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Effect of type of contact, counterface surface roughness and contact area on the wear and friction of extensively cross-linked, vitamin E stabilized UHMWPE

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Abstract

Novel extensively cross-linked, vitamin E stabilized polyethylene (VEXLPE) materials are expected to provide improved wear and oxidation resistance in orthopaedic implants. Noncyclic, multidirectional pin-on-disk (POD) wear tests were performed for VEXLPE with flat-on-flat (FoF) and ball-on-flat (BoF) specimen configurations against CoCr counterfaces of varying surface roughness (S_a = 0.02 µm to 0.74 µm). In addition, wear tests (FoF) were performed for VEXLPE pins of varying nominal contact area (7.07 mm^2 to 113 mm^2) with consistent load regimen against polished CoCr disks. All specimen couples were also friction tested with a multidirectional, circularly translating POD device. In all tests, calf serum was used as the lubricant. In comparison with earlier, similar tests for conventional, gamma-sterilized ultra-high molecular weight polyethylene (UHMWPE) and for extensively cross-linked, heat treated UHMWPE (XLPE), the tribological findings for the present VEXLPE appeared promising with respect to its possible clinical use in prosthetic joints, particularly as an acetabular liner against large-diameter femoral heads, and in non-conforming contacts. Contrary to the well-known, paradoxical behavior of conventional UHMWPE, the VEXLPE wear factor decreased with increasing contact area.

Keywords: biomedical devices; extensively cross-linked UHMWPE; vitamin E stabilization; noncyclic pin-on-disk

INTRODUCTION

Extensively cross-linked UHMWPE (XLPE), with various post-irradiation thermal treatments, has been shown to markedly improve the in vivo wear resistance in orthopaedic implants compared with conventional, gamma-sterilized UHMWPE.[1] XLPE may be susceptible to in vivo oxidation, however.[2] Novel extensively cross-linked, vitamin E stabilized UHMWPE (VEXLPE) materials are expected to provide superior oxidation resistance compared with XLPE and superior wear resistance compared with conventional UHMWPE.[3–8] Vitamin E hampers crosslinking, and so with a similar gamma irradiation dose the wear of VEXLPE is likely to be somewhat higher than that of XLPE.[9,10] VEXLPE may be used with a conforming contact (hip replacement) and with a non-conforming contact (knee replacement).[6,7] Metallic counterfaces of UHMWPE prosthetic joint components are sometimes roughened in vivo for various reasons, such as dislocation or third body action by bone cement particles.[11–15] Therefore, it is essential to study the UHMWPE wear behavior under abrasive conditions since the wear rate may increase manyfold.[16,17] Wear particles in large amounts are known to cause osteolysis and implant loosening.[18] The inflammatory response to VEXLPE particles is not significantly different from that to conventional UHMWPE particles.[5]

It has also been found that the clinical wear rate of conventional UHMWPE acetabular cups and liners increases with increasing diameter of the femoral head.[19,20] This indicates that a larger contact area is disadvantageous with respect to the wear rate with conventional UHMWPE.[21,22] The presence of vitamin E does not appear to affect friction.[23] The purpose of the present study was to provide an extensive evaluation of the tribological behavior of a high dose gamma-irradiated (100 kGy), extensively cross-linked VEXLPE with conforming and non-conforming contacts, varying contact area and against a range of counterface surface roughnesses. Such basic studies for VEXLPE are scarce in literature. It was hypothesized that (1) against counterfaces of varying roughness, the VEXLPE wear factor is between those of conventional, gamma-sterilized UHMWPE and XLPE, (2) the VEXPLE wear factor increases with increasing contact area, and (3) the frictional behavior of VEXLPE is similar to that of conventional UHMWPE.

MATERIALS AND METHODS

The computer-controlled, 16-station, multidirectional RandomPOD device and wear test method have been described in detail elsewhere.[24,25] The basic idea was that the relative motion and load between the pin and the disk were noncyclic in order to mimic real life variation. The average sliding velocity was 15.5 mm/s (range 0 to 31.4 mm/s) and the average load was 73 N (range 0 to 142 N). The lubricant was HyClone Alpha Calf Fraction serum SH30212.03 (GE Healthcare Lifesciences, HyClone Laboratories, Inc., South Logan, UT, USA), diluted 1:1 with ultrapure, deionized water, as recommended in the ISO 14242-1 standard.[26] The suitability of this serum for wear testing of orthopaedic implant materials is based on its stability against protein precipitation.[27] The protein concentration of the lubricant was 20 mg/ml, close to that of joint fluid of prosthetic joints.[28] In order to retard microbial growth and protein denaturation, the lubricant bulk temperature was kept at 20 °C.[29] The UHMWPE specimens were made from vitamin-E-stabilized, gamma-irradiated (100 kGy) GUR 1020-E (ASTM F648, ISO 5834-1,2, ASTM F2695, ASTM F2565). This extensively cross-linked material (0.1% blended alpha tocopherol, post-consolidation irradiated, no post-irradiation thermal treatment) is hereafter abbreviated as VEXLPE. Its counterface was CoCr (ISO 5832-12). Two types of specimen configurations, flat-on-flat (FoF) and ball-on-flat (BoF) (Fig. 1), were included in the following test programme (Table 1).

