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High frequency circular translation pin-on-disk method for accelerated wear testing of ultrahigh molecular weight polyethylene as a bearing material in total hip arthroplasty

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Abstract

The temporal change of the direction of sliding relative to the ultrahigh molecular weight polyethylene (UHMWPE) component of prosthetic joints is known to be of crucial importance with respect to wear. One complete revolution of the resultant friction vector is commonly called a wear cycle. It was hypothesized that in order to accelerate the wear test, the cycle frequency may be substantially increased if the circumference of the slide track is reduced in proportion, and still the wear mechanisms remain realistic and no overheating takes place. This requires an additional slow motion mechanism with which the lubrication of the contact is maintained and wear particles are conveyed away from the contact. A three-station, dual motion high frequency circular translation pin-on-disk (HF-CTPOD) device with a relative cycle frequency of 25.3 Hz and an average sliding velocity of 27.4 mm/s was designed. The pins circularly translated at high frequency (1.0 mm per cycle, 24.8 Hz, clockwise), and the disks at low frequency (31.4 mm per cycle, 0.5 Hz, counter-clockwise). In a 22 million cycle (10 day) test, the wear rate of conventional gamma-sterilized UHMWPE pins against polished CoCr disks in diluted serum was 1.8 mg per 24 h, which was 6 times higher than that in the established 1 Hz CTPOD device. The wear mechanisms were similar. Burnishing of the pin was the predominant feature. No overheating took place. With the dual motion HF-CTPOD method, the wear testing of UHMWPE as a bearing material in total hip arthroplasty can be substantially accelerated without concerns of the validity of the wear simulation.

Keywords: Accelerated wear testing; Circular translation; High frequency; Pin-on-disk; UHMWPE

1. Introduction

Wear tests of prosthetic joints and of their materials are time-consuming, because the implants are expected to perform without major problems for decades. The tests cannot be accelerated by increasing the sliding velocity to an unphysiological level, that is, much above 50 mm/s, since excessive velocity is likely to result either in overheating or in the formation of an unrealistic fluid film, depending on the geometry of the contact. In both cases, the wear simulation is distorted.

For the laboratory simulation of clinical wear mechanisms of prosthetic joints, the multidirectionality of the relative motion and a serum-based lubricant are known to be absolute prerequisites (Bragdon et al., 1996; Gevaert et al., 2005; Hua et al., 2014; Joyce et al., 2000; Rieker et al., 2002; Saikko, 1998; Saikko and Kostamo, 2011; Sawae et al., 2008; Scholes and Joyce, 2013; Wang et al., 1996). The higher the aspect ratio of the slide track in cyclic motion is, the lower is the wear factor of conventional UHMWPE (Saikko et al., 2004). In unidirectional or linear reciprocating motion, the wear factor can be 2 to 3 orders of magnitude lower compared with clinical observations. Circular translation (aspect ratio unity), in which the direction of sliding relative to the UHMWPE specimen rotates at a constant angular velocity, usually one revolution per second, produced the maximum wear factor (Saikko et al., 2004), the value of which was in agreement with clinical findings (Hall et al., 1996). The circular translation pin-on-disk (CTPOD) device (Saikko, 1998; Saikko, 2005) was a flat-on-flat modification of the widely used biaxial rocking motion (BRM) hip joint simulator (McKellop and Clarke, 1985; ISO 14242-3, 2009). In most BRMs, the circumference of the circular track drawn by the resultant force vector is $2\pi r\sin 23°$, where r is the radius of the femoral head (Saikko and Calonius, 2002). The angle of the leaning axis is usually 23°. It was found with a lower angle of the leaning axis, 11.5°, in a BRM simulator (the circumference of the force track was $2\pi r\sin 11.5°$) that the wear rate, expressed as mg/10^6

cycles, was insensitive to the circumference of the force track (Saikko et al., 2003). The fact that there was one revolution of the friction vector per second relative to the UHMWPE cup was the decisive factor. In other words, it appears that as long as the force track is circular, the wear rate (mg/10^6 cycles) is insensitive to the track diameter. A similar result was later published by Wang et al. (2013). One revolution is considered to represent one wear cycle. The number of cycles is assumed to determine the detachment of the microscopic surface asperities by fatigue. In the CTPOD device the diameter of the slide track is 10.0 mm.

