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Vesa Saikko

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Wear and friction of thin, large-diameter acetabular liners made from highly cross-linked, vitamin-E-stabilized UHMWPE against CoCr femoral heads

Vesa Saikko

Aalto University School of Engineering
Finland

Vesa Saikko, PhD

Aalto University School of Engineering
Department of Mechanical Engineering
PO Box 14300
FI-00076 Aalto
Finland

vesa.saikko@aalto.fi

+358 50 355 1757

Abstract

The experience of hip resurfacing with an ultra-high molecular weight polyethylene (UHMWPE) acetabular cup in the 1970s and 1980s was disappointing, partly because of the inadequate material properties of UHMWPE at the time. The use of state-of-the-art, vitamin-E-stabilized, highly cross-linked polyethylene, VEXLPE, should improve implant survivorship due to its advanced wear and oxidation resistance. Experimental, metal-backed VEXLPE liners of 4.0 mm thickness were wear and friction tested against 54 mm diameter CoCr femoral heads. The tests were conducted in a multidirectional hip joint simulator with an optimal (45°) and a high (65°) abduction angle of the acetabular component. Calf serum was used as the lubricant. The VEXLPE liners showed reasonable wear and friction behavior. The wear was linear with wear rates of $8.5 \pm 0.6 \text{ mg}/10^6 \text{ cycles}$ and $12.9 \pm 0.3 \text{ mg}/10^6 \text{ cycles}$ at 45° and 65° abduction, respectively. Before the wear test, the frictional torque with both positions was $3.6 \pm 0.3 \text{ Nm}$, and after the wear test, the frictional torques with 45° and 65° abduction were $2.6 \pm 0.3 \text{ Nm}$ and $2.4 \pm 0.6 \text{ Nm}$, respectively. The mean wear rate was 1.9-fold lower than that of a conventional total hip prosthesis, whereas the mean frictional torque was 1.7-fold higher.

Keywords: prosthetic design; vitamin E stabilization; cross-linked UHMWPE; hip resurfacing; hip simulator

1. Introduction

Hip resurfacing has benefits over total hip replacement, such as preservation of femoral bone, more natural stress transfer to the femur, and improved stability against dislocation due to the large diameter of the femoral head, 36 mm to 54 mm [1]. Metal-on-metal hip resurfacing has failed in the large scale, mostly because of unacceptable levels of metal release [2]. A high abduction (inclination) angle of the acetabular cup is one of the known exacerbating factors in metal-on-metal failure [3,4]. A steep position of the cup markedly changes the contact mechanics and lubrication mechanisms [5]. Attempts using metal-on-polyethylene resurfacing in the 1970s and 1980s failed, partly due to inadequate wear and oxidation resistance of the ultra-high molecular weight polyethylene (UHMWPE) used at the time [1]. UHMWPE wear particles in large amounts are known to cause osteolysis and implant loosening [6]. However, in total hip arthroplasty with head diameters from 22 mm to 32 mm, wear-particle-induced osteolysis rarely occurs if the wear rate is below 0.1 mm/year or 50 mm³/year [7]. Also, severe oxidation may cause a catastrophic loss of strength and consequently delamination and fracture of the UHMWPE component [8]. Recent advances in UHMWPE technology have revived the alternative of hip resurfacing with a polyethylene liner. State-of-the-art, highly cross-linked polyethylene (XLPE) materials provide substantially improved wear resistance [9–14]. For example, the wear rate of irradiated UHMWPE in a hip simulator decreased steeply with increasing dose of gamma irradiation used for cross-linking [15]. Vitamin E stabilization is also expected to provide permanent protection against the in vivo oxidation [16] that occurred in earlier cross-linked materials subjected to various heat treatments for eliminating free radicals [17]. The wear of UHMWPE cups does not become catastrophic with a high abduction angle of the cup [18,19], providing another significant advantage compared with metal-on-metal articulation and indicating that the lubrication is not altered to a high degree. Moreover, the metal release