Wear test no. 1 (FoF): cylindrical VEXLPE pins of 9.0 mm diameter against CoCr disks.[24] Multidirectional roughening of the CoCr disks was achieved by emery papers with grit sizes of 1000, 400, 240 and 120 (n = 4).[30] The arithmetical mean surface roughness S_a of the disks varied from 0.11 µm to 0.62 µm. The surface roughnesses were measured with a white light interferometry profilometer as described in.[30] Similar FoF tests against polished disks with S_a = 0.01 µm (n = 4) were carried out earlier.[32]

Wear test no. 2 (BoF): CoCr pins with a spherical end (radius = 28 mm) against VEXLPE disks.[25] The pins were either polished (S_a = 0.02 µm to 0.05 µm) or roughened by emery papers with grit sizes of 1000, 240 and 120 (n = 4). The S_a value of the roughened pins varied from 0.10 µm to 0.74 µm

Wear test no. 3 (FoF): VEXLPE pins with contact diameters of 3.0 mm, 4.75 mm, 6.0 mm, 7.0 mm, 8.0 mm, 10.0 mm, 11.0 mm and 12.0 mm (n = 2) against polished CoCr disks. Since similar load was applied to each pin, the variation of nominal contact pressure was 16-fold (0.65 MPa to 10 MPa with the average load, 73 N). The nominal contact area A varied from 7.07 mm^2 to 113 mm^2.

The duration of each test was 660 h (sliding distance = 37 km). Wear was evaluated gravimetrically at intervals of 9.2 km on the average and linear regression was used to calculate the wear rate in mg/km.[24,25] The wear factor k could then be calculated since the product of the instantaneous load and incremental sliding distance was numerically integrated at a frequency of 100 Hz.[24] According to the manufacturer, the density of VEXLPE was 0.941 mg/mm^3.

Friction tests. After the three RandomPOD wear tests, friction tests were carried out for each of the 48 wear test couples, and for the 4 couples from an earlier wear study[32] mentioned above in the section 'Wear test no. 1 (FoF)', using a multidirectional CTPOD device designed for friction measurements.[31] A constant load of 73 N was used in these measurements to obtain the coefficient of friction μ. Each test was run until the friction signal became steady, which took 30 min at the most. The lubricant and its temperature were similar to those in the wear tests.

RESULTS

In the wear test no. 1 (FoF), there was a power relationship between k and S_a, $k = 1.27 \times 10^{-5} \times S_a^{0.56}$ ($R^2 = 0.8118$). In the wear test no. 2 (BoF) however, there was a negative correlation between k and S_a in the S_a range of 0.02 µm to 0.16 µm (Fig. 2). With higher S_a values, the power relationship was positive, $k = 1.42 \times 10^{-5} \times S_a^{1.88}$ ($R^2 = 0.8656$). Hence, in the wear tests no. 1 and 2, k was proportional close to the square root and square of S_a, respectively. In the wear test no. 3 (FoF), the relationship between k and A was bimodal (Fig. 3). With low A values, k increased with increasing A, but above $A = 28$ mm^2, k decreased with increasing A.

In the friction tests with specimens from wear test no. 1, μ was insensitive to S_a, whereas with specimens from the wear test no. 2, there was a linear correlation between μ and S_a (Fig. 4). In the friction tests with specimens from the wear test no. 3, μ increased with increasing A, but not steadily.

With low A values, protuberances with a typical height of 20 µm formed close to the edge of the contact surface of the pins, whereas with larger A values, the entire contact surface was flat and burnished (Fig. 5). The random characteristics of the slide track were easily distinguished from the wear marks on the VEXLPE disks (Fig. 6).

DISCUSSION

Noncyclic RandomPOD wear tests were carried out for VEXLPE against CoCr. The wear test no. 1 (FoF) consisted of cylindrical VEXLPE pins against CoCr disks with varying surface roughness. The wear test no. 2 (BoF) consisted of spherical-ended CoCr pins with varying surface roughness against VEXLPE disks. The wear test no. 3 (FoF) consisted of cylindrical VEXLPE pins with varying nominal contact area A against polished CoCr disks. Finally, all wear test couples were friction tested with a CTPOD device. In the light of clinical observations and pin-on-disk studies with conventional UHMWPE and XLPE,[19,20,33–35] the most surprising finding was that k decreased with increasing A (Fig. 3), with the exception of the three lowest A values with which protuberances, that are not seen clinically, occurred, most probably due to excessive contact pressure. The variation of A in the present study was inspired by a recent hip simulator observation regarding the dependence of the VEXLPE liner wear on the acetabular inclination angle.[36] Contrary to conventional UHMWPE, the VEXLPE liner showed a higher wear rate with a higher acetabular cup inclination angle, that is, with a smaller contact area. Since the femoral head diameter was 54 mm, the contact stresses were relatively low. This was in agreement with the present findings with large A values. In the hip simulator study with a 2.5 kN peak load, the mean contact areas at the end of the 2.7-million-cycle test were 1 200 mm^2 and 930 mm^2 with inclination angles of 45° and 65°, respectively.[36] It appears to be characteristic of the present VEXLPE in serum-lubricated, multidirectional, conforming contact tests that the wear rate and wear factor decrease with increasing contact area with low contact pressures. This may be considered beneficial regarding the possible use of the present VEXLPE against large-diameter femoral heads, which is the current trend in the arthroplasty of the hip in order to reduce the propensity to dislocation. The BoF wear factors in general were lower than the FoF wear factors, although the nonconforming contact has higher contact stresses with the same load. This could be a beneficial characteristic of VEXLPE with respect to its use in tibial inserts of prosthetic knees. Another surprising observation was the insensitivity of μ to S_a in the wear test no. 1 (FoF) (Fig. 4). Note however, that μ was relatively high over the entire range of S_a compared with Saikko.[33,34]

As the present wear results regarding the counterface surface roughness are compared with an earlier, similar study with a conventional, gamma-nitrogen-sterilized (25 to 40 kGy) UHMWPE ('Sulene-PE') and an electron-beam-irradiated (95 kGy) and melted (150 °C) XLPE ('Durasul'),[30] it can be stated that hypothesis (1) was supported by the results (Fig. 7). The result is logical since the extent of crosslinking of the present VEXLPE is likely to be between those of Sulene-PE and Durasul.[9] The resistance to abrasion of present VEXLPE appears to be sufficient for implant applications since catastrophic wear, such as wearing out of specimens, did not occur even against the roughest CoCr counterfaces. Hypothesis (2) was not supported, as k decreased with increasing A (with the exception of the three lowest A values, with which unrealistic protuberance formation occurred), and therefore VEXLPE substantially differed from unirradiated and gamma-sterilized UHMWPE[33,34] in this sense (Fig. 8). Hypothesis (3) was supported as μ increased with increasing A and the value was mostly between those of Sulene-PE and unirradiated UHMWPE. Note still that although the present tests were carried out so that all test conditions and methods would be as similar as possible to those of Saikko et al.[30], the two studies may not be directly comparable because they were not carried out simultaneously.