It was hypothesized that in order to accelerate the wear test, the diameter of the track in a CTPOD device can be substantially reduced, and the cycle frequency correspondingly increased, and still the wear mechanisms remain realistic, as the sliding velocity is not increased. This requires another, slow motion to maintain the lubrication and to convey the wear debris away from the contact. A three-station, dual motion high frequency circular translation pin-on-disk (HF-CTPOD) device with a relative frequency of 25.3 Hz and average sliding velocity of 27.4 mm/s was designed. In the established CTPOD, one test of 3 million cycles takes 6 weeks (Saikko, 2005), whereas in the HF-CTPOD, 3 days may be sufficient as a test length, as the device produces 2.2 million cycles in 24 hours.

2. Materials and methods

In the three-station, dual motion HF-CTPOD device (Fig. 1), the pin holder circularly translated clockwise so that the circumference of the track was 1.0 mm, at a cycle frequency of 24.8 Hz, driven by an eccentric (0.16 mm) shaft via a needle bearing (Fig. 2). The eccentric shaft was fixed directly on the rotor shaft of an electric motor with a rotational speed of 1487 rpm, which was measured during the normal running of the test. The three pin holder shafts made from stainless steel were horizontally guided by polyacetal sleeves with a diametral clearance of 0.32 mm. Hence the pins were forced by the eccentric shaft to circularly translate so that the diameter of the slide track was 0.32 mm. The extent of motion was checked with a displacement indicator during the normal running of the test. The advantage of the above mechanism for producing circular translation in a high frequency application was that no roller bearings and eccentric shafts were needed above the test stations. The pins were made from conventional gamma-nitrogen-sterilized (25 kGy) UHMWPE (GUR 1020, ISO 5834-1/-2). Their diameter was 9.0 mm and length 12.0 mm. The contact was flat-on-flat.

The polished CoCr (ISO 5832-12, surface roughness R_a value 0.01 μm) disks circularly translated counterclockwise so that the diameter of the slide track was 10.0 mm, at a cycle frequency of 0.5 Hz. The motion plate of the disks was driven by another electric motor, similar to that driving the pin holder, via a 48:1 reduction. The so-called parallel crank mechanism was used (Saikko, 1998). Hence the relative cycle frequency was 25.3 Hz, and the relative sliding velocity varied between 9.1 mm/s and 40.5 mm/s (Fig. 3). The average relative sliding velocity was 27.4 mm/s. The velocity of the low frequency translation was chosen to be lower than that of the high frequency translation in order to produce a full rotation of the velocity vector relative to the pin during one high frequency cycle (0.04 s). The load (70.7 N) was applied by pneumatic loading cylinders to the pins via flexible rods (dia. 2 mm) made from spring steel. The use of the rods allowed the loading cylinders to be stationary, yet no load transfer mechanism between the cylinders and the pin holder was needed. The value of the nominal contact pressure, 1.1 MPa, was adopted from earlier SuperCTPOD work (Saikko, 2005). This value has been used also in other CTPOD studies (Hua et al., 2014; Scholes and Joyce, 2013; Smelt et al., 2013).

The lubricant was HyClone Alpha Calf serum (SH30212.03) diluted 1:1 with distilled water, without any additives. The protein concentration of the lubricant was 21 mg/ml, not too far from that of periprosthetic synovial fluid, 29 mg/ml (Yao et al., 2002). The use of a lubricant of this composition resulted in clinically relevant wear in the SuperCTPOD (Saikko,

2005) and in the RandomPOD (Saikko and Kostamo, 2011). The amount of lubricant in each chamber was 10 ml. Its temperature was monitored but not controlled. The relatively low volume was considered sufficient because the lubricant was changed every 24 hours, and the frictional power was estimated to be below 0.3 W. For efficient mixing of the lubricant during testing the internal diameter of the lubricant chamber was only 28 mm, a value adopted from the SuperCTPOD (Saikko, 2005), but the height of the chamber was reduced so that the pin holder sleeves could be made shorter for reasons of stability and rigidity of the pin holder (Figs. 1 and 2).

With the dual motion, a 10 day test of 22 million cycles was run at room temperature (mean 26 °C). The wear of the pins was measured gravimetrically at intervals of 24 hours (2.2 million cycles) using a Mettler AT261 DeltaRange balance with a resolution of 0.01 mg. The pins or the disks were not changed between test stations. Reference tests were run with the large, 0.5 Hz motion only, and with the short, 24.8 Hz motion only. In the calculation of the wear factor, a density value of 0.93 mg/mm^3 was used (Kurtz et al., 1997).