from a CoCr-on-UHMWPE articulation is significantly lower compared with that of CoCr-on-CoCr [20–22]. On the other hand, the large diameter may be a disadvantage, because UHMWPE wear in vivo and friction in vitro have been shown to increase with the femoral head diameter [19,23–26]. A larger head leads to a larger contact area and probably more asperity contacts; therefore, there is an increase in wear particle production. However, the literature shows that the beneficial effect of cross-linking is stronger than the negative effect of the larger diameter. High friction may cause detrimental frictional heating above 40 °C [27], place at risk the fixation of the acetabular component [28], and exacerbate the wear of the taper fixation at the femoral head [29]. The objective of the present study was to provide a useful evaluation of the in vitro wear and friction behavior of a thin, large-diameter experimental liner that was made from highly cross-linked, vitamin-E-stabilized UHMWPE against CoCr. To this end, tests used an established, multidirectional hip joint simulator. It was hypothesized that the liner shows (1) a lower wear rate but (2) a higher frictional torque compared with a conventional total hip prosthesis with a typical head diameter of 28 or 32 mm and an UHMWPE cup or liner that is unirradiated or gamma-irradiation-sterilized (25 to 40 kGy).

2. Materials and Methods

The study used an anatomic hip joint simulator HUT-4 as described elsewhere [30]. Briefly, the femoral head was subjected to a biaxial, sinusoidal oscillation so that the flexion-extension (range 46°) had a phase shift of $\pi/2$ relative to the abduction-adduction (range 12°). Hence, the relative motion was multidirectional. The test frequency was 1.06 Hz. The dynamic load of a double-peak profile (max. 2.5 kN) was applied vertically on the acetabular component that was self-centering on top of the femoral head (Fig. 1a). The joint was immersed in the lubricant, 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 [31]. The protein concentration of the lubricant was 20 mg/ml. Each lubricant chamber contained 450 ml of lubricant (Fig. 1b). The tests were run at room temperature to retard microbial growth and protein denaturation.

Figure 1. (a) Metal-backed VEXLPE liner of 4.0 mm thickness at 45° abduction angle and 54 mm diameter CoCr head installed in HUT-4 hip joint simulator. (b) Acrylic lubricant chamber filled with 450 ml of alpha calf serum diluted 1:1 with deionized water.

The hemispherical acetabular liner had an inner diameter of 54.5 mm and a thickness of 4.0 mm. It was 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. The liner was metal backed to fit into a stainless-steel holder. The rim was fully supported. The liner and its holder formed an experimental equivalent for a two-piece acetabular component. The polished femoral head

with 54.0 mm diameter was made from CoCr (LINK SP II System, ISO 5832-4, ASTM F75). A diametral clearance of 0.5 mm was chosen after preliminary friction trials with three different values, 0.5 mm, 0.75 mm, and 1.0 mm. The frictional torque after 24 h of running was found to be insensitive to the clearance. Thus, the lowest value of 0.5 mm was selected since the contact stresses were lower [32], although this was likely to increase the contact area and wear rate to some degree. Lower contact stresses are advantageous as they reduce fracture risk. Too low a clearance value may hamper lubricant ingress into the contact, leading to detrimental frictional heating. On the other hand, a low liner thickness tends to reduce the contact area and increase contact stresses [33].

The test setup consisted of six wear test couples and one loaded soak control couple for evaluating the weight gain by fluid absorption and the plastic deformation. Three liners were at an optimum abduction (inclination) angle of 45°, and three liners were at a high abduction angle of 65°. The test consisted of seven stages of 382,000 cycles (100 h) each. After each stage, the wear of the liners was evaluated gravimetrically [30]. The test was continued with fresh lubricant until steady-state, linear wear was attained.

Linear regression was used to determine the wear rate ($\text{mg}/10^6$ cycles) for each liner. The calculation of the wear factor required the integral of the product of an instantaneous load and an incremental sliding distance at the theoretical point of load application. For one cycle in the HUT-4 simulator, with a 2.5 kN peak load of the double-peak load cycle and a 27 mm head radius, the value of the numeric integral was 70.5 Nm [30]. Before and after the wear test, the frictional torque T for each liner against a 54 mm CoCr head was measured in the HUT-4 simulator, as described in [34], after 1 h of operation in a lubricant similar to that used in the wear test. The friction measurement accessory was removed from the simulator for the wear test, as the torque transducer located on the drive shaft was designed to test one prosthesis at a time. The parasitic effect caused by the simulator mechanism on the measured

signal was subtracted, and the remainder was considered the resultant frictional torque of the joint studied. The magnitude of the parasitic torque was determined by operating with a joint known to have minimal frictional torque: alumina-on-alumina in water. The resultant frictional torque at 25% of the gait cycle was recorded in the present study. After the tests, the reduction in liner thickness at the center of the load-bearing area was measured with a digital caliper. A reference frictional torque was similarly measured for previously worn, 28 mm diameter CoCr-on-UHMWPE total hip prostheses ($n = 3$; acetabular component abduction = 45° ; thickness of polyethylene = 12.0 mm; diametral clearance = 0.1 mm; metal-backed, conventional, unirradiated UHMWPE).