In a hip simulator (EndoLab) study against 36 mm alumina heads, VEXLPE (0.1% blended, 80 kGy electron-beam-irradiated), XLPE (75 kGy gamma-irradiated, remelted), and conventional UHMWPE (30 kGy gamma-irradiated) liners showed wear rates of 2.5 ± 0.5, 2.0 ±

0.3, and 19 ± 0.6 mg/10^6 cycles, respectively.[6] The wear ranking is similar to that of the present wear test no. 1 (FoF) results grouped together with Saikko et al.[30] (Fig. 7), but the difference between VEXLPE and XLPE in the hip simulator study is smaller, and the difference between VEXLPE and conventional UHMWPE is larger. This may be attributable to the different methods of crosslinking. In a knee simulator (EndoLab) study for a cruciate retaining, fixed bearing total knee arthroplasty design, VEXLPE (0.1% blended, 50 kGy electron-beam-irradiated) and conventional UHMWPE (30 kGy gamma-irradiated), artificially aged tibial inserts showed wear rates of 5.3 ± 0.9 and 12.4 ± 10.7 mg//10^6 cycles (before delamination), respectively.[7] The difference was similar to that of the present wear test no. 2 (BoF) results grouped together with Saikko et al.[30] (Fig. 7), although the specimens were not aged. In a bi-directional POD study, artificially aged VEXLPE (0.1% blended, 100 kGy gamma-irradiated) and XLPE (100 kGy gamma-irradiated and melted) showed wear rates of 2.1 ± 0.2 and 1.7 ± 0.3 mg/10^6 cycles, respectively.[9] It was concluded that the higher wear of VEXLPE was caused by the lower cross-link density.[9]

Protuberances observed with the three lowest *A* values were apparently caused by creep (Fig. 5). A shear stress due to friction was added to the high contact pressure, and because of the random motion, the entire edge was the leading edge, that endured the highest stresses, at times. Protuberances are not seen clinically.[19] Therefore, they may be considered a test artefact caused by excessive contact pressure. They probably enhanced lubricant ingress and consequently reduced wear, and were responsible for the anomalous wear and friction behavior with the three lowest *A* values. They have been observed earlier with unirradiated UHMWPE and conventional, gamma-sterilized UHMWPE with nominal contact pressures above 2 to 3 MPa.[31,33,34] It was therefore recommended that in POD studies the critical contact pressure of 2 to 3 MPa should not be exceeded. Based on the present tests, the same rule applies to VEXLPE. With nominal contact pressures below 2.6 MPa (with the average load of 73 N), a burnished appearance with mild criss-cross scratches dominated and resembled that of retrieved polyethylene acetabular cups.[19] With roughened counterfaces, the wear marks were the coarser the higher the CoCr S_a value was (Fig. 6).

It is recognized as a limitation of the study that the test device was a pin-on-disk machine, not a joint simulator for the testing of actual joint implants. It has nevertheless been shown in earlier papers that the FoF specimen configuration produces a realistic simulation of the wear mechanisms of a total hip prosthesis (conforming contact).[24,37] The BoF specimen configuration may be used to reproduce wear mechanisms of joints with a non-conforming contact, such as the total knee prosthesis, because the contact stress field continually moves multidirectionally relative to the polyethylene disk.[25,37] The RandomPOD motion was more multidirectional than the typical relative motion in prosthetic knees.[7] Hence, the RandomPOD test with the BoF specimen configuration was probably adverse condition testing in this sense because the conventional UHMWPE wear rate is known to increase with increasing multidirectionality of the relative motion.[38] Whether this applies similarly to VEXLPE is yet to be shown. Multidirectionality and serum lubrication are the two general prerequisites for a realistic reproduction of clinical wear mechanisms.[38] Pin-on-disk tests are a part of material-specific basic biotribology research, whereas joint simulator tests complement the research by being design-specific. In the former, the unparalleled capacity, up to 100 simultaneous tests with one machine,[39,40] is the main advantage, together with the low cost of testing. In a joint simulator, design-specific features such as the wear of the taper fixation of the femoral head and the backside wear of the UHMWPE liner can be studied in addition to the bearing surfaces.[41,42]

CONCLUSIONS

VEXLPE was wear and friction tested with conforming and non-conforming contacts against CoCr counterfaces with varying surface roughness. Conforming contact tests were also performed with varying nominal contact area against polished CoCr. The VEXLPE wear factor was lower than that of conventional, gamma-sterilized UHMWPE, but higher than that of 95 kGy electron-beam-irradiated and melted XLPE. The conventional UHMWPE and XLPE were studied earlier with the same POD device and test parameters. With conforming contact, the wear factor decreased with increasing contact area, with the exception of the smallest nominal contact areas that showed protuberances not seen clinically, probably caused by excessive contact pressure. Compared with conventional UHMWPE, the improved wear resistance due to extensive cross-linking of the present VEXLPE was promising with respect to its possible clinical use in prosthetic joints, particularly as an acetabular liner against large-diameter femoral heads, and in non-conforming contacts.

