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Cross-Shear in Metal-on-Polyethylene Articulation of Orthopaedic Implants and its Relationship to Wear

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Abstract

Wear of polyethylene (UHMWPE) is dependent on cross-shear. The aim of the present study was: 1) to develop a theoretical description of cross-shear, 2) to experimentally determine the relationship between cross-shear motion and UHMWPE wear using a wheel-on-flat apparatus, and 3) to calculate the work it takes to remove a unit volume of wear for the use in advanced computational models of wear. The theoretical description of cross-shear has been based on the previously reported finding that cross-shear is maximal when movement occurs perpendicular to fibril orientation. Here, cross-shear is described with a double-sinusoidal function that uses the angle between fibril orientation and velocity vector as input, and maximum cross-shear occurs at 90° and 270°. In the experimental part of the study, friction and wear of polyethylene were plotted against increasing sliding velocity vector angles, i.e. increasing cross-shear. It was found that wear intensified with increasing cross-shear, and wear depth could be predicted well using the double-sinusoidal function for cross-shear ($r^2=0.983$). The friction data were then used to calculate the work to remove a unit particle by integrating the frictional force over the directional sliding distance. Using the wear volumes, determined for both longitudinal and perpendicular motion directions, the work to remove a unit volume of material was $q_y=8.473 \times 10^8 \text{ J/mm}^3$ and $q_x=1.321 \times 10^8 \text{ J/mm}^3$, respectively. Hence, 6.4 times more work was necessary to remove a unit wear volume in the direction of principal motion (i.e. along the molecular fibril orientation) than 90° perpendicular to it. In the future, these findings will be implemented in computational models to assess wear.

Keywords

Polyethylene; Wear Factor; Cross-Shear; Unit Work; Wear Model

1. Introduction

Wear of the polyethylene component in total knee replacement is a major limiting lifetime factor. The prospect of accurately modelling wear of artificial implants is therefore particularly appealing. Validated analytical or numerical mathematical depictions would facilitate implant development—numerous tribological parameters could be sampled without the need of extensive and costly experiments. Some attempts have been made to develop competitive wear models for total knee replacement, and a recent increase in this

activity is observed [1–7]. The most widely used wear model in the orthopaedic literature is the ARCHARD equation [8]. It takes normal load and sliding distance as input variables and, by the introduction of a wear coefficient k , volumetric wear can be calculated. Although this method was originally developed for adhesive wear in metals, it has been extensively used for other materials and wear mechanisms. One of its shortcomings is that the experimentally derived wear coefficients apply only to a fixed set of parameters in the tribological system, such as constant sliding velocity and surface roughness. Therefore, any change of these values within the given tribosystem lead to new k -values which must be experimentally determined. Also, it is assumed that k is independent of the normal load F_N , which does not hold necessarily true for polyethylene. Hence, it becomes difficult to determine wear for total knee replacement, even for a single gait cycle where the normal load varies between 1- and 3-times body weights.

Another disadvantage of using ARCHARD's equation to predict polyethylene wear in artificial joints is that it does not account for changes in sliding direction and the related wear increase. It has been proposed by a number of researchers that the motion-dependent behaviour of UHMWPE wear can be attributed to the unique structure of UHMWPE, whose molecules orient preferentially in the direction of sliding. LAURENT et al. [9] included the effect of cross-shear motion into a mathematical description of wear. The initial linear wear index (LWI) was expanded with a trigonometric function, defining the directional wear intensity factor, or DWIF. This approach assumes that wear only occurs based on the proportion of sliding perpendicular to the main motion direction. LAURENT applied this theory to a simulator study with known motion paths. Herein, he compared the differences in wear volume between medial and lateral implant sides theoretically and experimentally and found a reasonable agreement.

TURELL et al. [10] tested the model suggested by WANG [12], which was the first paper providing a theoretical basis for cross-shear dependence of polyethylene. Cross-shear k was defined as the relation of motion path length along and perpendicular to the main motion direction by $k \propto A/(A+B)$. Herein, B defines the path length along the principal direction of motion and A the path length perpendicular to it. Experimentally, good agreement was found for $A/(A+B)$ ratios from 0 to 0.2, i.e. small cross-shear motions. HAMILTON et al. [11] compared the same experimentally determined wear coefficients to a newly introduced crossing intensity σ and found higher correlations for other cross-shear ratios. This is the first model that included motion path history for potential molecular alignment.