3. Results

The wear rates in the 2.674-million-cycle test with 45° and 65° abduction were 8.5 ± 0.6 mg/ 10^6 cycles and 12.9 ± 0.3 mg/ 10^6 cycles, respectively (Fig. 2). The 51% increase in the mean wear rate due to the high abduction angle was statistically significant ($p < 0.01$). The corresponding mean wear factors were 1.28×10^{-7} mm³/Nm and 1.94×10^{-7} mm³/Nm. The total wear of the liners with 45° and 65° abduction was 22.3 ± 1.9 mg and 36.0 ± 2.5 mg, respectively. The total weight gain of the loaded soak control liner was 2.2 mg. No fractures or any other damage of the liners occurred. The lubricant bulk temperatures during the testing with 45° and 65° abduction were typically 9°C and 6°C , respectively, above the room temperature of 23°C , due to frictional heating. The lubricant turned opaque during the tests (Fig. 3), and the bearing surfaces of the liners were burnished (Figs. 4 and 5). The reductions in liner thickness (1) at the center of contact of the loaded soak control liner, (2) of the wear test liner with 45° abduction, and (3) of the wear test liner with 65° abduction were 0.03 mm, 0.08 ± 0.01 mm, and 0.14 ± 0.01 mm, respectively.

The frictional torque T before the wear test with both positions was 3.6 ± 0.3 Nm (Fig.

6), and after the wear test, T at 45° and 65° abduction was 2.6 ± 0.3 Nm and 2.4 ± 0.6 Nm, respectively. With 45° and 65° abduction, the 28% and 34% decrease in the mean T due to the wear test was statistically significant ($p = 0.01$ and 0.04). The frictional torque of the 28 mm CoCr on UHMWPE reference prostheses was 1.5 ± 0.2 Nm. The 1.7-fold difference in the mean T compared with the worn 54 mm bearings at 45° abduction was statistically significant ($p < 0.01$).

Figure 2. Variation of wear of VEXLPE liners at 45° and 65° abduction angles with number of cycles.

Figure 3. Six wear tests run in HUT-4 hip joint simulator.

Figure 4. Burnished bearing surface of VEXLPE liner.

Figure 5. Optical micrographs from bearing surface of VEXLPE liner. (a) Border between unworn and worn surface showing original machining marks and crisscross scratches. (b) Center of contact showing polishing and mild crisscross scratches.

Figure 6. Frictional torque of VEXLPE liners at 45° and 65° abduction angles against CoCr heads before and after wear test. Presented is maximum frictional torque that occurred at 25% of gait cycle after ‘heel strike.’ Both wear and friction tests were performed with multidirectional HUT-4 hip joint simulator.

4. Discussion

Thin VEXLPE liners were wear and friction tested against 54 mm diameter CoCr femoral heads in a multidirectional hip joint simulator. The mean wear rate with a high abduction angle, 12.9 mg/10⁶ cycles, was 1.5-fold higher than that with an optimal abduction angle, 8.5 mg/10⁶ cycles. The mean frictional torque, initially 3.6 Nm, decreased by 28% to 34% during the wear test. The present simulator and test conditions were used earlier to study the wear of a conventional, modular total hip prosthesis [35]. The wear rate of the metal-backed (‘Allofit Alpha’), gamma-irradiation-sterilized (25 to 40 kGy in N₂) UHMWPE liner (‘Sulene-PE’, thickness = 6.0 mm, diametral clearance = 0.5 mm) was 19.6 ± 1.6 mg/10⁶ cycles at 45° abduction (n = 4) and 20.8 ± 1.3 mg/10⁶ cycles at 60° abduction (n = 4) against a 32 mm diameter, stainless-steel femoral head (‘Protasul-S30’). The difference in the wear rate between the two positions was not statistically significant (p = 0.3). The average wear rate of