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REFERENCES

1. de Steiger R, Lorimer M, Graves SE. Cross-linked polyethylene for total hip arthroplasty markedly reduces revision surgery at 16 years. J Bone Joint Surg 2018;100-A:1281–1288. https://doi.org/10.2106/JBJS.17.01221.
2. Currier BH, Currier JH, Collier JP, Mayor MB, Van Citters DW. In vivo oxidation of highly cross-linked UHMWPE bearings. 56th Annual Meeting of the Orthopaedic Research Society, paper no. 170. New Orleans, LA, USA, March 6–9, 2010.
3. Oral E, Christensen SD, Malhi AS, Wannomae KK, Muratoglu OK. Wear resistance and mechanical properties of highly cross-linked, ultrahigh–molecular weight polyethylene doped with vitamin E. J Arthroplasty 2006;21:580–591. https://doi.org/10.1016/j.arth.2005.07.009.
4. Uetsuki K, Sugimoto T, Turner AC, Tomita N. Controversial effects of blending vitamin-E with UHMWPE on the wear resistance of hip and knee prostheses. 58th Annual Meeting of the Orthopaedic Research Society, poster no. 1074. San Francisco, CA, USA, February 4–7, 2012.
5. Popoola OO, Orozco Villasenor DA, Fryman JC, Mimnaugh K, Rufner A. High cycle *in vitro* hip wear of and *in vivo* biological response to vitamin E blended highly cross-linked polyethylene. Biotribol 2018;16:10–16. https://doi.org/10.1016/j.biotri.2018.09.001.
6. Grupp TM, Holderied M, Mulliez MA, Streller R, Jäger M, Blömer W, Utzschneider S. Biotribology of a vitamin E-stabilized polyethylene for hip arthroplasty – Influence of artificial aging and third-body particles on wear. Acta Biomater 2014;10:3068–3078. https://doi.org/10.1016/j.actbio.2014.02.052.
7. Grupp TM, Fritz B, Kutzner I, Schilling C, Bergmann G, Schwiesau J. Vitamin E stabilised polyethylene for total knee arthroplasty evaluated under highly demanding activities wear simulation. Acta Biomater 2017;48:415–422. https://doi.org/10.1016/j.actbio.2016.10.031.
8. Smelt H, Siskey R, Baxter J, Stijkel L, Fuller B, Schuman D, et al. 24 weeks accelerated aging study for HALS and vitamin E stabilized 100 kGy irradiated UHMWPE. 6th UHMWPE International Meeting. Turin, Italy, October 10–11, 2013.

9. Oral E, Greenbaum ES, Malhi AS, Harris WH, Muratoglu OK. Characterization of irradiated blends of α-tocopherol and UHMWPE. Biomater 2005;26:6657–6663. https://doi.org/10.1016/j.biomaterials.2005.04.026.
10. Herrera L, Korduba LA, Essner A, Yau SS, Lovell TP. The effect of vitamin E on the wear resistance of highly cross-linked polyethylene. Orthop Proc 2010;92-B Supp 1:139.
11. Sychterz CJ, Engh CA Jr, Swope SW, McNulty DE, Engh CA. Analysis of prosthetic femoral heads retrieved at autopsy. Clin Orthop Relat Res 1999;358:223–234.
12. Mai KT, Verioti C, D'Lima D, Colwell CW Jr, Ezzet KA. Surface roughness of femoral head prostheses after dislocation. Am J Orthop 2010;39:495–500.
13. Ito H, Maloney CM, Crowninshield RD, Clohisy JC, McDonald DJ, Maloney WJ. In vivo femoral head damage and its effect on polyethylene wear. J Arthroplasty 2010;25:302–308. https://doi.org/10.1016/j.arth.2009.01.010.
14. Scholes SC, Kennard E, Gangadharan R, Weir D, Holland J, Deehan D, Joyce TJ. Topographical analysis of the femoral components of ex vivo total knee replacements. J Mater Sci Mater Med 2013;24:547–554. https://doi.org/10.1007/s10856-012-4815-z.
15. Kennard E, Scholes SC, Sidaginamale R, Gangadharan R, Weir DJ, Holland J, Deehan D, Joyce TJ. A comparative surface topographical analysis of explanted total knee replacement prostheses: Oxidised zirconium vs cobalt chromium femoral components. Med Eng Phys 2017;50:59–64. https://doi.org/10.1016/j.medengphy.2017.10.003.
16. Wang A, Polineni VK, Stark C. Dumbleton JH. Effect of femoral head surface roughness on the wear of ultra-high molecular weight acetabular cups. J Arthroplasty 1998;13:615–620.
17. Muratoglu OK, Burroughs BR, Bragdon CR, Christensen S, Lozynsky A, Harris WH. Knee simulator wear of polyethylene tibias articulating against explanted rough femoral components. Clin Orthop Relat Res 2004;428:108–113.
18. Harris WH. Wear and periprosthetic osteolysis – the problem. Clin Orthop Relat Res 2001;393:66–70.
19. Jasty M, Goetz DD, Bragdon CR, Lee KR, Hanson AE, Elder JR, Harris WH. Wear of polyethylene acetabular components in total hip arthroplasty. An analysis of one hundred and twenty-eight components retrieved at autopsy or revision operations. J Bone Joint Surg 1997;79-A:349–358.

