Saikko, Vesa; Morad, Omar; Viitala, Raine

Effect of type and temperature of serum lubricant on VEXLPE wear and friction

Published in:
Wear

DOI:
10.1016/j.wear.2021.203613

Published: 15/04/2021

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Effect of type and temperature of serum lubricant on VEXLPE wear and friction

Vesa Saikko, Omar Morad, Raine Viitala

PII: S0043-1648(21)00002-8

DOI: https://doi.org/10.1016/j.wear.2021.203613

Reference: WEA 203613

To appear in: *Wear*

Received Date: 23 October 2020

Revised Date: 7 December 2020

Accepted Date: 31 December 2020

Effect of type and temperature of serum lubricant on VEXLPE wear and friction

Vesa Saikko, **Omar Morad** and **Raine Viitala**
Aalto University School of Engineering
Finland

Corresponding author:
Vesa Saikko, PhD
Aalto University School of Engineering
Department of Mechanical Engineering
PO Box 14300
FI-00076 Aalto
Finland
Tel. +358 50 355 1757
E-mail: vesa.saikko@aalto.fi

Abstract

Multidirectional tests were carried out to study the influence of the type and temperature of serum lubricant on the wear and friction of vitamin E stabilized, extensively crosslinked ultrahigh molecular weight polyethylene (VEXLPE) against polished CoCr. To minimize the rates of protein denaturation and microbial growth, cold wear tests were performed for the first time so that the serum lubricant was at a refrigerator temperature of 4 °C. The highest wear factors and coefficients of friction were observed at the refrigerator temperature and the lowest at body temperature where the rates of protein denaturation and microbial growth were expected to be at their maximum. The VEXLPE mean wear factor in alpha calf serum (ACS) decreased by two orders of magnitude as the lubricant bulk temperature increased from 4 °C to 37 °C. Thermal analysis indicated that the contact temperature in the pin-on-disk test was less than 2 °C above the lubricant bulk temperature. It appears that a wide range of polyethylene wear rates and coefficients of friction can be obtained depending on the temperature. The type of serum also strongly affected the obtained wear rate at and above 20 °C.

Keywords: serum lubrication; multidirectional pin-on-disk; hip joint simulator; vitamin E stabilization; extensively cross-linked polyethylene; total hip prosthesis

1. Introduction

In orthopaedic tribology, the type of serum and its temperature are known to substantially influence the wear and friction of different types of ultra-high molecular weight polyethylene (UHMWPE) in multidirectional testing [1–13]. Many different types and temperatures are in use. Only in general terms there is a consensus that in order to make the reproduction of clinical wear mechanisms of orthopaedic implants possible, two conditions must be complied with, (1) the lubricant must be serum-based, and (2) the relative motion must be multidirectional [14]. Multidirectionality is shown in many different forms [15], and it is not straightforward to discern which form is more suitable than the other. Alpha calf serum (ACS) is one of the widely used types because of its proven suitability for wear testing, especially regarding its stability against denaturation, induced by heat [3,4]. Denaturation shows as protein precipitation and it has been suggested that precipitated protein may unphysiologically protect against wear by acting as a solid lubricant [1,8]. In vivo, denaturation is likely to be irrelevant because of the continual regeneration of the synovial fluid, and because the typical walking activity in a day is short, whereas the typical joint simulator activity is continuous. Nevertheless, frictional heating is a clinical reality [16].

The hip joint simulator standard ISO 14242-1 recommends a lubricant bulk temperature of 37 ± 2 °C [17]. However, in an attempt to mimic the physiologic conditions in this respect, denaturation and microbial growth may lead to unphysiological wear phenomena and high variation of wear [13]. The lubricant change interval is also known to affect the obtained wear rate [13]. ISO 14242-1 recommends an interval of 500 000 cycles. The addition of sodium azide to retard microbial growth is common although it has been shown to be ineffective [10,13]. Better results in retarding microbial growth were achieved by an antibiotic/antimycotic [10]. It needed to be added regularly because its efficacy tended to become exhausted with time [11,18–20]. The use of the antibiotic/antimycotic has not yet proceeded to the standard level. Instead, ISO 14242-1 only briefly mentions that sodium azide can be added, despite its inefficiency. It should also be emphasized that sodium azide is toxic and thus a health risk for the laboratory personnel. More research with the antibiotic/antimycotic is probably still be needed before its use could become general and standardized. With ACS, diluted with deionised water to a protein concentration of 20 mg/ml, denaturation and microbial growth at a cooled temperature of 20 °C apparently were so slow that they did not disturb the testing, and the resulting wear was similar to that known to occur clinically [21]. It would be interesting to test even at a refrigerator temperature because denaturation and microbial growth would thus likely to be minimized. Besides ACS, regular bovine calf serum (BCS) is widely used, probably due to its lower cost and better availability, but its stability may be inferior to that of ACS [3,4,10].

Recently, vitamin E stabilized, extensively cross-linked UHMWPE, 'VEXLPE', has been introduced because of its superior combination of oxidation resistance and wear resistance in laboratory tests [22–27]. Little is known about the dependence of VEXLPE wear and friction on the type and temperature of the serum lubricant. To shed light on these issues, multidirectional pin-on-disk and hip simulator tests were carried out for VEXLPE against CoCr with ACS and BCS. In the pin-on-disk tests, wear and friction were measured for a wide range of lubricant bulk temperatures, from refrigerator to body temperature. Since not only the lubricant bulk temperature but also the contact temperature is important with respect to the denaturation [1–3,7,8], a finite element thermal analysis was performed to estimate the contact temperature. It was hypothesized that similarly to UHMWPE, the VEXLPE wear and friction are sensitive to the type and temperature of the serum lubricant.

