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Published in: Wear

DOI: 10.1016/j.wear.2021.204190

Published: 15/02/2022

Document Version Publisher's PDF, also known as Version of record

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Please cite the original version:

Saikko, V., Morad, O., & Viitala, R. (2022). Effect of temperature on UHMWPE and VEXLPE friction and wear against CoCr in noncyclic tests. *Wear*, *490-491*, Article 204190. https://doi.org/10.1016/j.wear.2021.204190

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Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Effect of temperature on UHMWPE and VEXLPE friction and wear against CoCr in noncyclic tests

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ARTICLE INFO

Keywords: Orthopaedic tribology Noncyclic pin-on-disk Vitamin E stabilized, extensively cross-linked UHMWPE Dynamic friction measurement Servo-drive

ABSTRACT

In prosthetic joints, frictional heating may cause protein denaturation in synovial fluid which may affect its lubrication properties. In arthroplasty, conventional ultra-high molecular weight polyethylene (UHMWPE) is being gradually replaced by vitamin E stabilized, extensively cross-linked UHMWPE (VEXLPE) with a superior combination of wear and oxidation resistance. There is scarcity of literature on UHMWPE vs.VEXLPE friction. A noncyclic, single-station friction measurement device, the Friction RandomPOD, was recently introduced. The direction of sliding, velocity, acceleration, and load varied randomly within certain, biomechanically justified limits. The measurement of the coefficient of friction was based on a three-axial load cell. In order to increase the testing capacity, the number of test stations was now increased to 4 using similar load cells. One-week tests were performed with pins made of UHMWPE and VEXLPE against CoCr in calf serum lubrication at 4 °C, 20 °C and 37 °C. The lower temperatures were included to prevent or retard protein denaturation. The lowest friction and wear were observed at 37 °C. At this temperature, the mean of the coefficient of friction of VEXLPE was 55% lower than that of UHMWPE.

1. Introduction

Noncyclic tests have been introduced for wear and friction studies of orthopaedic bearing materials [1,2]. The basic idea of the noncyclic test is that it would reflect the biomechanical variability of everyday activities [3–5] better than a cyclic test [6]. Multidirectionality of the relative motion is important for the wear mechanisms of ultra-high molecular weight polyethylene (UHMWPE) [7]. Multidirectional motion together with serum-based lubrication result in a burnished appearance of the polyethylene bearing surface, which is typical of clinically retrieved acetabular components, and in clinically relevant wear particle size distributions [7–9]. Noncyclic tests are particularly multidirectional. In the noncyclic RandomPOD wear and friction test device, the change of the direction of sliding is 500°/s on the average [1,2].

Protein denaturation and consequently the tribological behavior of orthopaedic bearing materials are sensitive to the test temperature [10-12]. In cyclic SuperCTPOD tests, wear and friction of vitamin E stabilized, extensively cross-linked ultra-high molecular weight polyethylene (VEXLPE) against CoCr strongly decreased with increasing temperature [13]. The temperature dependent protein denaturation thus was assumed to influence wear and friction. It was considered

interesting to see if the same holds true for noncyclic tests, regarding especially friction, and also including UHMWPE as a control. VEXLPE has been introduced in the arthroplasty because of its appropriate combination of wear resistance and oxidation resistance [14]. To increase the testing capacity, the number of the test stations of the noncyclic, multidirectional, single-station Friction RandomPOD [2] was increased to 4. The temperature dependence of polyethylene tribology has not been studied much. The same holds true for the comparison of UHMWPE vs. VEXLPE friction against polished CoCr. The present study intended to shed light on these issues. It was hypothesized that (1) the coefficient of friction and wear show significant temperature dependence, and (2) the friction of UHMWPE is close to that of VEXLPE.

2. Materials and methods

The single-station, computer-controlled Friction RandomPOD wear test device has been described in detail elsewhere [2]. The friction measurement was based on a 3-axial load cell (Forsentek MAC 200 N). In the present study, the number of test stations was increased to 4 (Fig. 1). The load cells were fixed on the motion plate and they were calibrated using weights as in Ref. [2]. The relative motion consisted of two

https://doi.org/10.1016/j.wear.2021.204190

Received 23 June 2021; Received in revised form 21 October 2021; Accepted 20 November 2021 Available online 23 November 2021 0043-1648/© 2021 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).







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Fig. 1. Four-station Friction RandomPOD with three-axial load cells. White Verderprene hoses are for cooling/heating water circulation.

perpendicular translations so that the random slide track remained within a circle of 10 mm diameter [1]. The sliding velocity v varied between zero and 31.4 mm/s and the maximum acceleration was 300 mm/s². The vertical load *L* varied randomly between zero and 150 N. With the maximum load of 150 N, the nominal contact pressure did not exceed 2.5 MPa, which is known to be the limit, above which the worn surface shows protuberances [15] not seen clinically in retrieved acetabular cups [7–9]. The limits for the maximum sliding velocity and acceleration were based on the waveforms of angular motion in a gait study [16], and in the fact that 36 mm is the most common femoral head diameter presently.