20. Haw JG, Battenberg AK, Huang D-CT, Schmalzried TP. Wear rates of larger-diameter cross-linked polyethylene at 5 to 13 years: does liner thickness or component position matter? J Arthroplasty 2017;32:1381–1386. https://doi.org/10.1016/j.arth.2016.11.022.
21. Wang A, Essner A, Klein R. Effect of contact stress on friction and wear of ultra-high molecular weight polyethylene in total hip replacement. Proc Instn Mech Eng H: J Eng Med 2001;215:133–139. https://doi.org/10.1243/0954411011533698.
22. Korduba LA, Essner A, Pivec R, Lancin P, Mont MA, Wang A, Delanois RE. Effect of acetabular cup abduction angle on wear of of ultrahigh-molecular-weight polyethylene hip simulator testing. Am J Orthop (Belle Mead NJ) 2014 Oct;43:466–471.
23. Turner A, Okubo Y, Teramura S, Niwa Y, Ibaraki K, Kawasaki T, Hamada D, Uetsuki K, Tomita N. The antioxidant and non-antioxidant contributions of vitamin E in vitamin E blended ultra-high molecular weight polyethylene for total knee replacement. J Mech Behav Biomed Mater 2014;31:21–30. https://doi.org/10.1016/j.jmbbm.2012.12.006.
24. Saikko V, Kostamo J. RandomPOD—a new method and device for advanced wear simulation of orthopaedic biomaterials. J Biomech 2011;44:810–814. https://doi.org/10.1016/j.jbiomech.2010.12.024.
25. Saikko V. In vitro wear simulation on the RandomPOD wear testing system as a screening method for bearing materials intended for total knee arthroplasty. J Biomech 2014;47:2774–2778. https://doi.org/10.1016/j.jbiomech.2014.04.039.
26. ISO 14242-1. Implants for surgery — Wear of total hip-joint prostheses — Part 1: Loading and displacement parameters for wear-testing machines and corresponding environmental conditions for test. International Organization for Standardization, Geneva, Switzerland, 2014.
27. Brandt J-M, Charron K, Zhao K, MacDonald SJ, Medley JB. Calf serum constituent fractions influence polyethylene wear and microbial growth in knee simulator testing. Proceedings of the Institution of Mechanical Engineers H: Journal of Engineering in Medicine 2012;226:427–440. https://doi.org/10.1177/0954411912444248.
28. Yao JQ, Laurent MP, Gilbertson LN, Blanchard CR, Crowninshield RD, Jacobs JJ. A comparison of biological lubricants to bovine calf serum for total joint wear testing. 48th Annual Meeting of the Orthopaedic Research Society, poster no. 1004. Dallas, TX, USA, February 10–13, 2002.

29. Saikko V. Effect of lubrication conditions on the wear of UHMWPE with noncyclic motion and load. Tribology Transactions 2018;61:1141–1150. https://doi.org/10.1080/10402004.2018.1506071.
30. Saikko V, Vuorinen V, Revitzer H. Effect of CoCr counterface roughness on the wear of UHMWPE in the noncyclic RandomPOD simulation. J Tribol 2017;139:021606. https://doi.org/10.1115/1.4033648.
31. Saikko V. Effect of contact pressure on wear and friction of ultra-high molecular weight polyethylene in multidirectional sliding. Proc Instn Mech Eng H: J Eng Med 2006;220:723–731. https://doi.org/10.1243/09544119JEIM146.
32. Saikko V. Effect of serum dilution fluids on the wear of unirradiated and high dose gamma-irradiated, vitamin E stabilized UHMWPE. Wear 2019:430–431:76–80. https://doi.org/10.1016/j.wear.2019.04.022.
33. Saikko V. Effect of contact area on the wear and friction of UHMWPE in circular translation pin-on-disk tests. J Tribol 2017;139:061606. https://doi.org/10.1115/1.4036448.
34. Saikko V. Effect of contact area on the wear of ultrahigh molecular weight polyethylene in noncyclic pin-on-disk tests. Tribol Int 2017;114:84–87. https://doi.org/10.1016/j.triboint.2017.04.020.
35. Kandemir G, Smith S, Joyce TJ. The influence of contact stress on the wear of cross-linked polyethylene. Proc Instn Mech Eng H: J Eng Med 2018;232:1008–1016. https://doi.org/10.1177/0954411918796047.
36. Saikko V. Wear and friction of thin, large-diameter acetabular liners made from highly cross-linked, vitamin-E-stabilized UHMWPE against CoCr femoral heads. Wear 432–433, 242948. https://doi.org/10.1016/j.wear.2019.202948.
37. Saikko V, Vuorinen V, Revitzer H. Analysis of UHMWPE wear particles produced in the simulation of hip and knee wear mechanisms with the RandomPOD system. Biotribol 2015;1–2:30–34. https://doi.org/10.1016/j.biotri.2015.03.002.
38. Wang A, Stark C, Dumbleton JH. Mechanistic and morphological origins of ultra-high molecular weight polyethylene wear debris in total joint replacemant prostheses. Proc Instn Mech Eng H: J Eng Med 1996;210:141–155. https://doi.org/10.1243/PIME_PROC_1996_210_407_02.

39. Baykal D, Siskey RS, Underwood RJ, Briscoe A, Kurtz SM. The biotribology of PEEK-on-HXLPE bearings is comparable to traditional bearings on a multidirectional pin-on-disk tester. Clin Orthop Relat Res 2016;474:2384–2393. https://doi.org/10.1007/s11999-016-4989-7.
40. Baykal D, Siskey RS, Haider H, Saikko V, Ahlroos T, Kurtz SM. Advances in tribological testing of artificial joint biomaterials using multidirectional pin-on-disk testers. Journal of the Mechanical Behavior of Biomedical Materials 2014;31:117–134. https://doi.org/10.1016/j.jmbbm.2012.12.020.
41. Bhalekar RM, Smith SL, Joyce TJ. Wear at the taper-trunnion junction of contemporary ceramic-on-ceramic hips shown in a multistation hip simulator. J Biomed Mater Res B 2019;107:1199–1209. https://doi.org/10.1002/jbm.b.34213.
42. Scott DL, Campbell PA, McClung CD, Schmalzried TP. Factors contributing to rapid wear and osteolysis in hips with modular acetabular bearings made of Hylamer. J Arthroplasty 2000;15:35–46. https://doi.org/10.1016/S0883-5403(00)91103-3.

Table 1. Summary of tests.