2. Materials and methods

Materials

VEXLPE (100 kGy gamma-irradiated GUR 1020-E, ASTM F648, ISO 5834-1,2, ASTM F2695, ASTM F2565, 0.1% blended alpha tocopherol, no stabilizers or processing aids, compression moulded, post-consolidation irradiated, no post-irradiation thermal treatment) was tested against polished CoCr (ISO 5832-12).

Lubricants

1. HyClone alpha calf serum (ACS) SH30212, diluted with deionized water to a protein concentration of 20 mg/ml. No additives were used.

2. HyClone bovine calf serum (BCS) SH30076, diluted with deionized water to a protein concentration of 20 mg/ml. No additives were used.

Both sera were triple 0.1 μm sterile filtered, collected and processed in the USA, and supplied by GE Healthcare Life Sciences, HyClone Laboratories, Logan, Utah, USA.

Hereafter, the abbreviations ACS and BCS are used for the diluted serum lubricants.

Test devices

1. SuperCTPOD for wear testing [21].

2. CTPOD for friction measurements [28].

3. HUT-4 hip joint simulator for wear testing [29,30].

Tests

In the SuperCTPOD wear tests and CTPOD friction tests, the pin translated, without rotation, along a circular track of 10 mm relative to the disk, and so the direction of sliding relative to the pin changed continually. The sliding speed was 31.4 mm/s and the load was 71 N. The cylindrical pin (diameter 9.0 mm, length 12 mm) was made from VEXLPE and the polished disk was made from CoCr. The contact was flat-on-flat. The tests were performed at four different temperatures so that the lubricant bulk temperature was maintained at 2 °C to 4 °C, 14 °C to 16 °C, 19 °C to 21 °C, and 36 °C to 38 °C by cooling or heating. The lubricant volume was 16 ml per test station. In the wear tests, the test length was 1.2 million cycles.

The gravimetric wear evaluation was made at 0.6 and 1.2 million cycles. First, the wear rate was determined by linear regression. Then the wear factor k was computed by dividing the wear by the density, 0.935 mg/mm^3, and by the product of the load and the sliding distance. The total number of pins in the wear tests was 16 so that 8 were tested in ACS and another 8 in BCS. The same pins were used at different temperatures to avoid a material related source of variation. Before the test, the pins were pre-worn (burnished) by 0.6 million cycles in ACS and BCS at 20 °C. There were also two soak control pins. In the friction tests, the average duration was 20 h, and the coefficient friction μ was computed as the measured frictional force divided by 71 N. A k-type thermocouple (diameter 1 mm) was placed on the centre axis of the pin, in a drill-hole, at a distance of 0.5 mm from the contact surface that was pre-worn (burnished). From this subsurface temperature and from the lubricant bulk temperature measured with another k-type thermocouple, an estimate of the true contact temperature was computed by finite element thermal modelling, see below, in which the power dissipated by the friction force was computed as μ multiplied by the sliding speed and normal load. The temperature measurement system was checked and adjusted with ice and boiling water baths. Its estimated accuracy was ±0.2 °C.

In the HUT-4 hip simulator wear tests, specimens from a previous study were used, and the test conditions were also similar, that is, level walking according to biomechanical literature, 'Phase III' [30], except for the BCS lubricant and for the lubricant change interval. Briefly, the polished CoCr femoral head of 54 mm diameter rocked bi-axially so that the relative motion was multidirectional. The anatomically positioned, stationary, self-aligning acetabular component consisting of a thin, VEXLPE liner with an internal diameter of 54.5 mm and a stainless steel shell was vertically and dynamically loaded with a peak force of 2 kN. Three similar prostheses were tested with ACS and BCS. There was also one loaded soak control prosthesis. The test frequency was 0.9 Hz. The tests were run at room temperature of 21 °C. The test duration was 3 × 164 h corresponding to 3 × 550 000 cycles with both lubricants. After each 550 000 cycles, the wear was measured gravimetrically and the test was then continued with fresh lubricant. The lubricant volume was 450 ml per test station. In the previous study [30], the test duration was 3 × 100 h, which resulted in a wear factor of 2.36 ± 0.04 × 10^{-7} mm^3/Nm, the reference value. The lubricant change interval was the only variable with ACS.

Since the wear factor has been shown to be normally distributed [18], the Student's t-test was used to determine possible statistical significance of difference in mean wear factors with a threshold p-value of 0.05.

Finite element thermal modelling and analysis of CTPOD tests

To estimate the contact surface temperature, the CTPOD was modelled in COMSOL Multiphysics® 5.5 (COMSOL Inc., Burlington, MA, USA), with some simplifications. The model is shown in Fig. 1. Water was circulated through the bath via a laboratory cooler/heater, with a flow rate of 400 ml/min, to maintain the lubricant temperature at the desired level. The flow was not modelled for simplicity. Water was modelled as a fixed temperature on the inside boundary of the base of the bath, as the water temperature was monitored to be higher at the 37 °C, and lower in the 4 °C, 15 °C and 20 °C tests. The difference was about 1 °C. The motion was modelled as pure rotation, assuming thermal similarity to circular translation. Solid domains had a prescribed angular velocity of 1 rev/s. The mean values of μ and temperatures at locations A and B were taken from the last hour of the test. Material properties are shown in Table 1.

