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Performance analysis of the RandomPOD wear test system

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Abstract

The type of relative motion between the bearing surfaces of prosthetic joints is known to strongly influence their wear behaviour. The previously validated 16-station wear simulator of the pin-on-disc type, called RandomPOD, was used to study the wear of a conventional, gamma-sterilized ultra-high molecular weight polyethylene (UHMWPE). The counterface was polished CoCr and the lubricant was diluted calf serum. Two test conditions were compared, random motion/random load and circular translation/static load. With random motion, the accumulated change of the direction of sliding was 2.8 times higher than that with circular translation. The test duration with both test conditions was 880 h. Random motion/random load resulted in a mean wear factor 23 per cent higher than that produced with circular translation/static load. The difference was statistically significant. The wear mechanisms however were similar and in agreement with clinical observations. As earlier studies have shown that the type of load is of secondary importance, the present study confirms the earlier findings that the type of relative motion is tribologically of fundamental importance. In particular, the complex, yet biomechanically realistic non-cyclic motion, represented by the random track, resulted in a wear factor significantly higher than that produced by a fixed slide track shape.

Keywords: Bio-tribology, joint prostheses; Wear testing; Sliding wear; Polymers

1. Introduction

The type and rate of wear of prosthetic joints strongly depend on the type of relative motion between the articulating surfaces [1]. Laboratory wear tests for orthopaedic biomaterials have shown that the way in which the direction of sliding changes is of fundamental importance [2,3]. Circular translation [4] has been shown to produce the highest wear rate together with realistic wear mechanisms [5]. Many different activities take place daily, and the relative motions in a certain activity, say, level walking, do not remain unchanged. Until recently, mainly fixed slide track patterns have been used in wear testing, which undoubtedly differs from the clinical situation [6]. Therefore, there is a growing interest in orthopaedic tribology research to use more diverse motion input in wear simulation studies [7].

A new wear test method and device of a pin-on-disc type, called RandomPOD, was recently described and validated [8]. With a certain type of biomechanically realistic random motion between the pin and the disc, the wear factor of conventional, non-irradiated ultra-high molecular weight polyethylene (UHMWPE) was almost twice that with circular translation. The basic idea in the RandomPOD is that the biaxial random motion includes a wide variety of track features with a view to producing wear that is as realistic as possible. The principle of random motion and random load is unique and it differs fundamentally from all earlier methods used in this field.

The main differences between the validation paper [8] and the present study are that this time, the UHMWPE pins were gamma-sterilized, the tests were longer, and the lubricant temperature was lower. Moreover, the sliding velocity of circular translation was halved so that it was equal to the average velocity of random motion. The distribution of the random travel was presented for the first time. The hypothesis was that with the clinically most used bearing material, gamma-sterilized UHMWPE, the mean wear factor with random motion exceeds that obtained with a fixed, multidirectional motion.

2. Methods

The 16-station RandomPOD design (Fig. 1) has servo-electric x-y motion and proportional-pneumatic loading. The motions and the load are computer-controlled. The range of both motions is 10 mm, and the maximum load is 150 N per station. The random motion was programmed so that the slide track of the pin always remained inside a circle of 10 mm diameter (Figs. 2 and 3). The sliding velocity varied from zero to 31.4 mm/s so that the average value was 15.7 mm/s. The acceleration varied from zero to 300 mm/s^2. The radius of curvature of the track varied from zero to infinity. The occasional reversals were smooth, as in a reciprocator driven by a crank. The random load varied from zero to 142 N with an average close to 71 N. The load set value was a smoothened 5 Hz random step signal. The maximum load change rate of the set value signal was limited to 300 N/s. In the random track, the accumulated change of direction of sliding (absolute value of computed increment summed) was 2.8 times that of the circular track with the same sliding distance. In circular translation, the pin translated along a circular track of 10 mm diameter relative to the disc with constant sliding velocity of 15.7 mm/s, and so the direction of sliding relative to the pin changed at a constant rate, π/s. This was half of that used in the validation study [8] in order to have a sliding velocity equal to the average sliding velocity of the random motion. With circular translation, a constant value of load, 71 N, was applied.