Type of test	No.	Device	Type of contact	No. of couples	Pin material	Disk material	Variable	n
Wear	1	RandomPOD	flat-on-flat (FoF)	16	VEXLPE	CoCr	CoCr roughness	4
Wear	2	RandomPOD	ball-on-flat (BoF)	16	CoCr	VEXLPE	CoCr roughness	4
Wear	3	RandomPOD	FoF	16	VEXLPE	CoCr	Pin contact area	2
Friction		CTPOD	FoF, BoF	52*	VEXLPE, CoCr	CoCr, VEXLPE	Roughness, area	4, 2

*All 48 wear test couples and 4 couples from an earlier wear study (9.0 mm pin diameter, polished disk, DW diluent).[32]

Figure captions

Figure 1. Forty-eight VEXLPE and CoCr specimens used in RandomPOD tests, (a) wear test no. 1 (FoF) with 9.0 mm diameter VEXLPE pins and varying CoCr disk surface roughness, (b) wear test no 2. (BoF) with VEXLPE disks and varying CoCr pin surface roughness, and (c) wear test no. 3 (FoF) with varying VEXLPE pin contact surface diameter and polished CoCr disks. Contact surface of pins is turned upwards. In (a) and (b), CoCr surface roughness increases from back to front row. After wear tests, all 48 couples were friction tested with CTPOD.

Figure 2. Variation of VEXLPE wear factor with CoCr counterface surface roughness using flat-on-flat and ball-on-flat contacts in noncyclic RandomPOD tests. Lubricant was alpha calf serum diluted 1:1 with DW. FoF wear factors with polished disks (S_a = 0.01 µm) from Saikko.[32]

Figure 3. Variation of VEXLPE wear factor and coefficient of friction mean values with contact area against polished CoCr (n = 2). Wear factor with A = 63.6 mm^2 (n = 4) from Saikko.[32] Burnishing is clinically relevant, whereas protuberances are not.

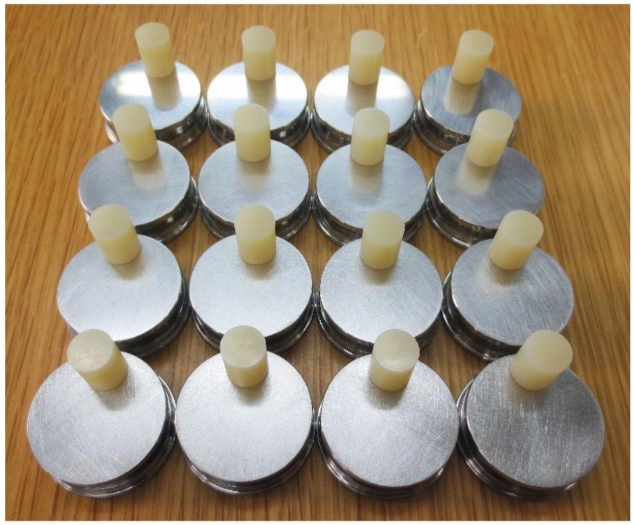
Figure 4. Variation of VEXLPE/CoCr coefficient of friction with CoCr counterface surface roughness in CTPOD tests.

Figure 5. Optical micrographs of worn VEXLPE pins with contact diameters of (a) 3.0 mm, (b) 4.75 mm, (c) 6.0 mm, (d) 7.0 mm, (e) 8.0 mm, (f) 9.0 mm (from Saikko[32]), (g) 10.0 mm, (h) 11.0 mm, and (i) 12.0 mm. Counterface was polished CoCr. Note protuberance formation on (a) to (c), and flat topography with no orientation on (d) to (i).

Figure 6. Optical micrographs of VEXLPE disks worn against spherical CoCr pins with counterface surface roughness S_a = 0.05 µm (a) and 0.35 µm (b). Note fine criss-cross scratches on burnished surface on (a) and randomly directed, curved, coarse wear tracks on (b).

Figure 7. Present k vs. S_a power relationships for VEXLPE compared with those of Sulene-PE (conventional, 25 to 40 kGy gamma-sterilized UHMWPE) and Durasul (95 kGy electron beam irradiated and melted XLPE) observed in similar RandomPOD test conditions, Saikko et al.[30]

Figure 8. Present k vs. A (RandomPOD) and μ vs. A (CTPOD) linear relationships for VEXLPE compared with Sulene-PE and unirradiated UHMWPE observed in similar test conditions, Saikko.[33,34]