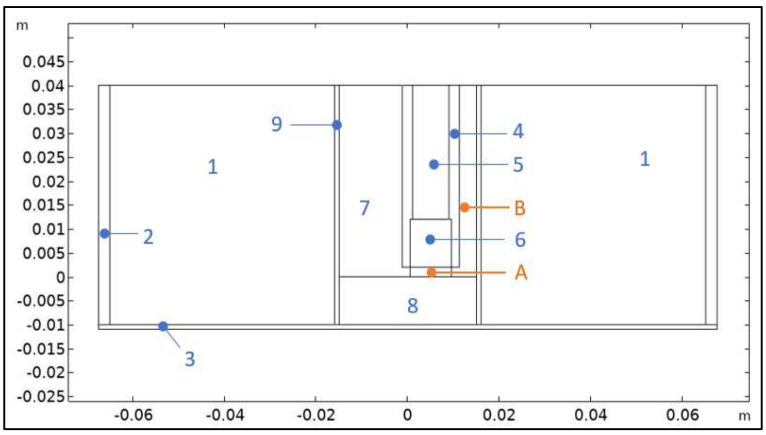

Fig. 1. Schematic of CTPOD thermal model. 1 Water bath, 2 Wall of water bath, 3 Base of water bath, 4 Polyacetal sleeve, 5 Pin guiding and loading shaft made from stainless steel, 6 Polyethylene pin, 7 Lubricant, 8 CoCr disk, 9 Stainless steel casing, A pin subsurface thermocouple, B lubricant thermocouple.

Table 1. Material properties used in thermal analysis.

Material	Density (kg/m^3)	Thermal conductivity (W/mk)	Specific heat (J/kgK)
UHMWPE	935	0.41	1842
Polyacetal	1420	0.23	1500
CoCrMo	8400	13	450
Stainless steel	7900	20	500
Water	997	0.607	4.18

Heat transfer to ambient air was calculated using equation (1), where the setup was treated as a disk rotating in air. In the equation, Nu_D is the average Nusselt number, h_c is the average heat convection coefficient, $k = 0.025\ \mathrm{W/mK}$ is the thermal conductivity of air, D is the outermost diameter = 0.13 m, $\omega = 1\ \mathrm{rev/s}$ is the rotational velocity in, and $\nu = 1.6 \times 10^{-5}\ \mathrm{m^2/s}$ is the kinematic viscosity. All properties were for 25 °C that was the ambient temperature. The heat transfer was applied to all exterior surfaces. From the equation follows that $h_c = 2.25\ \mathrm{W/m^2K}$.

$$(1) \qquad Nu_D = \frac{h_c D}{k} = 0.36\left(\frac{\omega D^2}{\nu}\right)^{1/2}$$

3. Results

In the SuperCTPOD wear tests with ACS, the mean wear factor decreased with increasing temperature, and each decrease step was statistically significant (Fig. 2). At 4 °C and 15 °C, the mean *k* values with ACS and BCS were close to each other. At 20 °C and 37 °C, the mean *k* with BCS was significantly higher than that with ACS. With BCS, the variation of wear at 20 °C and 37 °C was larger than that with ACS. The weight changes of the soak control pins were of the order of 0.01 mg. Typically, the color of the used lubricant was yellow-brown (Fig. 3). At 4 °C, the color of ACS and BCS turned white (Fig. 4). Visual precipitation as in Fig. 1 of [8], or rather flocculation, occurred at 4 °C only (Fig. 5). No precipitation was observed in the soak controls. At 37 °C, the color of the BCS lubricant turned green (Fig. 6), but the color varied between the test stations. Irrespective of the type and temperature of serum, the contact surface of the pins was burnished (Fig. 7), and the CoCr disks were virtually unchanged.

The results of the CTPOD friction tests and thermal analysis are shown in Table 2. The simulation showed less than ±0.5 °C difference from measured temperatures, except at 37 °C, which had a larger difference. The temperature difference between the computed contact surface temperature and measured lubricant bulk temperature did not exceed 2 °C. An example of the computed temperature contours is shown in Fig. 8.

In the HUT-4 hip simulator wear tests, the VEXLPE liner wear factors in ACS and BCS were $1.87 \pm 0.28 \times 10^{-7}$ mm^3/Nm and $4.32 \pm 0.22 \times 10^{-7}$ mm^3/Nm, respectively (Fig. 9). These values corresponded to 10.5 ± 1.56 mg/10^6 cycles and 24.2 ± 1.23 mg/10^6 cycles, respectively. The difference in means was statistically significant ($p = 0.0004$). The maximum weight changes of the soak control liners were of the order of 0.5 mg. The lubricant bulk temperature was 27 °C on the average. The color of the BCS lubricant turned green.