3. Results

The wear per 24 h of the UHMWPE pins in the dual motion test, 1.80 ± 0.05 mg/24 h, was considerably higher than that in the single motion tests (Table 1). The above wear rate corresponded to 0.82 ± 0.02 mg/10^6 cycles (Fig. 4). The worn pins had a burnished appearance (Fig. 5). No overheating took place, nor was there any damage on the CoCr disks, such as scratching or polyethylene transfer. The surface roughness of the disks after the tests was not increased. In the tests with short motion only, the worn UHMWPE surface showed abnormal features in the form of separate ‘islets’ with coarser topography, probably caused by local deficiency of lubrication (Fig. 6).

4. Discussion

For the first time, a substantially accelerated, multidirectional pin-on-disk study was performed with the most common material combination used in prosthetic joints, conventional gamma-inert-sterilized UHMWPE against polished CoCr, so that no overheating took place and the wear mechanisms were realistic. The increase of the lubricant temperature (4 °C) relative to the environment temperature was moderate, and it was in line with that measured in the 12-station CTPOD device (Saikko, 1998). Burnishing is a phenomenon typical of retrieved UHMWPE prosthetic components (Kurtz, 2009; McKellop et al., 1995). The absence of overheating was attributable to the fact that the average sliding velocity, 27.4 mm/s, was not excessive with respect to actual prosthetic joints. The sliding velocity varied between 9.1 mm/s and 40.5 mm/s which is a range typical of contemporary prosthetic hips (Calonius and Saikko, 2003). The average sliding velocity was actually *lower* than the constant sliding velocity in the established 1 Hz CTPOD devices, 31.4 mm/s (Saikko, 1998; Saikko, 2005). With the dual CTPOD motion, the lubrication of the contact was maintained, and wear debris was conveyed away from the contact which was not miniaturized but was of real size, 63.6 mm^2, and still the test was highly accelerated with respect to the cycle frequency, 25.3 Hz. An additional advantage of the present test protocol was that the effect of temporal degradation of serum was reduced as the lubricant change interval was 24 h only.

The most commonly used cycle frequency in wear testing of orthopaedic biomaterials is 1 Hz (Affatato et al., 2008; Kurtz, 2009). A frequency of 2 Hz, resulting in an average sliding velocity of 60 mm/s, has been used in pin-on-disk testing (Bragdon et al., 2001). With a hip simulator also, 2 Hz has been used (Bragdon et al., 1996). In these two studies, the wear of UHMWPE with 2 Hz was close to that produced with 1 Hz. An exceptional 5 Hz single-axis, water lubricated hip simulator test has been done (Pappas et al., 1995), but the maximum sliding velocity in the test apparently was close to 200 mm/s, which is excessive. In 1 Hz testing, efficiency can be increased by large capacity, such as 100 test stations (Saikko, 2005). Another way of increasing the efficiency is to increase the cycle frequency, as shown in the present study.

With similar specimens, load and lubricant, the mean wear rate with 1 Hz frequency in the SuperCTPOD test (sliding velocity constant 31.4 mm/s) was 3.40 mg/10^6 cycles (n = 100), corresponding to 0.29 mg per 24 h, and the mean wear factor was 1.63×10^{-6} mm^3/Nm (Saikko, 2005). Compared with these results, the wear per 24 h with dual motion in the present study was 6.1 times higher, the wear factor was 7.1 times higher, whereas the wear rate expressed as mg/10^6 cycles was one fourth. This indicates that the short motion is not as efficient in completely removing the wear particle from the pin wear surface as the large motion is, but still the wear in a unit time and the wear factor were substantially increased. It is possible that some of the particles removed by the short motion remained between the contacting surfaces and were not readily conveyed into the lubricant bath, and thus they reattached and did not reduce the weight of the UHMWPE pin. The importance of the large motion in conveying wear debris away from the contact was proven by the test with short motion only which showed a wear rate of an order of magnitude lower than that with dual motion. The type of wear with short motion only (Fig. 6) indicated local deficiency of lubrication. In addition, occasional, subtle scratches were observed, the diameter of which was close to the designed slide track diameter, 0.32 mm, of the short circular translation, which proved that the drive mechanism worked as intended.

A limitation of the study was that only one material combination was tested. The applicability of the novel HF-CTPOD method to combinations other than conventional UHMWPE against polished CoCr needs to be evaluated with additional studies in the future.

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Table 1. Wear test results for UHMWPE pins with different types of relative motion in HF-CTPOD device (mean values).