The pins (diameter 9.0 mm, length 12 mm) were conventional GUR 1020 UHMWPE (ISO 5834-1/-2). They were gamma-irradiated by 25–40 kGy in nitrogen, a method used in the sterilization of prosthetic components. The discs were polished CoCrMo wrought alloy (ISO 5832-12) with a surface roughness R_a value of 0.01 µm. The contact was flat-on-flat (area 63.6 mm^2). The lubricant was HyClone Alpha Calf Fraction serum SH30212.03, diluted 1:1 with Milli-Q-grade distilled water. The total protein concentration of the lubricant was 20 mg/ml. The RandomPOD has a separate lubricant chamber for each test station, containing 18 ml of lubricant.

A new temperature control system was added to the device. The lubricant chambers were surrounded by circulating cooling water. The control system kept the lubricant temperature at 20 ± 0.5 °C with a view to retarding the detrimental denaturation and degradation of serum.

The test duration was 36 days, and the total sliding distance was c. 50 km. The accumulated change of direction of sliding was 1.6×10^9 degrees with random motion and 0.57×10^9 degrees with circular translation. The test was stopped every 6 days for the weighing of the pins. In this way, 6 points were obtained for the determination of the wear rate using linear regression. From this, the wear factor was calculated using the numerically integrated product of the instantaneous load and sliding increment [8], and the density of UHMWPE. Two consecutive 36 day tests were run, first with random motion/random load and then with circular translation/static load. The same pins were used in both tests. The wear factors were compared with a t-test. In each reassembly, the position and location of the specimens were randomized (Table 1), and the lubricant chambers were filled with fresh serum.

In addition, two shorter tests of 6 day duration were done with the same specimens to check the following. First, whether the wear factor in the circular translation/static load mode using the 15.7 mm/s sliding velocity differs from that produced by the device with the sliding velocity of 31.4 mm/s used in the earlier study [8]. Second, with random motion/random load, after the circular translation/static load tests were completed, to see if the wear factor returns to the value obtained in the first 36 day test.

3. Results

Under both test conditions, the wear surface of the pins became flat and highly polished (Fig. 4). On the discs there was no damage, such as transfer layers, depositions, or scratches. The appearances were checked at each wear measurement stop, and the above held true for the entire course of the tests. Wear was highly linear, and the mean wear factor resulting from random motion/random load was 23 per cent higher than that resulting from circular translation/static load (Table 2). The difference was statistically significant ($p = 2 \times 10^{-7}$).

The observations from the shorter, 6 day tests were as follows. First, there was no significant difference in the mean wear factors produced by the device in the circular translation mode with two different sliding velocities, 15.7 mm/s and 31.4 mm/s ($p = 0.98$). The wear rate with the higher velocity was 0.195 ± 0.043 mg/km and the wear factor was 2.93 ± 0.65×10^{-6} mm^3/Nm. Second, there was no significant difference between the mean wear factors produced with random motion/random load in the 36 day test and in the 6 day test ($p = 0.55$), between which the circular translation/static load tests were run, i.e., the wear factor did return to the higher value. In the 6 day test, the wear rate was 0.308 ± 0.034 mg/km and the wear factor was 4.50 ± 0.49×10^{-6} mm^3/Nm. The wear factors of the 6 day tests were compared with those of the first 6 day stages of the 36 day tests after the running-in stage.

4. Discussion

The present test results produced by the RandomPOD device confirmed the earlier findings that the complex relative motion, random track, produced a significantly higher wear rate compared with a fixed circular slide track [8]. The reason for this most probably was the fact that the accumulated change of direction of sliding in random motion was 2.8 times higher than that in the circular translation. The effect could be compared to fatigue testing. The rupture in this case is the detachment of microscopic surface asperities which thus turn into wear particles. In great numbers the particles are clinically harmful, because the tissue reaction to them may lead to osteolysis and component loosening. The more the local frictional force changes its direction in unit time, the faster is the generation of particles. Note that the change of the sliding direction on the ‘force track’ of the hip during one walking cycle may be much higher than 360 degrees [6,9].