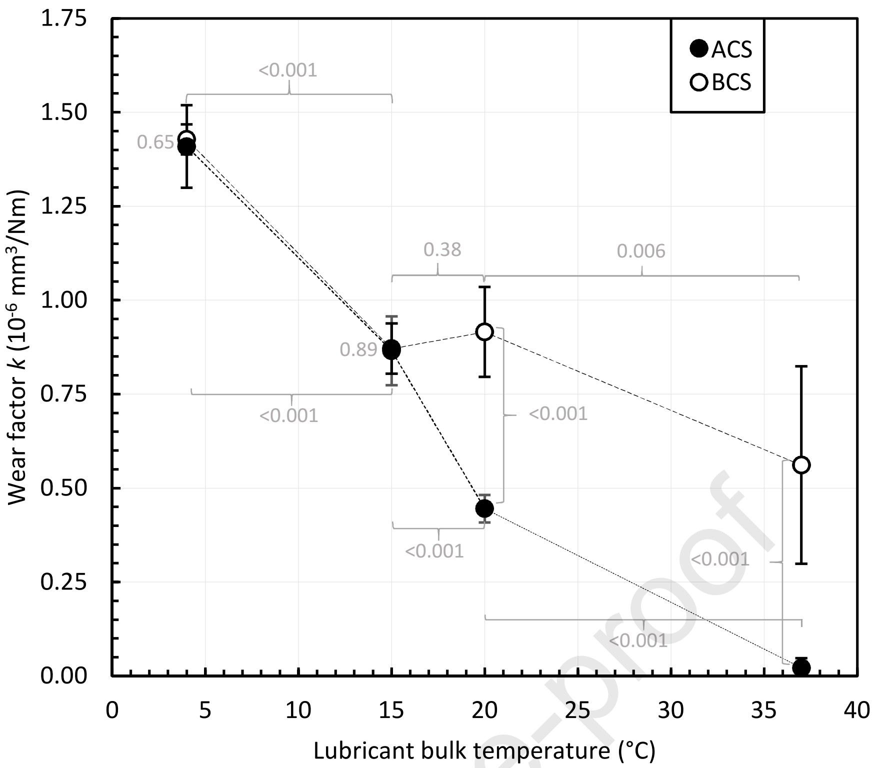

Fig. 2. Variation of VEXLPE wear factor (mean ± SD) with lubricant bulk temperature in SuperCTPOD tests. Numbers indicate p-values of t-test between two test conditions.

Fig. 3. Lubricant chambers in water bath of SuperCTPOD after 0.6 million cycles at 20 °C showing typical opaque appearance and yellow-brown color of used serum lubricant. Upper row ACS, lower row BCS.

(A)

(B)

Fig. 4. Plastic 'sub-bath' of SuperCTPOD through which refrigerated water (inlet temperature 1 °C to 2 °C) was circulated in cold testing. Note thin stainless steel lubricant chambers for improved heat conductivity, as estimated friction power was 0.7 W per test station. Test disk formed bottom of chamber. (A) Before start ACS was transparent, (B) after 0.6 million cycles (1 week) at 2 °C to 4 °C, ACS had turned opaque and white.

Fig. 5. Flocculation in used ACS lubricant of SuperCTPOD test at 4 °C (left), and for comparison, bottle of fresh, thawed, unshaken alpha calf serum (right).

Fig. 6. Greenish color of used BCS lubricant of SuperCTPOD test at 37 °C.

Fig. 7. Optical micrograph of VEXLPE pin worn in ACS at 4 °C, burnished to mirror finish. Individual nodules are probably reattached, flattened wear particles. Extremely flat topography allowed use of 100× objective with adequate depth of field.

Table 2. CTPOD friction and temperature measurements and thermal analysis results.

Cooling water average temperature	μ	A: Pin subsurface temperature (°C)			B: Lubricant bulk temperature (°C)			Maximum contact surface temperature (°C)	
		Measured	Computed	ΔT Error	Measured	Computed	ΔT Error	Computed temperature	ΔT to lubricant measured
Alpha calf serum									
3.70	0.31	6.20	5.77	-0.43	4.70	4.99	0.29	6.31	1.60
13.82	0.29	15.86	15.66	-0.20	14.82	14.70	-0.12	16.17	1.35
19.29	0.29	21.22	21.11	-0.11	20.29	19.99	-0.31	21.63	1.34
37.49	0.13	36.60	38.15	1.55	36.49	37.26	0.77	38.40	1.91

Bovine calf serum									
4.10	0.29	5.71	5.80	0.09	5.10	5.35	0.25	6.30	1.20
13.98	0.22	15.46	15.42	-0.04	14.98	14.74	-0.24	15.85	0.87
18.70	0.23	20.58	20.13	-0.46	19.70	19.30	-0.39	20.54	0.84
37.37	0.06	36.45	37.64	1.19	36.37	37.04	0.67	37.78	1.41

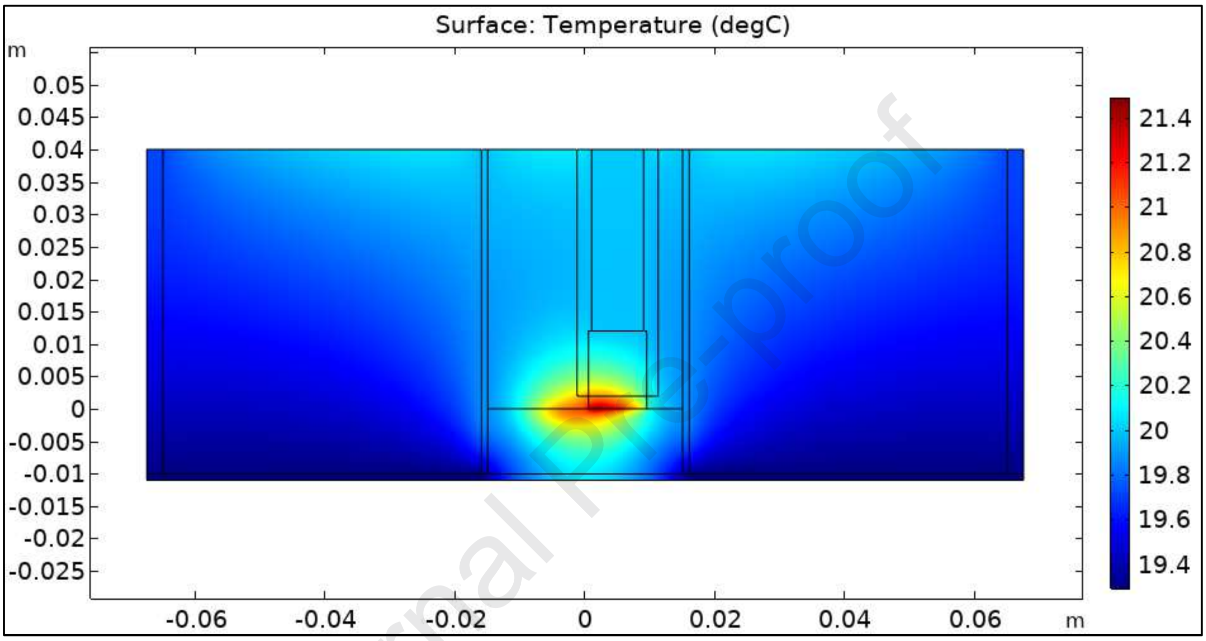

Fig. 8. Computed temperature distribution in 20 °C CTPOD test.