Type of motion	Test duration (h)	Test length (10^6 cycles)	Wear rate (mg/24 h)	Wear rate (mg/10^6 cycles)	Wear factor (10^{-6} mm^3/Nm)	ΔT^* (°C)
Dual CT**	240	21.9	1.80	0.82	11.6	4
Large CT	72	0.134	0.27	6.05	2.93	1
Short CT	72	6.42	0.20	0.09	1.40	5

*Increase of lubricant temperature relative to environment temperature

**Circular Translation

Figure captions

Figure 1. Three-station, dual motion HF-CTPOD device; (A) test chamber, (B) central drive shaft (eccentricity 0.16 mm, speed 1487 rpm), (C) triple pin holder (short, fast circular translation, track circumference 1.0 mm), (D) guide sleeve (made from polyacetal, diametral clearance 0.32 mm) of pin holder shaft, (E) counterweight disk, (F) disk motion plate (large, slow circular translation, track circumference 31.4 mm, drive shaft speed 31 rpm), (G) pneumatic loading cylinder, (H) loading rod.

Figure 2. Triple pin holder, shown upside down. Pin holder sleeves (press fit) are made from 316L stainless steel (ASTM F138). Needle bearing has spherical housing which ensures uniform loading among pins.

Figure 3. Variation of relative sliding velocity between UHMWPE pin and CoCr disk with time in dual motion with HF-CTPOD device. In 0.04 s, direction of sliding rotated 360° relative to pin.

Figure 4. Variation of wear of UHMWPE pins with number of cycles in dual motion HF-CTPOD test.

Figure 5. Optical micrograph from edge of worn UHMWPE surface, which was burnished and flat, after dual motion HF-CTPOD test.

Figure 6. Optical micrograph from worn UHMWPE surface after test with short motion only. Separate 'islets' with coarser topography are not typical of clinical wear. Diameter of scratches (top right) indicate that true relative motion of short circular translation was of intended extent.

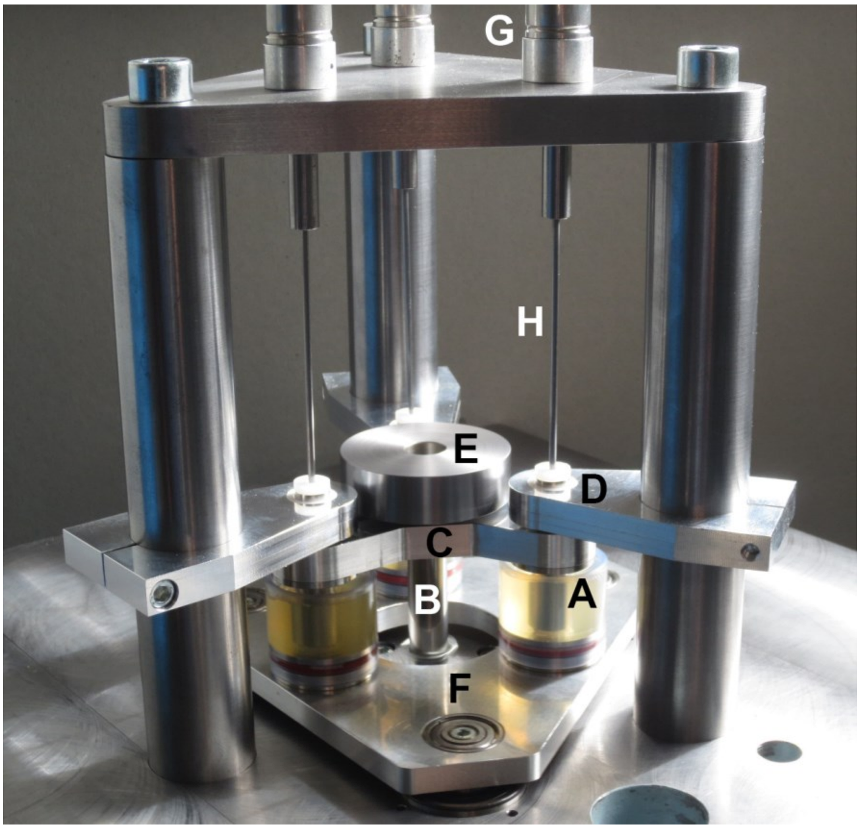
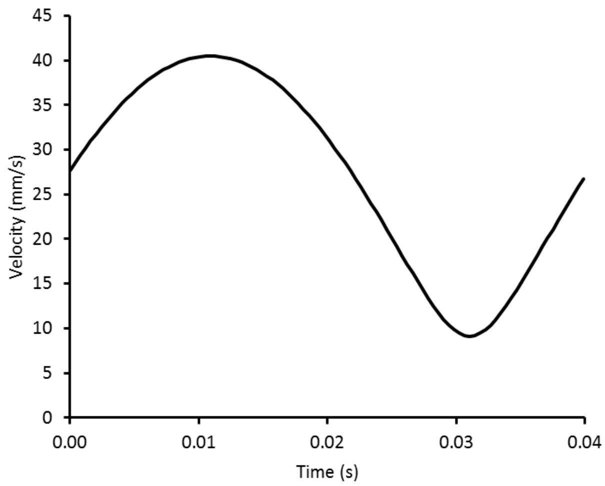