the Allofit Alpha liners, 20.2 mg/10⁶ cycles, was 1.9-fold higher than the average wear rate found in the present study, 10.7 mg/10⁶ cycles, and the difference was statistically significant ($p < 0.01$). For the wear comparison, the most relevant benchmark was considered the conventional total hip prosthesis instead of a large-diameter liner made from conventional UHMWPE with dimensions similar to those of the VEXLPE liner. When new attempts in hip resurfacing are made, it is unlikely that conventional UHMWPE will be used because much more wear-resistant UHMWPE materials are available [9–14]. Hypothesis (1) of the study was supported by the results, and it appears that the lower wear in the present study compared with [35] was due to a high dose gamma-irradiation induced extensive crosslinking that was not negated by the effect of the large diameter.

As pointed out in [36], the clinical literature is equivocal regarding the correlation between the acetabular abduction angle and the polyethylene wear rate in total hip arthroplasty. One study [36] observed a 50% higher mean polyethylene wear rate with abduction greater than 45° (0.18 mm/year) compared with the wear rate for abduction less than 45° (0.12 mm/year). The present results are in agreement with this observation. In other works, however [37,38], no significant correlations between abduction angle and wear rate were found. The cup (insert) design, especially the rim, is likely to be one of the important factors that cause this discrepancy. A review on this subject is presented in [18]. Other problems pertinent to a high abduction angle, such as fracture of an unsupported rim, dislocation, and impingement, are beyond the scope of the present study. Typically, the wear rate of conventional UHMWPE increases with increasing contact area and with decreasing contact stress, both in a hip simulator and in pin-on-disk tests [39–41]. The effect of the abduction angle on the wear of a large-diameter VEXLPE liner has not been studied in a hip simulator before, according to published studies. The present finding, that the higher abduction angle and thus higher contact stresses resulted in a higher VEXLPE wear rate,

seems to be a novel one. Within the range of contact stresses that prevailed in the present tests (that were relatively low due to the large diameter), the higher contact stresses resulted in a higher wear rate of the VEXLPE liner. By a rough graphic estimation, the average worn areas after the tests on the liners with 45° and 65° abduction were 1,200 mm² and 930 mm², respectively. Note that burnishing, crisscross scratches, and the distinct border between the worn and unworn surfaces (Figs. 4 and 5) are typical findings on retrieved UHMWPE liners [23,42]. They are characteristic of the combined multidirectional relative motion and protein-based lubrication that regulates clinical wear mechanisms. A multidirectional pin-on-disk test programme will be useful to possibly corroborate the observation of the contact area dependence of VEXLPE wear. With the pin-on-disk method, a wide range of contact stresses and areas can efficiently be covered with sufficient n values [43]. As the correlation between the abduction angle and polyethylene wear appears controversial clinically, it certainly remains an important subject of study in vitro.

In a hip simulator (MTS) study with 36 mm CoCr heads, liners of 1.9 mm, 3.9 mm, 5.9 mm, and 7.9 mm thickness made from highly cross-linked (sequentially gamma-irradiated to 30 kGy followed by annealing three times with a total gamma dose of 90 kGy, 'X3') UHMWPE showed wear rates of 5.0 ± 0.5 , 3.2 ± 0.3 , 2.5 ± 1.1 , and 2.2 ± 1.3 mm³/10⁶ cycles, respectively [44]. In another MTS hip simulator study, with a 44 mm head diameter and a 3.8 mm liner thickness, the wear rates of unspecified VEXLPE and X3 liners were 8.1 ± 0.7 and 3.8 ± 1.3 mm³/10⁶ cycles, respectively [45]. It was suggested that the 2.1-fold difference in the mean wear rates was due to the hampering of cross-linking by vitamin E. Pin-on-disk studies agree with this conclusion [46]. VEXLPE (0.1% blended, 80 kGy electron-beam-irradiated), XLPE (75 kGy gamma-irradiated, remelted), and conventional UHMWPE (30 kGy gamma-irradiated) liners were compared with the EndoLab hip simulator against 36 mm alumina heads [47]. The wear rates were 2.5 ± 0.5 , 2.0 ± 0.3 , and 19 ± 0.6 mg/10⁶ cycles,

