excluding the 0 cycle wear data point. A one-way analysis of variance (ANOVA) was used with a post hoc Tukey multiple comparison tests to detect statistical differences between sliding distances within XLK™ and GVFTM materials (experimentwise $\alpha = 0.05$ within materials).

3. Results

In general, the average wear per cycle increased as the sliding distance between turns increased, but appears to plateau after 5–10 mm for both GVFTM and XLK™ (Fig. 3). In other words, increasing the amount of sliding changes in direction over an order of magnitude from 5 mm to 100 mm produced little to no concomitant wear. The GVFTM groups wore nearly twice as much as XLK™ for all conditions (Fig. 4).

Statistical analysis revealed significant differences between the wear rates of some groups in GVFTM. This trend was similar in XLK™, but did not reach statistical significance likely due to the large standard deviations associated with the 0 mm and 100 mm groups in XLK™. If these groups are removed, differences between the sliding distances emerge. This data can also be expressed ‘per turn’ rather than ‘per cycle’ through scale factor of 2 given that each cycle included two turns (Fig. 4a and b).

When wear is normalized by sliding distance, the conditions with shorter travel between turns appear more severe (Fig. 4c). Groups with 1–2 mm of sliding between turns produced high val-

---

**Fig. 3.** Wear of (a) GVFTM and (b) XLK pins for several sliding conditions (see text for details). Inset shows the average slope for each group. Note: The 0 mm group exhibited weight gain and is not visible on the graph. Error bars represent standard deviation. Note that the time duration and sliding velocity of each interval was held constant to maintain similar testing conditions; consequently the cycle count per interval for each group was different. Statistical differences within each material (experimentwise $\alpha = 0.05$) are denoted by asterisks (*).

**Fig. 4.** Wear normalized by (a) number of cycles, (b) number of turns, and (c) total sliding distance for the GVFTM and XLK™ pins under several sliding conditions (see text for details). Note: The 0 mm group exhibited weight gain and is not visible on the graph. Error bars represent standard deviation.
ues that diminished in the other groups to near zero for the 100 mm group. It is important to note that some sliding is required to produce wear—simply rotating the pins (0 mm sliding between turns) produced no measurable wear. In fact, the pins in this group gained weight, typically 0.1 mg over the course of testing.

4. Discussion

The cumulative wear increased proportionally with the number of cross-shear events (i.e. turns) and the results point towards a variable wear rate. The total wear amount increases as the number of turns increases – more wear is observed with increasing cycle count (Fig. 3) – as long as the pins experience some sliding after the turn. The wear subsequent to a change in direction, however, is not constant as evidenced by the changing values of wear normalized by total sliding distance (Fig. 4c). This may indicate a return to ‘uni-directional’ sliding as hypothesized (recall Fig. 1). Furthermore, the data suggests that the transition from a high instantaneous wear rate to a low wear rate occurs very rapidly (less than 5 mm).

Conceptually the wear paths used in this investigation represent different size squares, i.e. squares with 1, 2, 5, 10, and 100 mm sides. It is important to note that current wear algorithms reported in the literature [19,22,23] do not account for the observed varying wear rate and would incorrectly scale wear results with the overall length of the sliding path. Specifically, they would predict a 20-fold increase in the wear per cycle of the 100 mm path compared to the 5 mm path, which is in stark contrast to the nearly uniform results between these groups observed in the current study.

Wear is an important factor in the long-term success of joint arthroplasty. Computer simulations can potentially provide insight into wear performance, but at this time are effective only at qualitative comparisons. The data presented here may improve computational tools and promote quantitative analysis for the design process. Early and ongoing applications in spine [27] and knee [28] have shown promise. Additional work is needed to better understand and apply joint-specific tribological conditions that might further improve the predictive power over direct extrapolations of these pin-on-disk results.