Wear intensity calculations, in comparison to wear coefficients as initially introduced by ARCHARD, allow a prediction of the potential wear location and wear distribution. They do not provide estimates of actual wear volumes. However, if wear intensity was linked with wear volume, an actual volumetric prediction might be possible. WANG et al. [12] was the first bridging this gap by presenting the “unified theory of wear” for polyethylene—a model based on the physical work that is required to remove a unit particle in multi-directional sliding of artificial implants. The model treats the physical process of wear debris generation as an intermolecular splitting phenomenon. The UHMWPE surface is assumed to consist of numerous micro-fibrils, which are oriented along the principal sliding. A wear particle is produced when a fibril separates from its neighbours by tearing rupture in the secondary sliding direction, thus considering wear as an anisotropic behaviour. While WANG's model included material specific information as well as a representation of angular changes in the motion path, the approach has limitations in that it assumes wear only to be generated due to motion perpendicular to the main sliding direction. A similar shortcoming applies to LAURENT et al. [9].

Therefore, the aim of the present study was: 1) the development of an improved theoretical description of cross-shear motion applicable to total knee replacement, 2) the experimental determination of the relationship between cross-shear motion and UHMWPE wear, and 3) the calculation of work required to remove a unit volume of wear based on of the theoretical cross-shear description and experimental wear results and to derive an advanced model for motion directionality in total joint replacement.

2. Cross-Shear Model

Two principal directions of motion are defined in the contact between metal condyle and opposing polyethylene (PE) tibial plateau: the first axis, or y-axis, points in the direction of main fibril orientation, and the second axis, or x-axis, points in to the direction that is perpendicular to the fibril orientation (Fig. 1). This approach is in agreement with WANG et al. and follows the general observation that the molecular chains in the surface layer of the PE material are aligned along the main axis of motion [12].

Our description of cross-shear is based on a circular running vector (Fig. 2a). The portion of the velocity vector, which acts perpendicular to fibril orientation can easily be obtained by trigonometry. In order to assign values of cross-shear ranging from 0 to 1 for a full 360° of possible motion directions, a double-sinusoidal form is chosen:

$$k(\vartheta) = \frac{1}{2} (\sin(2 \cdot \vartheta - 90^\circ) + 1) \quad (1)$$

where ϑ is the angle between sliding velocity vector and fibril orientation. Hence, zero cross-shear occurs when the motion is along the main PE fibril orientation, while it is maximal in motion direction perpendicular to the fibril orientation.

By this definition, maximum cross shear occurs at the velocity vector angle $\vartheta = 90^\circ$, while cross-shear is minimal at vector angle $\vartheta = 0^\circ$. Similarly, another cross-shear minimum can be found at $\vartheta = 180^\circ$, while a second maximum occurs at $\vartheta = 270^\circ = -90^\circ$. Consequently, cross-shear k follows a sinusoidal curve relative to fibril orientation (Fig. 2b).

If the relationship of cross-shear and wear can be assumed directly linear, then the above equation can be directly transformed into expressions to calculate wear depth:

$$\text{Wear depth: } |z(\vartheta)| = (\sin(2 \cdot \vartheta - 90^\circ) + 1) \cdot a + b \quad (2)$$

where 'a' is a material dependent "cross-shear intensity factor" (which includes the factor 0.5 from Eq.1) and 'b' denotes wear and creep without cross-shear. Both parameters are system dependent and have to be determined experimentally.