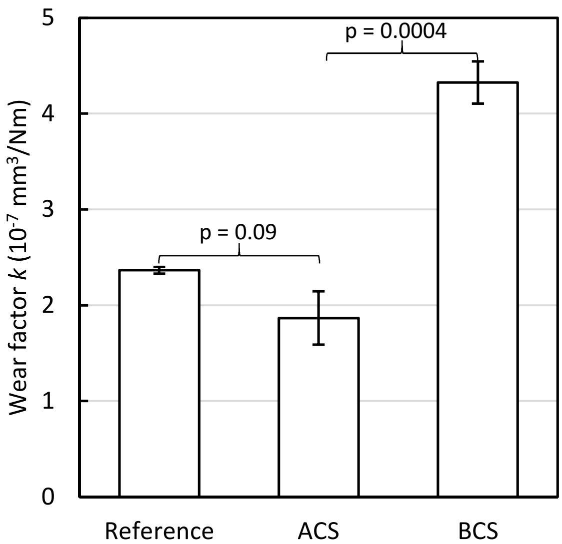

Fig. 9. Wear factors of VEXLPE liners (mean ± SD) in HUT-4 hip simulator tests of 3 × 550 000 cycles duration. Reference is from [30], in which test duration was 3 × 320 000 cycles and lubricant was ACS. Lubricant bulk temperature was 27 °C.

4. Discussion

Multidirectional pin-on-disk and hip simulator tests were carried out for VEXLPE against CoCr. The CTPOD testing included both wear and friction and covered a wide range of temperatures with two different serum lubricants. Cold testing so that the serum lubricant was at a refrigerator temperature was performed for the first time. This resulted in by far the highest wear factors (Fig. 2). Warm testing so that the serum lubricant was at 37 °C, resulted in by far the lowest wear factors. The principal type of wear, indicated by burnishing (Fig. 7), was insensitive to the temperature and type of serum. The finite element thermal analysis resulted in estimated maximum contact temperatures less than 2 °C above the lubricant bulk temperature. CTPOD and hip joint simulator tests showed higher wear factors with BCS at and above 20 °C compared with ACS.

The mechanisms by which protein denaturation and microbial growth possibly affect polyethylene wear are still poorly known. Worldwide, little research effort seems to be currently directed at these phenomena, although a lot of routine, quality control type of wear testing, based on the ISO 14242-1 standard [17], is apparently done (but not published) by testing labs and the orthopaedic industry. It has been suggested that precipitated protein may unphysiologically protect against wear by acting as a solid lubricant [1,8]. It was further suggested that precipitation would require contact temperatures above 60 °C [2], far above those of the present study. Substantial precipitation was observed only at 4 °C (Fig. 5), but its possible effect on wear was opposite to that suggested in [1,8]. The fact that all used serum was opaque indicated that denaturation of some kind occurred at all temperatures. A phenomenon called cold denaturation is known, but it is not likely to be active in the present temperature range [31]. It occurs at temperatures below 0 °C with solvents other than water. The possibility that denaturation would result from mechanical shear stresses at the contact interface has been suggested [10]. This could be a mechanism separate from the heat induced denaturation. Admittedly, it still would not explain the observed strong temperature dependence of wear. There is of course the possibility that this dependence is due to a phenomenon other than denaturation or microbial growth.

Green color of newborn calf serum lubricant at 37 °C was observed in multidirectional pin-on-disk tests for conventional, gamma-sterilized UHMWPE against CoCr [11]. The color probably originated from airborne fungi, spores of ubiquitous Penicillium mold. The presence of fungi was associated with an increased wear rate and a larger variation of the wear rate, which is in agreement with the present results at 37 °C in the comparison BCS vs. ACS (Figs. 2 and 6). However, temperature dependencies were not studied in [11]. The fact that the wear rate with BCS at 20 °C and 37 °C was higher than that with ACS is in agreement with multidirectional hip and knee simulator studies of other groups [5,10]. However, the opposite has also been found [3,4]. Only one type of BCS was included in the present study, and it is possible that there is substantial variation among bovine calf sera with respect to their behavior as lubricants in orthopaedic tribology. In a multidirectional pin-on-disk device, a wear rate of 2.0 mg/10^6 cycles was obtained for VEXLPE similar to that of the present study in a room temperature test with bovine calf serum [22]. This is in agreement with the present result with BCS at 20 °C since the mean wear factor value (Fig. 2) corresponded to a wear rate of 1.9 mg/10^6 cycles.