One limitation of the study is the manner that we achieved long sliding distances. In order to attain 100 mm of sliding we reciprocated the pins 5 mm. We assert that reciprocal motion, without any deviation from linear sliding, does not contribute significantly to wear. This has been borne out in the literature [18–21] as well as internal testing. Specifically, the results in the current study comport with wear rates of these same polyethylene materials when articulated in a square articulation path. When similar GVF and XLK pins were articulated in 10 mm × 10 mm squares they generated wear rates of 2.10 ± 0.03 and 1.07 ± 0.07 mg/Mturns, respectively [29], which compares quite well to the wear rates in this study of 2.40 ± 0.18 and 1.13 ± 0.21 mg/Mturns for the 10 mm groups of GVF and XLK, respectively. Another limitation is the length of testing. Each test was restricted to a 2-week duration with 50 h testing intervals and a sliding speed of 64 mm/s. These constraints provided uniform exposure to serum, which denatures during testing, and limited potential viscoelastic effects from creeping into the results while completing the testing matrix in a reasonable amount of time. The cumulative weight loss of all conditions display linear trends, which offers some evidence for stable wear. Extending testing would be required to strengthen this claim, but several investigators have found that pin on disk investigations have shown stable wear [19,21,30,31]. Additionally, it would have been interesting to evaluate sliding distances smaller than 1 mm, however, this was not feasible for two reasons: (1) limitations on the resolution of the OrthoPOD motion and (2) the expected weight loss would be on the same order as the standard deviations observed in this study and therefore approaching the limit of our ability to detect differences (i.e. signal to noise ratio). Lastly, we did not measure surface characteristics at a molecular or macromolecular level and cannot comment on the mechanism of the observed wear phenomenon. Further experimentation and additional techniques are required to capture the transient behavior without introducing artifact.

It is important to note that the reciprocal motion used in this experiment provided a homogenous cross-shear condition across the entire pin area during sliding. This is due to the method of articulation. Specifically the orientation of the pin is always parallel to the sliding direction even if it travels on the broad arc. Cross-shear is only introduced after the pin is rotated and articulates in a direction skewed from the previous sliding direction. If the OrthoPOD test machine was used to create square or rectangular motion paths, it would not be able to achieve long sliding distances and it could only accomplish these motions through simultaneous pin translation and rotation leading to heterogeneous cross-shear conditions (as recognized by previous studies [19]). By decoupling the sliding and rotation motions we have avoided these complications.

While this study advances the fundamental understanding of polyethylene wear, care should be taken when interpreting and applying these results to other testing conditions. We have applied two different crosslinked polyethylenes in unique sliding motions against cobalt chrome disks in specific environmental surroundings. Other polyethylenes are likely to exhibit similar trends but their exact behavior will depend on their base resin, additives, and extent of crosslinking [19,32–34]. Also the current study employed only 90° changes in direction. It is not clear how smaller changes in direction would affect wear. Intuitively, the wear will decrease monotonically as the change in direction is reduced from 90° down to 0°; however, the exact relationship is not known and is an area of further exploration. It is also important to note that we tested in 90% bovine serum supplemented with EDTA and sodium azide. The serum concentration and choice of anti-bacterial agent can significantly influence wear and should be appreciated when comparing results from different laboratories [35–37].

In conclusion, we have provided evidence that the wear of moderately crosslinked polyethylene varies along a sliding path, which contrasts to the Archard relationship, which states that wear is linearly related to sliding distance. Our results suggest that the wear after a discrete cross-shear event (i.e. a change in sliding direction) is higher, but with continued linear sliding the wear rate appears to drop abruptly to near zero—returning to the low wearing condition of unidirectional sliding [18–21]. The data further suggests that this transition occurs less than 5 mm from the change in direction. The results of this study could aid the development of improved computational tools. Additional studies are required for non-orthogonal articulation paths as well as exploration into the underlying mechanism of wear.

Acknowledgements

The authors greatly appreciate the technical assistance and input from Michelle Ross, Adam Schlachter, Mark Heldreth, Dan Auger, Lauren Brett, Jennifer Tikka, and Sarah Aust as well as Aaron Winery for his help creating some of the figures.

References