In general, work that potentially leads to material removal can be calculated as follows:

$$W(s, t) = \int_{s_1}^{s_2} \vec{F}(s) \cdot d\vec{s} = \int_{t_1}^{t_2} \vec{F}_t(t) \cdot \vec{v}(t) dt \quad (4)$$

where $F_t(t)$ represents the tangential force and $v(t)$ the sliding velocity vector at each time point. The cross-shear dependent wear behaviour of PE suggests a distinction between the portion of the work W_x that is released perpendicular to the molecular orientation and the portion of the work W_y that is released in the direction of molecular orientation. Both can be calculated as:

$$W_x = \int_{t_1}^{t_2} F_{t,x} v_x dt = \int_{t_1}^{t_2} \vec{F}_t \cdot \vec{v} \sin^2 \theta dt \quad (5)$$

$$W_y = \int_{t_1}^{t_2} F_{t,y} v_y dt = \int_{t_1}^{t_2} \vec{F}_t \cdot \vec{v} \cos^2 \theta dt \quad (6)$$

Thus, the work required to remove a unit volume of material, the unit work, can be calculated:

$$q_x = \frac{W_x}{V_x} \quad (7)$$

$$q_y = \frac{W_y}{V_y} \quad (8)$$

where V_x and V_y are the wear volumes based on tractive motion in the respective directions. The unit work q describes how much energy needs to be introduced to remove a unit of material. Tribology related variables such as surface roughness, contact geometry, and lubricant properties are incorporated in it.

3. Cross-Shear Experiment

1.1 Materials & Methods

The experimental part of the present study employed a wheel-on-flat (WOF) material-screening concept. The custom built tribological testing device has been specifically developed to test material pairings for artificial knee joints. Various kinematic and kinetic conditions at the implant interface can be parametrically examined under physiologically relevant conditions. The WOF simulator is comprised of a vertically positioned wheel that is pressed against a flat horizontal sample (Fig. 3). The cobalt-chromium wheel, resembling a femoral condyle, rotates around its horizontal axis. The flat polyethylene specimen, resembling the medial or lateral compartment of the tibial plateau, translates along its longitudinal axis and also rotates around its vertical axis. All motions are realized using servo-hydraulic cylinders, which are closed-loop controlled in displacement or, in the case of the vertical load actuator, load mode. All four cylinders accept independent input profiles and act highly synchronized.

Design and configuration of the apparatus result in a motion pattern that keeps the vertical rotation axis of the flat specimen always in the centre of the WOF contact area. The contact centre also always stays on the centreline of the flat specimen as it translates and rotates underneath the wheel (Fig. 4). This simulator layout allows for the investigation of several wear-related parameters. Further, parameters can be varied over the length of the PE flat and their wear impact can be examined along the y-axis, the principal axis of motion, as shown in Figure 5.

For this study, displacement characteristics of wheel and flat over time were programmed resulting in a kinematic profile with a velocity vector of constant magnitude (50 mm/s) and changing vector angles. The vector angle changed at a constant rate as the contact area moved along the principal direction of motion the surface of the PE flat. Two consecutive passes with opposite rotation of the PE flat led to increasing cross shear over the polyethylene plateau and will be defined as one cycle (Fig. 5).

Two test profiles (Test 1 and Test 2) were applied to separate PE samples. The combination of wheel and flat motions of the first profile resulted in a velocity vector with a 0° angle at the beginning of the wear track, which then continuously increased to 20.4° at the end of the track. The second profile switched the positions of minimum and maximum vector angle to the end and beginning of the wear track respectively. This means the vector angle gradually decreased to 0° towards the end of the path.

For both tests, the angle ϑ between velocity vector and PE flat centreline was changed at an angular velocity of $4.6^\circ/\text{s}$. The angle ϑ varied from 0° to $\pm 10.2^\circ$, with a sign change after each pass. The total track length was 50 mm, whereby the PE flat travelled with 25 mm/s through the contact zone. The sliding velocity magnitude was kept at constant 50 mm/s independent of vector angle. A vertical load of 1500 N was applied during each pass. When the end of the track was reached, the load was removed and wheel and flat were brought out of contact to return them to their starting positions. The load was then re-applied and a second consecutive pass was started and the angle ϑ was rotated in the opposite direction. As a result, the range of ϑ varied from 0° to 20.4° at defined locations along the wear track on the PE flat. This choice of angle variation has been based on knee implant kinematics derived from patient measurements in the laboratory [13, 14]. One entire test cycle took 4.8 s including return motions. 500,000 cycles were applied in total, leading to 1 million passes in alternating rotational direction.