In multidirectional RandomPOD tests for conventional, gamma-sterilized UHMWPE against CoCr, the mean wear factor with ACS at 20 °C was 2.9 fold higher than that in 37 °C [13]. The k values were $3.92 \pm 0.26 \times 10^{-6}$ mm^3/Nm and $1.34 \pm 0.24 \times 10^{-6}$ mm^3/Nm, respectively. This observation is in line with the findings of the present study with the exception that the latter value is still of substantial magnitude. It could be speculated that the properties of conventional, gamma-sterilized UHMWPE and of the present VEXLPE are such that their multidirectional wear resistance tends to increase with increasing temperature. However, it is not plausible that the effect would be as strong as seen in Fig. 2, two orders of magnitude for VEXLPE with ACS between 4 °C and 37 °C. Nevertheless, such an effect could not be separated from the results since clinically relevant wear can be produced with serum lubrication only. The lower wear at 37 °C could partly be attributable to the lower friction at this temperature (Fig. 2, Table 2). This could also be thought so that the higher friction at lower temperatures was partly attributable to larger amounts of wear particles in the lubricant, and vice versa. However, there were large differences in wear between 4 °C, 15 °C, and 20 °C but no corresponding large differences in friction. Temperature dependent reattachment of wear particles, that could explain differences in wear, was not observed (Fig. 7). The principal type of wear ('wear mechanism'), burnishing, was found to be insensitive to temperature, and therefore cold testing could be contemplated as a realistic way to accelerate the wear test. Burnishing is the dominating feature on the bearing surface of retrieved polyethylene acetabular cups [14]. It is attributable to protein-based lubrication and multidirectional motion [14].

With ACS, the sensitivity of VEXLPE wear to temperature was striking. At 4 °C, the mean k was two orders of magnitude higher than that at 37 °C. At 37 °C, the mean k was almost negligible, 2.2×10^{-8} mm^3/Nm. This corresponded to weight changes that were of the same order of magnitude as the precision of the gravimetric method, ±0.05 mg. A decrease of the temperature by five degrees only, from 20 °C to 15 °C, resulted in a two-fold increase of the mean k. A decrease from 20 °C to 4 °C resulted in a three-fold increase of the mean k. The wear behavior in BCS was different. At 37 °C, the wear was of substantial magnitude and its variation was high so that the standard deviation was 47 per cent of the mean value. At 20 °C, the mean k in BCS was twice higher than that in ACS. At 4 °C and 15 °C, the mean wear factors with ACS and BCS were so close to each other as if there was no difference between the two sera. Interestingly, not only the highest but also the lowest variation in the study was observed with BCS, i.e., at 4 °C. In the largest k value in the study, $1.43 \pm 0.04 \times 10^{-6}$ mm^3/Nm, the standard deviation was only 2.8 per cent of the mean. However, such a low percentage value is not uncommon in SuperCTPOD testing with ACS at 20 °C [32].

A thermal analysis similar to the present one was performed for a biaxial rocking motion (BRM) hip simulator with an inverted component position, the primary concern being that high contact temperatures could lead to unphysiological denaturation [1]. This could be the case especially in the early version of the BRM that had a lubricant volume of only 40 ml in each test chamber [1]. Consequently, this was increased to 400 ml per test chamber in the later version of the BRM [8]. The CTPOD and the BRM are tribologically analogous so that the CTPOD is in fact a planar modification of the BRM. Hence, it was considered interesting to perform a thermal analysis for the CTPOD, too. Unlike the CTPOD, the BRM did not have a cooling system. Cooling of the BRM was mainly evaporation to ambient air, and the thermal model considered a thin column of PE from the subsurface to the contact surface. Since the friction was unknown, a transient temperature was assigned to the contact surface. The simulation was stopped when the simulated subsurface temperature was within ±0.5 °C of the measured one. The measured lubricant bulk temperature was 35.8 ± 1.4 °C, and the subsurface temperature was 40.4 ± 1.8 °C with polyethylene against CoCr. The contact temperature from the thermal analysis was 60 °C, resulting in a 24.2 °C difference between the contact and serum bulk temperatures. In the present study, the largest difference was an order of magnitude lower (Table 2). This can be explained by the differences in the setups. The first difference can be seen in the measured values of subsurface and serum bulk temperatures. The CTPOD showed a maximum difference between these values of 1.5 °C, while BRM showed 4.6 °C. This can be explained by the efficient water cooling in the CTPOD, compared to mainly natural convection in the BRM, in addition to the polyurethane mold of the acetabular cup that probably acted as an effective heat insulator. It was assumed in the BRM analysis that heat primarily dissipated radially, which can result in errors. The cup has substantially more material circumferentially than radially and it is constantly exposed to the serum at the rim. Heat absorption by the CoCr femoral head was not considered, even though the head was found to be at a higher temperature than the cup subsurface, which could be substantial due to the larger thermal conductivity compared with polyethylene, and the subsequent dissipation to the lubricant. The magnitude of this heat dissipation would need to be studied, as it is not easy to estimate the thermal behavior with many boundary conditions.

A demonstration of the effect of heat dissipation to the lubricant is presented in the following. The present thermal finite element analysis resulted in a less than 1 °C difference between the contact and subsurface temperatures. Conversely, using the Fourier's law of heat conduction $q = kA(T_1\text{-}T_2)/x$, where q is the heat generated by friction, k is the thermal conductivity of polyethylene, A is the area of the contact surface of the pin, T_1 and T_2 are the contact and subsurface temperatures, respectively, and x is the subsurface distance, the resulting ΔT is 10.8 °C with ACS at 20 °C. The ΔT from the finite element analysis is much lower due to the inclusion of the effects of the surroundings, namely the cooling water, while the BRM case [1] is closer to a linear conduction problem.