Figure 1.

Figure 2.



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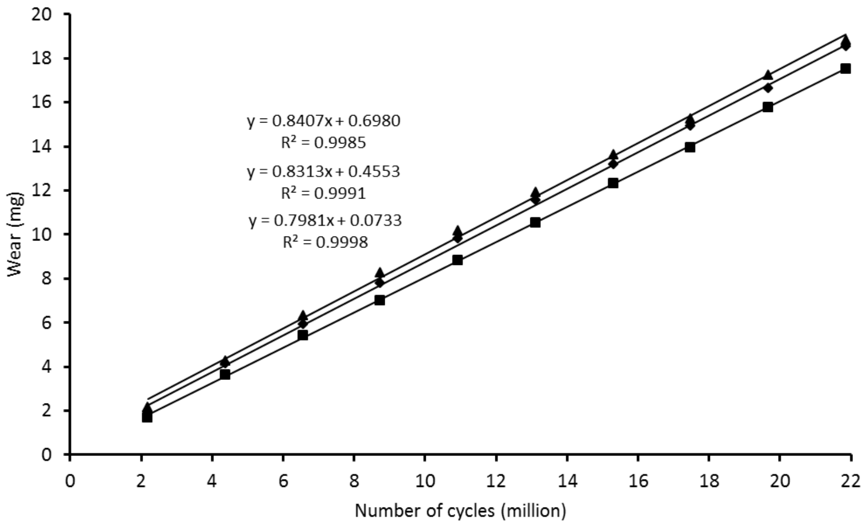

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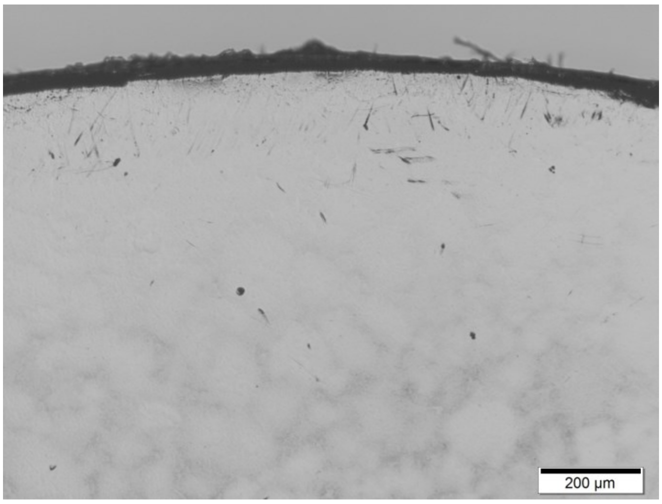

Figure 5.

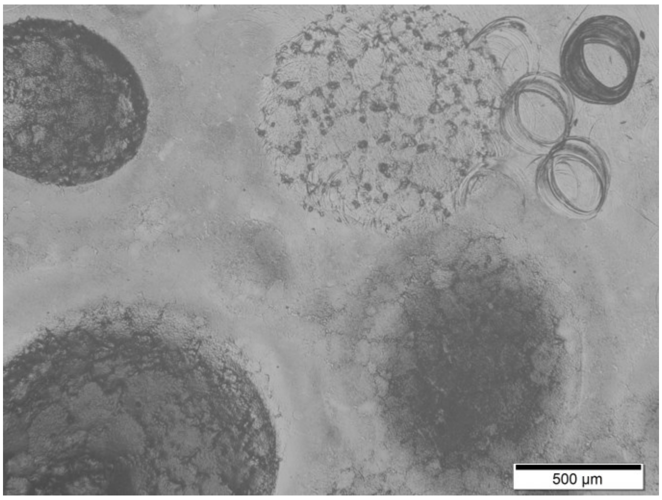

Figure 6.