Test samples were manufactured with the intent to match the bulk and surface properties of MG II total knee replacements. Wheels made of cobalt-chromium were used, machined from cast raw material and polished to medical grade surface finish (diameter: 100 mm, thickness: 20 mm, $R_a = 20$ nm). The flat, rectangular PE specimens were machined from slab molded GUR 1050 (dimensions: $100 \times 40 \times 8$ mm³). They were gamma-sterilized (dose: 2.50–3.25 Mrad, temperature: 45°C) and packaged in nitrogen. Packages were opened immediately before testing.

After mounting samples onto the simulator, the specimens were submersed in 200 ml of a bovine serum mixture, diluted to 30 g/l protein to mimic in vivo conditions. The enclosing chamber was covered with a flexible latex balloon to prevent fluid evaporation and contamination. Tests were conducted at room temperature: $22 \pm 2^\circ\text{C}$.

Upon test completion, the surfaces of the PE flats were scanned to measure wear depth. An optical coordinate measurement machine was used (SmartScope, Optical Gaging Products, Inc. - Rochester, NY USA). Grid resolution of the measurement points was set to 0.5×0.5 mm². The accuracy of this profilometer is ± 1.5 μm in the vertical (z-) direction and ± 3.1 μm in the horizontal (x-, y-) directions for a maximum measurement length of 100 mm.

1.2 Experimental Results

The wear depth increased with increasing velocity vector angle for both tests (Fig. 6). This held true, except for the starting and end positions of the track, where creep and wear due to extended contact with the wheel may have played a role.

The friction coefficient ranged from 0.036 to 0.058 (mean $\pm$ s.d.: 0.046 ± 0.008) throughout the experiment and was dependent on velocity vector angle as shown in Figure 7.

4. Wear Model and Calculation of Unit Work

Equation 2 was used to determine parameters 'a' and 'b' from the depth profiles of the two PE samples used in Tests 1 and 2 (Tab. 1).

Thus, the wear depth equation for this particular wear system after n full cycles is expressed as

$$|z(\theta, n)| (mm) = (\sin(2 \cdot \theta - 90^\circ) + 1) \cdot 0.13 + 0.018 \cdot \frac{n}{5 \cdot 10^5} \quad (9)$$

When comparing above mathematical description with the experimentally measured depth profiles (Fig. 6), excellent agreement is found ($r^2=0.983$).

The calculated wear depth profile can be separated into two parts: a portion z_y that was caused by sliding in the PE fibril direction and a portion z_x that was caused sliding perpendicular to the fibril direction (Fig. 8).

Wear volumes for each portion are calculated taking the integrals of z_y and z_x over position Y along the wear track and multiplying it by the wear track width (i.e., the width of the wheel). The minimum wear depth at vector angle 'zero' represents the portion of wear resulting from motion along the predominant PE fibril direction. The associated wear volume for a wear track length from zero to maximum vector angle is

$$V_y = d_w \cdot z_y \int_{y(\theta_0)}^{y(\theta_{\max})} dy(\theta) \quad (10)$$

where d_w denotes the width of the wheel. The remaining portion of the wear depth profile represents the amount of material that is removed by rising vector angles. This volume V_x can be calculated by

$$V_x = d_w \cdot \int_{y(\theta_0)}^{y(\theta_{\max})} z_x(\theta) \cdot dy(\theta) \quad (11)$$

Here $V_y = 1.775 \times 10^{-5} \text{ mm}^3$ and $V_x = 1.105 \times 10^{-5} \text{ mm}^3$. Using the equations for frictional work (Eq.s 5 and 6) and including the frictional forces that were measured on the wheel-on-flat simulator throughout the experiment (exemplified in Fig.8) over 500,000 cycles of testing, one obtains $W_y = 15.04 \cdot 10^3 \text{ J}$ and $W_x = 1.46 \cdot 10^3 \text{ J}$. Hence, the work per unit volume of worn off PE was $q_y = 8.473 \times 10^8 \text{ J/mm}^3$ and $q_x = 1.321 \times 10^8 \text{ J/mm}^3$ (using Eq. 7 and 8).