In the previous HUT-4 hip simulator study with ACS and a lubricant change interval of 320 000 cycles, the wear factor of the VEXLPE liners was $2.36 \pm 0.04 \times 10^{-7}$ mm^3/Nm [30]. The value in the present study with a lubricant change interval of 550 000 cycles was $1.87 \pm 0.28 \times 10^{-7}$ mm^3/Nm for the same liners (Fig. 9). The difference was not statistically significant ($p = 0.09$). This indicates that the change interval recommended by ISO 14242-1, 500 000 cycles, is not excessive. The mean wear factor with BCS was 2.3-fold higher than that with ACS, which was in agreement with the SuperCTPOD results. The difference may have been at least partly due to the microbial growth in BCS (green color), as indicated by the SuperCTPOD results. However, the variation of wear with BCS was lower in the hip simulator compared with the SuperCTPOD. The hip simulator tests with BCS were inspired by the idea of finding a serum with low cost and good availability, possibly a replacement for the alpha calf serum. Note that as much as 450 ml of lubricant is needed for each test chamber for one week's testing. Green color was never seen in ACS, and so the present BCS proved disappointing and discouraging for further biotribological or microbiological studies.

5. Conclusions

1. Cold testing at the refrigerator temperature resulted in the highest wear factors and coefficients of friction, whereas warm testing at the body temperature resulted in the lowest wear factors and coefficients of friction.

2. The principal type of wear, burnishing, which is the dominating feature on the bearing surface of retrieved acetabular cups, was insensitive to the type and temperature of the serum lubricant.

3. At the refrigerator temperature, the mean wear factor of VEXLPE with ACS was two orders of magnitude higher than that at the body temperature.

4. Refrigerator temperature could be contemplated as a realistic way to accelerate the wear test.

5. Based on finite element thermal modelling, the estimated maximum contact temperature in the CTPOD tests was less than 2 °C higher than the serum bulk temperature. This was likely to be attributable to the efficient cooling of the test disk by the lubricant, the temperature of which was controlled. Hence, heat induced precipitation was unlikely to occur.

6. The suitability of ACS as a lubricant in orthopaedic tribology was supported by the results.

7. Both in the hip simulator and pin-on-disk tests, the wear factors were higher with BCS compared with ACS at temperatures ≥ 20 °C. This may have been partly due to microbial growth in BCS.

Conflict of interest statement

The authors have nothing to declare.

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. The authors thank Dr Pauli Salminen for instructing in the thermal modelling.

References

[1] Lu, Z., McKellop, H., 1997. Frictional heating of bearing materials tested in a hip joint wear simulator. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 211, 101–108. https://doi.org/10.1243/0954411971534728.

[2] Lu, Z., McKellop, H., Liao, P., Benya, P., 1999. Potential thermal artifacts in hip joint wear simulators. J. Biomed. Mater. Res. 48B, 458–464. https://doi.org/10.1002/(SICI)1097-4636(1999)48:4<458::AID-JBM9>3.0.CO;2-B.

[3] Liao, Y.-S., Benya, P.D., McKellop, H.A., 1999. The effect of protein lubrication on the wear properties of materials for prosthetic joints. J. Biomed. Mater. Res. 48B, 465–473. https://doi.org/10.1002/(SICI)1097-4636(1999)48:4<465::AID-JBM10>3.0.CO;2-Y.

[4] Wang, A., Polineni, V.K., Essner, A., Stark, C., Dumbleton, J.H., 1999. Quantitative analysis of serum degradation and its effect on the outcome of hip joint simulator wear testing of UHMWPE. 45th Annual Meeting of the Orthopaedic Research Society, February 1–4, 1999, Anaheim, CA, USA.

[5] Furman, B., Bhattacharyya, S., Soccalingame, M., Li, S., 2000. Effect of protein concentration and serum dilution on the wear rate of UHMWPE cups. 46th Annual Meeting of the Orthopaedic Research Society, poster no. 0578, March 12–15, 2000, Orlando, FL, USA.

[6] Yao, J.Q., Laurent, M.P., Gilbertson, L.N., Blanchard, C.R., Crowninshield, R.D., Jacobs, J.J., 2002. 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, February 10–13, 2002, Dallas, TX, USA.

[7] Liao, Y.-S., McKellop, H., Lu, Z., Campbell, P., Benya, P., 2003. The effect of frictional heating and forced cooling on the serum lubricant and wear of UHMW polyethylene cups against cobalt-chromium and zirconia balls. Biomater. 24, 3047–3059.
https://doi.org/10.1016/S0142-9612(03)00148-0.

[8] Wang, A., Essner, A., Schmidig, G., 2004. The effects of lubricant composition on in vitro wear testing of polymeric acetabular components. J. Biomed. Mater. Res. 68-B, 45–52. https://doi.org/10.1002/jbm.b.10077.

[9] Harsha, A.P., Joyce, T.J., 2011. Challenges associated with using bovine serum in wear testing orthopaedic biopolymers. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 225, 948–958. https://doi.org/10.1177/0954411911416047.

[10] Brandt, J.-M., Charron, K., Zhao, K., MacDonald, S. J., Medley J. B., 2012. Calf serum constituent fractions influence polyethylene wear and microbial growth in knee simulator testing. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 226, 427–440.

https://doi.org/10.1177/0954411912444248.

[11] Wimmer, M.A., Sah, R., Laurent, M.P., Virdi, A.S., 2013. The effect of bacterial contamination on friction and wear in metal/polyethylene bearings for total joint repair—A case report. Wear 301, 264–270. https://doi.org/10.1016/j.wear.2012.11.022.

[12] Scholes, S.C., Joyce, T.J., 2013. In vitro tests of substitute lubricants for wear testing orthopaedic biomaterials. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 227, 693–703. https://doi.org/10.1177/0954411913481549.