With the load cells, the horizontal frictional force components and *L* were measured. To obtain μ , the resultant frictional force was divided by the instantaneous load at a frequency of 200 Hz. With small *L* values, μ was inaccurate, and therefore μ values obtained with *L* values below 5 N were excluded. The nominal contact pressure *p* was *L*/63.6 mm², where the denominator is the cross-section area of the 9.0 mm diameter cylindrical pin. Hence, *p* varied between zero and 2.4 MPa. The product *pv*, commonly used with polymer bearings [17], was computed so that μ vs. *pv* graphs could be produced.

The pins were made of 2 different polyethylenes, (1) conventional UHMWPE (GUR 1020, ISO 5834-2, ASTM F648-14) and (2) vitamin E stabilized (0.1% blended), extensively cross-linked (100 kGy gammairradiation dose) UHMWPE, (GUR 1020, ASTM F648, ISO 5834-1,2, ASTM F2695, ASTM F2565), abbreviated as VEXLPE. The disks were polished CoCr (ISO 5832-12) with a surface roughness R_a value of 0.01 μ m. The lubricant was HyClone alpha calf serum (SH30212) diluted 1:1 with deionized water. The protein concentration of the lubricant was 20 mg/ml. Antibiotic/antimycotic solution (HyClone SV30079) was added to the lubricant (1 ml/100 ml) to reduce microbial growth. The thin-walled, stainless steel lubricant chambers were from Ref. [13]. They were located in water chambers. The two fluids were separated by o-rings. Water was sucked from the water bath by a 4-channel peristaltic pump and circulated through a laboratory cooler/heater back to the water bath. To avoid measurement errors, the inlet and outlet pipes were not in contact with the water chambers (Fig. 1). The lubricant bulk temperature was kept at 3 different temperatures, 4 °C, 20 °C or 37 °C [13]. Protein denaturation and its effect on friction and wear was assumed to be prevented at 4 °C, retarded at 20 °C, and maximal at 37 °C. The duration of each test (n = 4) was 1 week. As the measurement frequency was 200 Hz, one test thus consisted of 121 million measurements per test station. The additional benefit of the 4 test stations was that the device could also serve as a wear test device of reasonable capacity. Before the tests, the pins were run in until the original machining marks were worn off and the wear faces were burnished. The wear was evaluated gravimetrically [1,2]. Each pin and disk was always in the same test station. For every four test pins, there was a soak control pin for the evaluation of the amount of fluid absorption.

3. Results

The wear faces of the pins remained burnished in the tests. The CoCr disks showed no wear marks, nor any polyethylene transfer. The *u* distributions were non-symmetric, and therefore mode values were computed for the distributions instead of mean values (Fig. 2). At 37 °C. the mean of mode μ values of VEXLPE was 55 per lower than that of UHMWPE, and the difference was statistically significant (p = 0.007). VEXLPE showed higher variations of mode μ values, especially at 4 °C, than UHMWPE (Fig. 3). With both materials, the mean of mode μ values and the mean wear were lower at 37 $^\circ$ C than at 4 $^\circ$ C and 20 $^\circ$ C, and the differences were statistically significant. The mean wear of UHMWPE at 37 °C was 44% lower than that 20 °C and the difference was statistically significant (p = 0.017). At every temperature, the mean VEXLPE wear was significantly lower than that of UHMWPE. The dependence of μ on the product pv is shown as color maps for test station 1, with the characteristic shape that is blunt with low pv values and narrows off with increasing pv (Fig. 4). The locations of the darkest red areas agreed with the mode values (Fig. 2).

4. Discussion

Non-cyclic tribological tests of 1-week duration were performed for UHMWPE and VEXLPE pins against polished CoCr disks in diluted calf serum lubricant at temperatures of 4 °C, 20 °C and 37 °C (n = 4). Average friction and wear at 37 °C were significantly lower than those at 4 °C and 20 °C. At 37 °C, the mean of mode μ values of VEXLPE, 0.039, was 55% lower than that of UHMWPE, 0.086. This finding is novel and interesting from the clinical point of view. Clinically, this would mean lower contact temperatures and therefore less heat induced protein denaturation in synovial fluid. It could be speculated that the lower friction was at least partly due to the presence of vitamin E and its thermal behavior.