respectively. In a hip simulator (MTS) study with a 51 mm CoCr head diameter and a 4.0 mm liner thickness, the wear rates of 75 kGy gamma-irradiated, remelted (155 °C) XLPE and conventional, unirradiated UHMWPE liners were 11.5 mg/10⁶ cycles and 149.6 mg/10⁶ cycles, respectively [48]. In another hip simulator (similar to MTS) study of modular total hip prostheses, the wear of electron-beam-irradiated (95 kGy) and melted (150 °C) XLPE liners ('Durasul', thickness = 12.0 mm, diametral clearance = 0.1 mm) against 28 mm CoCr heads was so low that it could not be quantified with a balance of 0.01 mg resolution [49]. In the same study, the wear rate of conventional, gamma-sterilized (25 to 40 kGy in N₂) UHMWPE liners ('Sulene-PE') with a similar shape was 11.6 ± 0.1 mg/10⁶ cycles. It was also impossible to quantify any weight loss in liners with a 3.0 mm thickness made from XLPE similar to Durasul in hip simulator (AMTI) tests, even with a 46 mm CoCr head diameter [25]. The control liners made from UHMWPE, gamma-sterilized by 25 to 40 kGy in N₂, showed wear rates of 13 ± 1.9, 17 ± 1.2, and 48 ± 4.9 mg/10⁶ cycles against heads of 22, 28, and 46 mm diameter, respectively. Vitamin E blended (> 0.1%), electron-beam-irradiated (> 100 kGy) VEXLPE ('Vivacit-E') showed a wear rate of 1.9 ± 0.3 mm³/10⁶ cycles in a hip simulator study against 40 mm diameter CoCr heads [14]. The wear of control liners made from gamma-sterilized (30 kGy in N₂) UHMWPE against 32 mm heads was 38 ± 2.8 mm³/10⁶ cycles. A very low wear rate, 1.0 ± 0.5 mg/10⁶ cycles, was also obtained for UHMWPE liners that were gamma-irradiated (85 kGy), doped with vitamin E, and annealed at 120 °C in argon, in a hip simulator (AMTI) against 36 mm CoCr heads [12]. The wear rate of control liners, made from gamma-argon-sterilized UHMWPE, against 28 mm heads was 9.5 ± 0.7 mg/10⁶ cycles. It is unfortunately difficult to draw specific conclusions based on the above-mentioned studies due to the variety of test conditions and material preparation. It remains obvious that cross-linking in general efficiently improves the wear resistance of thin, large-diameter polyethylene liners in vitro compared with conventional UHMWPE.

In hip resurfacing, a clinical mean wear rate of 0.05 mm/year (range 0.03 to 0.10 mm/year) has been obtained for a metal-backed, cross-linked (90 kGy gamma dose, annealed below melting temperature) XLPE liner with 3.8 mm thickness against a 40 or 44 mm CoCr femoral head [11]. In examining the clinical wear of XLPE liners from different manufacturers, made from different types of XLPE, against ≥ 36 mm CoCr or ceramic heads, mean wear rates of 0.05 mm/year and 41 mm³/year were found with liner thickness < 6.5 mm [19]. Considering the density of the present VEXLPE, 0.941 mg/mm³, and assuming that one million cycles in the simulator corresponds to one year in vivo, the present gravimetric wear rates for 45° and 65° abduction correspond to 9.1 mm³/year 13.7 mm³/year, respectively. These values are lower than the above-mentioned clinical value and below the ‘osteolysis threshold’ of 50 mm³/year [7]. This threshold means that a certain maximum amount of annually generated polyethylene wear particles, which are of submicron size [50,51] and therefore biologically most active [6], can be tolerated without osteolysis so severe that it would lead to implant loosening. Particles were not analyzed in the present study, but in another hip simulator study, the inflammatory response to VEXLPE particles was not significantly different from that to conventional UHMWPE particles [14]. However, other studies observed a reduced inflammatory potential due to the presence of vitamin E in the wear particles [52,53]. It nevertheless appears that the presence of vitamin E has no adverse effects [54].