[13] Saikko, V., 2018. Effect of lubrication conditions on the wear of UHMWPE with noncyclic motion and load. Trib. Trans. 61, 1141–1150. https://doi.org/10.1080/10402004.2018.1506071.

[14] McKellop, H.A., Campbell, P., Park, S.H., Schmalzried, T.P., Grigoris, P., Amstutz, H.C., Sarmiento, A., 1995. The origin of submicron polyethylene wear debris in total hip arthroplasty. Clin. Orthop. Relat. Res. 311, 3–20.

[15] Calonius, O., Saikko, V., 2003. Force track analysis of contemporary hip simulators. J. Biomech. 36, 1719–1726. https://doi.org/10.1016/S0021-9290(03)00166-0.

[16] Bergmann, G., Graichen, F., Rohlmann, A., Verdonschot, N., van Lenthe, G.H., 2001. Frictional heating of total hip implants. Part 1. measurements in patients. J. Biomech. 34, 421–428. https://doi.org/10.1016/S0021-9290(00)00188-3.

[17] ISO 14242-1:2014(E)/Amd.1:2018(E). 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, 2014/2018.

[18] Brandt, J.-M., Mahmoud, K.K., Koval, S.F., MacDonald, S.J., Medley J.B., 2013. Antimicrobial agents and low-molecular weight polypeptides affect polyethylene wear in knee simulator testing. Tribol. Int. 65, 97–104. https://doi.org/10.1016/j.triboint.2013.02.019.

[19] Brandt, J.-M., Vecherya, A., Guenther, L.E., Koval, S.F., Petrak M.J., Bohm, E.R., Wyss, U.P., 2014. Wear testing of crosslinked polyethylene: wear rate variability and microbial contamination. J. Mech. Behav. Biomed. Mater. 34, 208–216. https://doi.org/10.1016/j.jmbbm.2014.02.016.

[20] Guenther, L.E., Turgeon, T.R., Bohm, E.R., Brandt, J.-M., 2015. The biochemical characteristics of wear testing lubricants affect polyethylene wear in orthopaedic pin-on-disc testing. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 229, 77–90. https://doi.org/10.1177/0954411914567930.

[21] Saikko, V., 2005. A hip wear simulator with 100 test stations. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 219, 309–318. https://doi.org/10.1243/095441105X34301.

[22] Oral, E., Greenbaum, E.S., Malhi, A.S., Harris, W.H., Muratoglu, O.K., 2005.

Characterization of irradiated blends of α-tocopherol and UHMWPE. Biomater. 26, 6657–6663. https://doi.org/10.1016/j.biomaterials.2005.04.026.

[23] Bracco, P., Oral, E., 2011. Vitamin E-stabilized UHMWPE for total joint implants: a review. Clin. Orthop. Relat. Res. 469, 2286–2293. https://doi.org/10.1007/s11999-010-1717-6.

[24] Grupp, T.M., Holderied, M., Mulliez, M.A., Streller, R., Jäger, M., Blömer, W., Utzschneider, S., 2014. Biotribology of a vitamin E-stabilized polyethylene for hip arthroplasty – Influence of artificial aging and third-body particles on wear. Acta Biomater. 10, 3068–3078. https://doi.org/10.1016/j.actbio.2014.02.052.

[25] Popoola, O.O, Orozco Villasenor, D.A., Fryman, J.C., Mimnaugh, K., Rufner, A., 2018. High cycle in vitro hip wear of and in vivo biological response to vitamin E blended highly cross-linked polyethylene. Biotribol. 16, 10–16. https://doi.org/10.1016/j.biotri.2018.09.001.

[26] Feskanin, H., Barnes, B., Loftus, E., Stroud, N., 2019. Hip wear simulator results of vitamin E-blended highly crosslinked polyethylene. Orthop. Proc. 101-B, Supp. 5, 106.

[27] Kaku, N., Tagomori, H., Akase, H., Tabata, T., Kataoka, M., Tsumura, H., 2019. Efficacy of vitamin E for mechanical damage and oxidation of polyethylene rim by stem neck impingement. Clin. Biomech. 68, 8–15. https://doi.org/10.1016/j.clinbiomech.2019.05.024.

[28] Saikko, V., 2006. Effect of contact pressure on wear and friction of ultra-high molecular weight polyethylene in multi-directional sliding. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 220, 723–731. https://doi.org/10.1243/09544119JEIM146.

[29] Saikko, V., 2005. A 12-station anatomic hip joint simulator. Proc. Inst. Mech. Eng., Part H: J. Eng. Med. 219, 437–448. https://doi.org/10.1243/095441105X34419.

[30] Viitala, R., Saikko, V., 2020. Effect of random variation of input and various daily activities on wear in a hip joint simulator. J. Biomech. 106, 109831. https://doi.org/10.1016/j.jbiomech.2020.109831.

[31] Privalov, P.L., 1990. Cold denaturation of proteins. Crit. Rev. Biochem. Molec. Biol. 25, 281–306. https://doi.org/10.3109/10409239009090612.

[32] Saikko, V., 2010. Performance analysis of an orthopaedic biomaterial 100-station wear test system. Proc. Inst. Mech. Eng., Part C: J. Mech. Eng. Sci. 224, 697–701. https://doi.org/10.1243/09544062JMES1626.

Highlights

- Multidirectional pin-on-disk and hip simulator tests were performed for VEXLPE
- VEXLPE wear and friction were highly sensitive to temperature
- Type of serum had a strong effect on wear and friction at and above 20 °C
- Alpha calf serum proved superior to bovine calf serum
- Thermal analysis showed that POD contact temperature was close to serum temperature

Conflict of interest statement

The authors have nothing to declare.