a

b

c

Figure 1

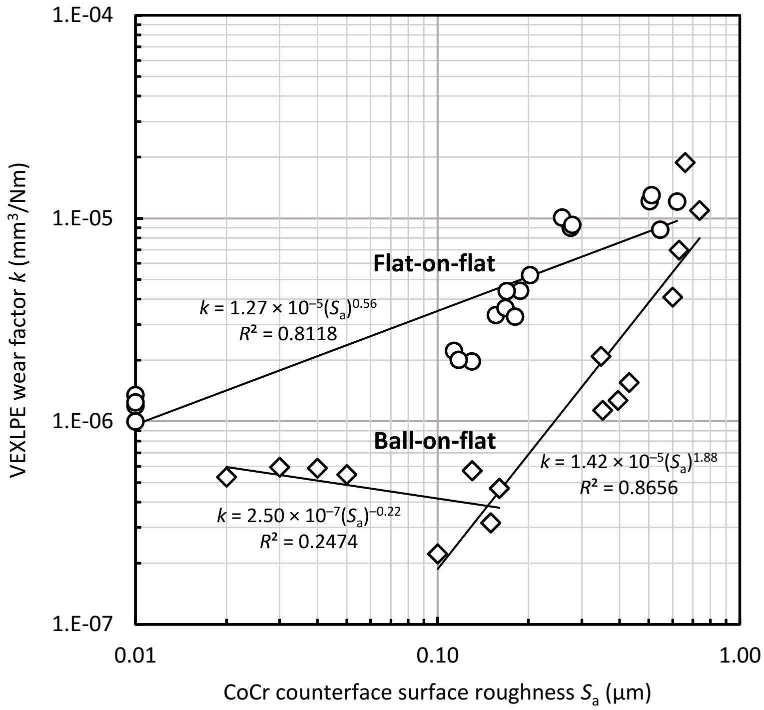


Figure 2

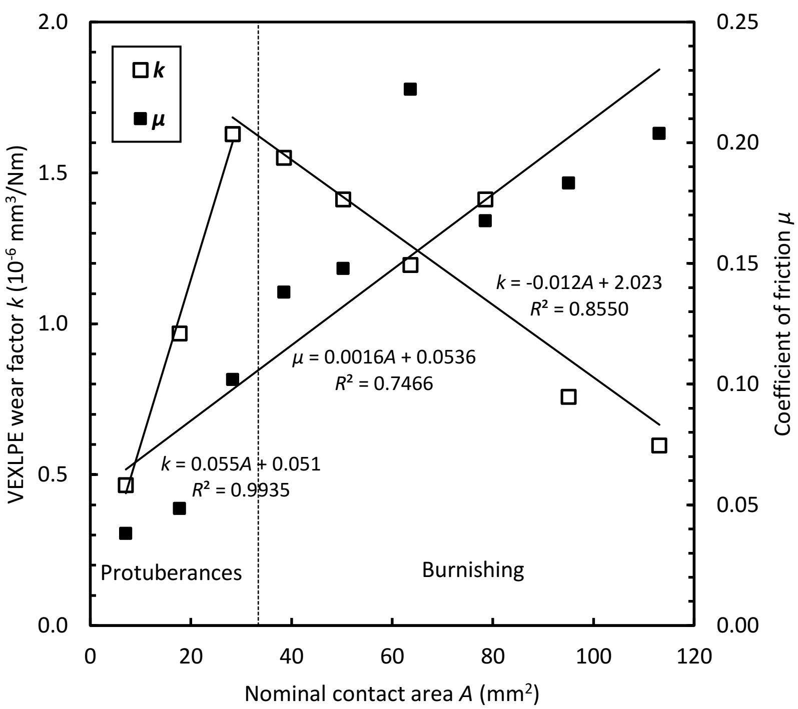
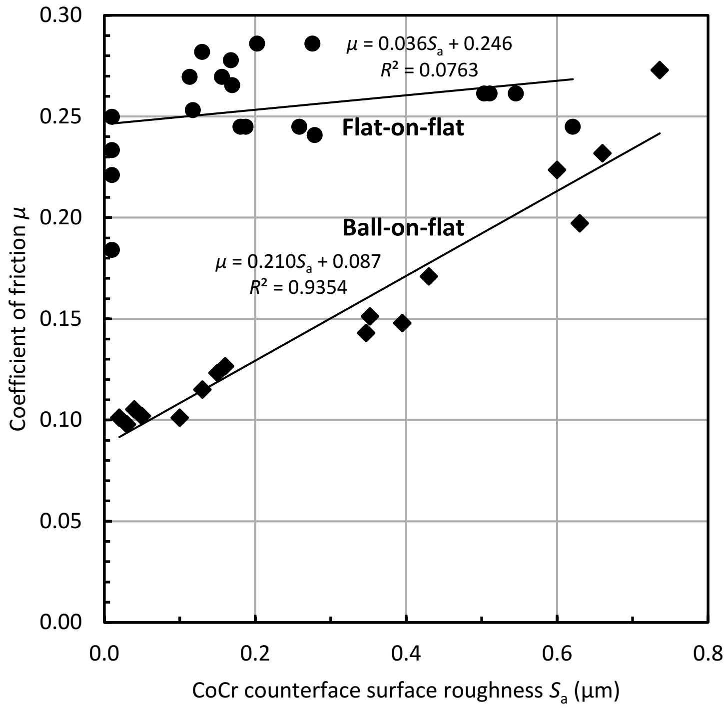


Figure 3



0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
Coefficient of friction μ
CoCr counterface surface roughness S_a (μm)
$\mu = 0.036S_a + 0.246$
$R^2 = 0.0763$
Flat-on-flat
Ball-on-flat
$\mu = 0.210S_a + 0.087$
$R^2 = 0.9354$