At 37 °C, one of the VEXLPE pins showed a weight loss of 0.2 mg, whereas 3 pins showed no weight loss at all. The fact that the mean wear of VEXLPE was significantly lower than that of UHMWPE at every temperature was obviously due to the cross-linking. Interestingly, VEXLPE showed high variation of mode μ values but low variation of wear at 4 °C. The wear of UHMWPE at 20 °C was 1.8-fold higher than that at 37 °C. This was in agreement with an earlier RandomPOD wear study in which the corresponding difference for gamma-sterilized UHMWPE was 2.9-fold [18]. Moreover, the higher variation of UHMWPE wear at 37 °C compared with 20 °C was in agreement with [18]. From the wear point of view, the 1-week test duration could be mentioned as a limitation of the present study. For the next stage, a 4-week test duration is contemplated.

Looking at the darkest red in Fig. 4, one can see that the majority of the μ values, close to the modes, occurred with pv values between 0.5 and 2.0×10^4 N/ms. The color map is a novel way of presenting μ vs. pv three-dimensionally (note that μLv is the frictional power and



Fig. 2. Distributions of μ for UHMWPE and VEXLPE pins against polished CoCr disks in diluted alpha calf serum at temperatures of 4 °C, 20 °C and 37 °C.



Fig. 3. Variation of mode μ values and wear of UHMWPE and VEXLPE against CoCr with temperature.



Fig. 4. Color maps of μ vs. pv for test station no. 1. Colors indicate number of μ -pv pairs of values in unit rectangle with x-y-dimensions of 500 N/ms \times 0.002. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

 $L = p \times 63.6 \text{ mm}^2$) using 121 million measurements per test. The coefficient of friction is sensitive to p [15] and possibly also to v, although this has not yet been studied in multidirectional conditions. From the color map, the relationship between μ and pv can be perceived at a glance. The frictional power is an important consideration in order to avoid overheating of the contact, which could produce misleading results [13,15]. The burnished wear surfaces, similar to those observed in clinically retrieved acetabular cups [7–9], indicated that overheating did not occur in the present study.

It should be borne in mind that the protein denaturation was likely to be at its maximum at 37 °C. Therefore, it could be claimed that the lower wear and friction were mere test artefacts. However, the present understanding of these issues is far from complete, although substantial efforts to gain more insight have been made [10-12]. For instance, it is unknown whether substantial denaturation of synovial fluid relative to its natural replenishment rate takes place in long walks during which the contact temperature increases considerably [19]. It is still interesting to note that if denaturation was substantial at 37 °C, its effect did not appear directly detrimental in the sense that the friction and wear were at their lowest at 37 °C. It is of course possible that the reason for the lower friction and wear at 37 °C was not related to denaturation.

The present VEXLPE test at 20 °C was a repetition of the tests of the first Friction RandomPOD study, in which the mode μ was 0.101 ± 0.002 [2]. The 3-axis transducer was the one used in station 1 of the present study, in which the mode μ value now was 0.102. Considering all 4 test stations, the difference in the mode μ values of VEXLPE at 20 °C between the 2 studies was not statistically significant (p = 0.2). None of the 4 test stations showed a systematically lower or higher mode μ value than the others (Fig. 2). Naturally, some of the variation may have been attributable to the individual pins that were always in the same test stations. Comparison of the present friction values with literature is not straightforward because noncyclic studies have not been published by other research groups. If comparison is made with cyclic tests with specimens and lubricant similar to those of the present study, it is noted that the temperature dependence of friction and wear were in agreement with circular translation pin-on-disk (CTPOD) results [13]. The CTPOD tests with constant load and constant velocity along a circular track resulted in considerably higher μ values, though, so that μ was 0.3 at 4 °C, 15 °C and 20 °C, and 0.13 at 37 °C [13]. It is likely that in the present dynamic test conditions, lubricant ingress to the flat-on-flat contact was facilitated and friction reduced, especially because the load often dropped to low values. In a multidirectional hip joint simulator wear and friction study, μ of VEXLPE acetabular cups against 40 mm diameter CoCr femoral heads was 0.070 ± 0.005 [20]. This value is between the mean mode μ values measured at 20 °C and 37 °C in the present study. In summary, it can be stated that hypothesis 1 was supported by the results whereas hypothesis 2 was not.

5. Conclusions

Multidirectional, noncyclic pin-on-disk tests showed that the coefficient of friction of VEXLPE against CoCr in serum at body temperature was 55% lower than that of UHMWPE. The difference was statistically significant. Clinically, a lower coefficient of friction would result in lower contact temperatures and less heat induced denaturation of synovial fluid proteins. For both materials, the lowest mean friction and wear values were obtained at body temperature. Since the present tests were dynamic, the coefficients of friction were lower than those produced earlier with constant load and constant velocity (CTPOD). At every temperature studied the VEXLPE wear was lower than that of UHMWPE, apparently because of extensive cross-linking of VEXLPE by a gamma dose of 100 kGy that is known to improve the wear resistance. Burnished appearance of worn polyethylene surfaces was in agreement with observations from clinically retrieved acetabular cups.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The study was funded by Aalto University. This research did not

receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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