Friction is important clinically, because high friction may cause detrimental frictional heating above 40 °C [27], pose a risk to the fixation of the acetabular component [28], and exacerbate the wear of the taper fixation of the femoral head [29]. The 28% to 34% decrease in the mean frictional torque T due to the wear test and the insensitivity of T to the abduction angle were conspicuous (Fig. 6). It appears that accommodating the femoral head to the acetabular liner and burnishing this liner create more favorable conditions for lubrication due

to wear and creep as the contact area increases (Figs. 4 and 5). The mean T value measured after the wear test at 45° abduction was 1.7-fold higher than that measured for a 28 mm CoCr-on-UHMWPE total hip prosthesis. The difference was in line with the 1.9-fold difference in the head diameters. Hence, hypothesis (2) was supported. It should be noted as a limitation of this comparison that the 28 mm liner was made of conventional, unirradiated UHMWPE. With instrumented hip implants, clinical friction factors ranging from 0.02 to 0.12 were obtained during the first four steps after a rest for a 32 mm alumina-on-polyethylene articulation and a 2.4 kN peak load [55]. The friction factor can be calculated for the present T values by dividing the frictional torque (Nm) by the peak load (2,500 N) and by the radius of the head (0.027 m). Hence, with 45° abduction, the friction factors before and after the wear test were 0.053 ± 0.005 and 0.038 ± 0.004 , respectively. The values were within the clinical range observed for a 32 mm head. In another hip simulator study, in which friction was measured in connection with a wear test, a stable friction factor of 0.046 ± 0.003 was obtained for an XLPE liner against a 44 mm diameter CoCr head [56], which is close to the present values. With large-diameter CoCr-on-CoCr prostheses, the frictional torque was found to be of the order of 1 Nm under optimal conditions, but values as high as 20 Nm were measured in connection with severe edge wear at 70° inclination angle of the cup [34]. Such edge wear rate could be 300 times higher than the wear rate under optimal conditions, i.e., 1 mg/10⁶ cycles vs. 300 mg/10⁶ cycles [34]. In the present CoCr-on-VEXLPE design, the mean wear rate with 65° abduction was only 1.5-fold higher than that with 45° abduction (Fig. 3). The frictional torque of the VEXLPE liner against the 54 mm CoCr head appeared to be of reasonable magnitude and insensitive to the cup abduction angle.

A limitation of the study was that the bearing was not from an existing hip resurfacing system. The acetabular design was experimental, and for practical reasons, a commercial femoral head with a taper fixation was used instead of a hip resurfacing head. An earlier

paper showed that the method of fixation is unimportant in tribological studies as long as it is firm [5]. Second, in a laboratory wear study, the biological lubricant degraded in a way that does not occur in vivo. The effects of degradation mechanisms on wear are not well known presently. The degradation that can be observed by the lubricant turning opaque is caused by protein denaturation and precipitation, which may affect the wear because precipitated protein acts as a solid lubricant [57]. However, it is common knowledge that only with serum-based lubricants can clinical wear mechanisms be reproduced [58]. Because of the degradation, the lubricant change interval was kept relatively short at 100 h. It is also important that the fluid volume be large enough (Fig. 1b) for there to be ample soluble protein for lubrication, since denaturation manifested as precipitation is inevitable in implant wear testing. Despite these limitations, it is believed that the test setup as a whole gave a realistic and certainly not overoptimistic picture of the wear and friction behavior of a thin VEXLPE liner against a large CoCr head.

5. Conclusions

The thin experimental acetabular liner made from VEXLPE showed reasonable wear resistance and frictional behavior in a hip simulator study against a 54 mm diameter CoCr femoral head. The present VEXLPE, as studied in an experimental, metal-backed, hemispherical acetabular design with a wall thickness of 4.0 mm against a 54 mm diameter polished CoCr femoral head, appeared to be a suitable material for an acetabular liner in hip resurfacing. Compared with conventional total hip prostheses, the mean wear rate was 1.9-fold lower, and the mean frictional torque was 1.7-fold higher. The mean wear rate with 65° abduction was 1.5-fold higher than with 45° abduction. The frictional torque decreased by 28% to 34% during the wear test.

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Declarations of interest

none

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Highlights

- with total hip replacement, THR
- Cross-linked PEs have been designed for advanced wear and oxidation resistance
- Novel VEXLPE acetabular liners were tested in a multidirectional hip simulator
- Wear was 1.9-fold lower and frictional torque was 1.7-fold higher compared with THR
- With state-of-the-art VEXLPE liners, improved implant survivorship may be expected