Figure 4

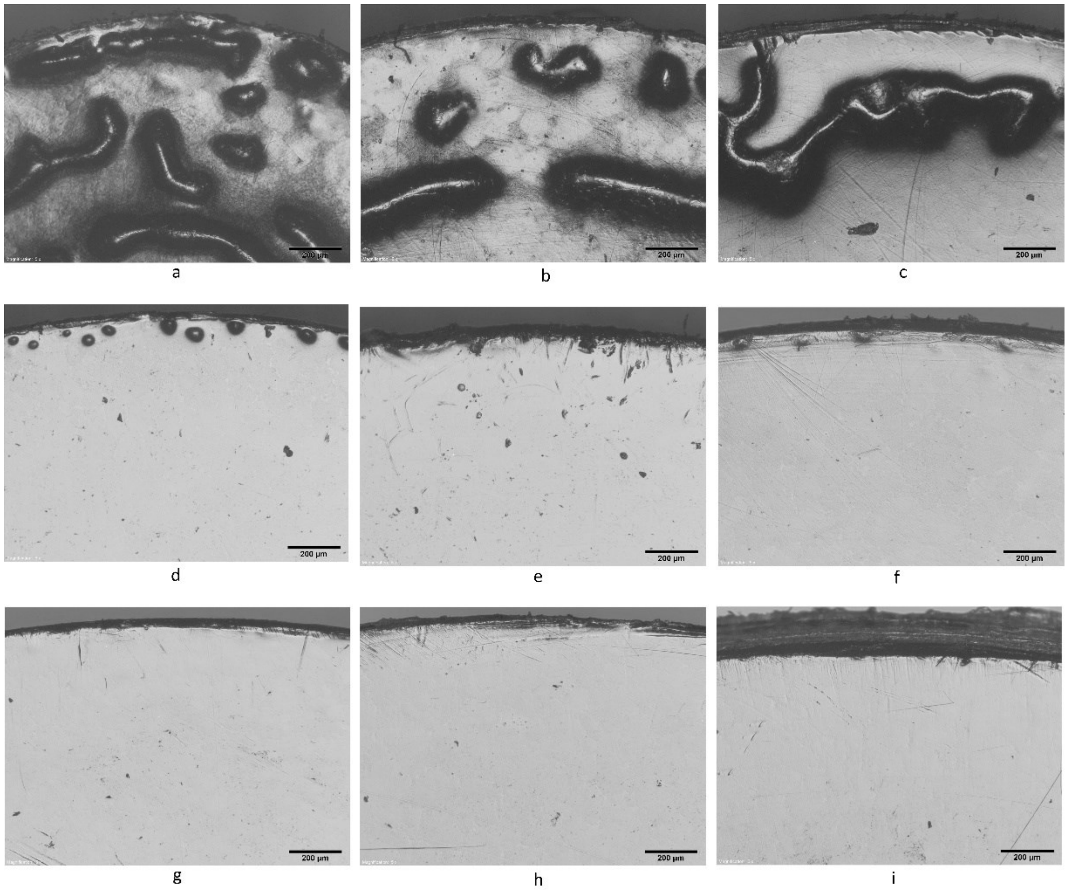


Figure 5

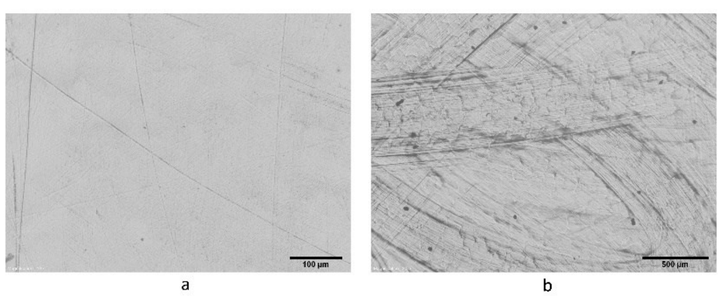


Figure 6

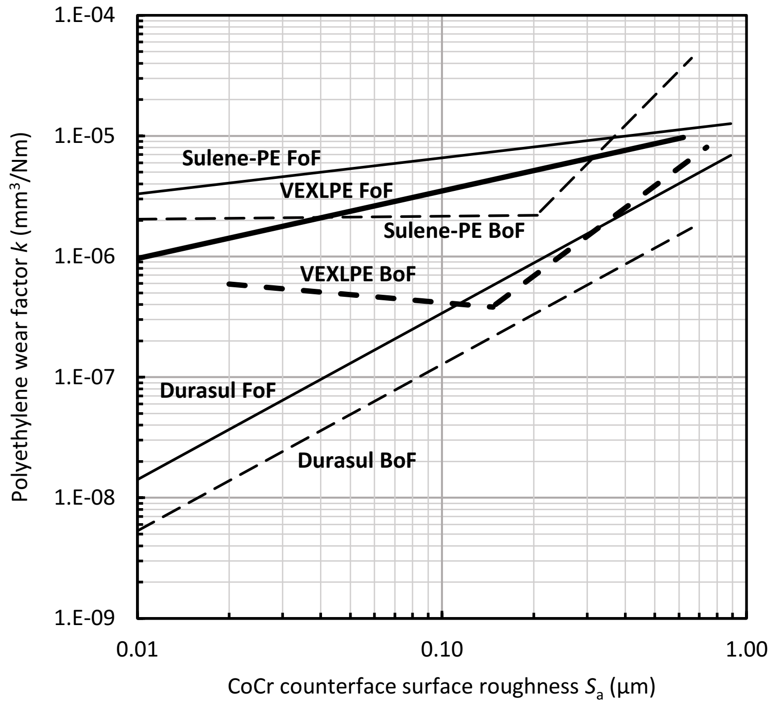


Figure 7

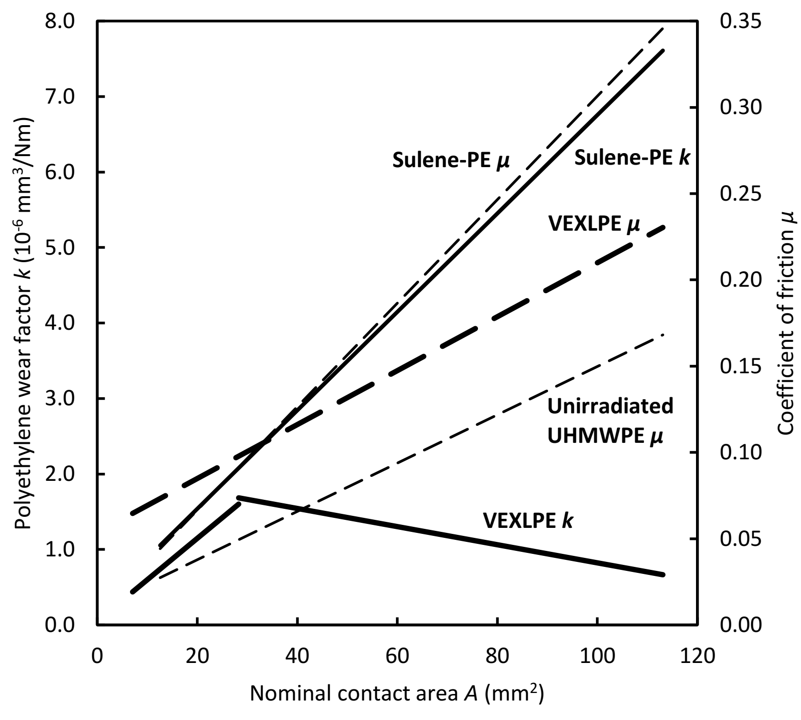


Figure 8