These numbers are specific for the tested system conditions, namely an UHMWPE sample that was slab molded from GUR 1050 and subsequently gamma-sterilized, a CoCr wheel with a roughness of $R_a = 20\text{nm}$, and the applied lubrication conditions. It is apparent that the required work to remove a unit volume of particles along the molecular orientation is significantly higher than the work that is required in the perpendicular direction. Based on the results of the wheel-on-flat experiment, the ratio

$$\frac{q_y}{q_x} = 6.4 \quad (12)$$

5. Discussion

The goal of this study was to 1) to develop a theoretical description of cross-shear, 2) to experimentally determine the relationship between cross-shear motion and UHMWPE wear using a wheel-on-flat apparatus, and 3) to calculate the work it takes to remove a unit volume of wear for the use in advanced computational models of wear. All three goals were successfully addressed.

The mathematical formulation to describe cross-shear motion resulted in excellent agreement with the actual wear profiles. The approach is different than the often-cited model established by WANG [12] and seems to work very well for vector angles expected for total knee replacement. It is noteworthy that the model by WANG has been recently improved in an attempt to correct its limitations [21]. A comparison of the WANG approach and the experimental data of this study is discussed elsewhere [13].

Given the possibility to measure or compute frictional forces, the proposed model will allow the calculation of wear volumes based on these measurements. Once a material is characterized for the particular tribosystem (i.e. unit work determined experimentally for both principal directions), the total wear volume can be computed based on measured interface kinematics and tractive force, with the latter providing the input variables to calculate work perpendicular and along the PE-fibril orientation:

$$V_{total} = \frac{W_x}{q_x} + \frac{W_y}{q_y} \quad (13)$$

This approach is applicable to any artificial implant or other tribological system. The unit work numbers presented in this paper should be considered as realistic estimates but it might be necessary to validate those with improved and more accurate methods in future studies. They are also only valid for the particular type of polyethylene and metal counterface.

Wear of polyethylene is a function of sliding distance, so it is important to reflect on this variable. One particular feature of the test set-up is that there is a migrating contact area on the PE flat (shown as pink rectangle in Fig.4). Using a Hertzian model (cylinder-on-flat; $E = 1000 \text{ MPa}$, $\nu = 0.45$) and inputting the testing conditions above, the contact area on the PE flat is a narrow rectangle of width 3.9 mm and length 20 mm being in contact for 0.15 s. Hence, every point on the PE wear track is exposed to a sliding distance that amounts 15.6 mm per cycle (7.8 mm per pass) given the 50 mm/s relative sliding velocity in the contact. Both sliding distance and sliding velocity are in the range of what has been reported for tibio-femoral motion in total knee replacement during walking gait [13,14].

Typically, the wear coefficient k is used to compare wear severity between tribological systems [8]. As outlined in the discussion, k is an empirically derived factor - a concept that was originally developed for metals. However, a constant k value is not appropriate for polyethylene because of its anisotropic wear behaviour and its wear dependence on contact stress [15]. A k value that depends on changes in sliding direction and normal force is required. In contrast, the energy approach is based on the concept of frictional work, and tractive forces are treated as a variable during computation. This accounts for the dynamics of the system better than the use of a "static" wear coefficient k . Moreover, tractive forces can be easily be measured during experiments, or computed using mathematical models [16]. Once the relationship between energy input and wear output has been determined, wear can be calculated for many scenarios.

Although advantageous, this newly developed modelling approach is subject to some limitations. First, there is no proof that the utilized trigonometric description is the best possible approach to address cross-shear intensity. Second, material deformation and creep of the tested PE samples have not been considered in the present analysis and they may have affected the wear profile. Third, sample numbers were limited, and more replicates would be required to strengthen testing results. It is noteworthy, however, that the wear depth that was calculated for zero velocity angle matches well with the wear depth that developed during a similar experiment [17]. Another limitation relates to the wheel-on-flat simulator set-up to

measure frictional forces. Presently, the horizontal load data are offset by bearing forces. Although verified by non-loaded runs to correct for the bearing friction it could not be excluded entirely. At the same time, the computed coefficient of friction values compare well with ranges that are reported in the literature [18, 19].

Questions remain of how quickly and to what extent surface molecules of polyethylene material align in the predominant motion direction. Very few studies have been reported in the literature that are able to prove the re-orientation of the fibrils [20] and the underlying mechanisms and duration of this process are not known. The assumption that all fibrils did align along the anterior-posterior direction of the knee tibial plateau during simulator testing might not be accurate—a fact that might have added to the discrepancy between wear predictions and simulator gravimetric wear. As a promising approach, HAMILTON et al. [11] suggested to apply statistical measures for predictions on the molecular alignment. The term crossing intensity was introduced to describe the cumulative cross-shear that each point within a contact area would be exposed to. The inclusion of this approach might improve the predictive power of the proposed wear model herein.

In conclusion, a theoretical depiction of cross-shear using a trigonometric function was established and experimentally validated using a wheel-on-flat simulator. Further, it was demonstrated that 6.4 times more work is necessary to remove a unit wear volume in the direction of principal motion (i.e. along the presumed molecular fibril orientation) than perpendicular to it. In the future, these mathematical descriptions may be useful for establishing computational wear models in total joint replacement.

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Nomenclature

ν	Poisson's ratio
ϑ	angle between sliding velocity vector and predominant molecular PE fibril orientation
a	wear intensity for wear depth
b	zero wear for wear depth
d_w	width of wheel
E	Elastic modulus
F	Force
k	cross-shear
n	number of cycles
s	distance
t	time
v	sliding velocity
V	wear volume
W	work
q	unit work
x	vector direction, perpendicular to PE fibril orientation
y	vector direction, along PE fibril orientation
Y	position along wear track
z	vector direction, perpendicular to PE surface (pointing outward)
$ z $	wear depth (absolute value)

Fig. 1.
The angle ϑ between sliding velocity vector and predominant molecular orientation of the PE fibrils.

Fig. 2.

(a) Circular running vector to describe cross-shear. (b) Cross-shear is defined as the portion of the velocity vector angle that acts perpendicular to the main fibril orientation. Thus, maximum cross-shear occurs at 90° and 270°.

Fig. 3. Picture of the wheel-on-flat simulator. The dashed circle marks the wheel and the flat PE sample sitting inside of the simulator. Three actuators are labelled; the fourth actuator, applying PE flat rotation around its vertical axis, is mounted below the simulator base plate and only partially visible.

Fig. 4. Kinematics of the wheel-on-flat simulator, viewed from top. The centre of rotation of the flat specimen remains in the contact centre and on the centreline of the flat sample at all times. Arrows indicate motions of the PE flat.

Fig. 5. Wheel-on-flat simulator concept and orientation of sliding velocity vectors on PE flat. Two consecutive passes are shown (which make one full cycle).

Fig. 6.

Wear depth profiles after one million cycles for increasing (top) and decreasing (bottom) sliding velocity angles along the principal motion direction (coordinate system according to Fig. 1). The curves represent an average of eleven traces (± 5 mm from the centreline of the PE flat). Mathematical approximations of the profiles have been fitted as discussed in the following paragraph and are shown with dashed lines. Excluded contact areas at the beginning and end of the wear track are highlighted.

Fig. 7.
Coefficient of friction relative to velocity angle towards the end in Test 1

Fig. 8. Wear depth profile plotted over Y, representing the average of the two wheel-on-flat tests with changing velocity vector angle. Wear portions resulting from motion along the PE molecular orientation (z_y) and perpendicular to it (z_x) are highlighted.

Tab. 1

Wear intensity (a) and zero wear depth (b) for the two wheel-on-flat experiments.

	a	b
Test 1 ($\vartheta \uparrow$)	0.15	0.0215
Test 2 ($\vartheta \downarrow$)	0.11	0.0140
Average	0.13	0.0178