Considering the large difference in the total change of sliding direction, that was 2.8 times, the difference in the wear factors was moderate, yet significant. As the difference in mean wear factors was not higher than 23 per cent, the fact that the p value was as low as 2×10^{-7} is an indication of an excellent performance of the RandomPOD wear test system. The above was mainly due to the low standard deviations of wear factors (7 and 11 percent of the mean), and high n values (16). Historically, the typical n value in orthopaedic tribology research has been 3, mainly due to inadequate testing capacity. This problem has recently been solved by the 100-station SuperCTPOD [10,11], and its commercial versions (TE 87), the current users of which represent universities, producers of orthopaedic implant materials, manufacturers of orthopaedic implants, and testing service companies. Regarding the testing capacity, the RandomPOD is the second most powerful device available.

The wear mechanisms were similar with both test conditions. The UHMWPE wear surface was highly burnished (Fig. 4b) and the CoCr counterface was undamaged. These are typical observations with multidirectional motion and protein-containing lubricant, in the absence of abrasives [2,4,10,12–15].

It was encouraging to note that in the final 6 day test run with random motion/random load, the wear factor returned to a value very close to that obtained in the first 36 day test with the same conditions. The null hypothesis could not be rejected ($p = 0.55$). This is a proof that the difference in wear factors between the two 36 day tests really was caused by differences in the type of motion, and not, e.g., by some time-dependent changes in the wear resistance of the polyethylene material. The type of load was shown in earlier tests to be unimportant [8]. The pins were packed and gamma-irradiated in nitrogen two months before the tests were initiated, so the possibility of oxidation damage was virtually zero. Oxidation is known to take years to become significant with respect to mechanical properties [16].

In the CTPOD mode, the difference in the mean wear factors produced with two values of constant sliding velocity, 15.7 mm/s and 31.4 mm/s, corresponding to cycle frequencies of 0.5 Hz and 1 Hz, was not statistically significant ($p = 0.98$). This indicates that the higher value can very well be used in order to produce more cycles in a unit time, without the risk of abnormal wear phenomena caused by, for instance, excessive frictional heat. Whether the above-mentioned higher value could still be doubled for accelerated testing would need further trials to see if the wear mechanisms and the wear factor would remain unchanged. The 2 Hz cycle frequency has been used earlier in pin-on-disc studies with a rectangular slide track (10 mm × 5 mm) so that the average sliding velocity was 60 mm/s [17]. The wear did not differ from that produced in the reference test of 1 Hz frequency.

In the validation study [8], non-irradiated pins were used. With random motion/random load, the present wear factor was 43 percent lower, and with circular translation/static load, 27 per cent lower. Even the relatively moderate dose of gamma-irradiation used in the sterilization of UHMWPE components (25–40 kGy) apparently improves the wear resistance by crosslinking. A high dose (100 kGy) has been shown to result in a reduction of wear rate by as much as an order of magnitude [11,18]. The similar clear difference is already seen clinically [19].

A review of different types of relative motion that have been used in pin-on-disc studies of orthopaedic biomaterials is presented in [7]. It is interesting to note that a very complex slide track pattern is generated between the femoral and tibial bearing surfaces of total knee prostheses [20]. This becomes especially obvious in laboratory wear tests with a force control of the anterior-posterior translation and of the internal-external rotation. The slide track pattern under these circumstances is strongly influenced by the shape of the bearing surfaces of the design in question. Moreover, the pattern changes with the wear of the UHMWPE bearing surfaces in an uncontrolled manner. Hence the RandomPOD with a ball-on-flat specimen configuration can be a valuable tool in the study of knee wear as well. The same – but rather with the present flat-on-flat configuration – most likely holds true with respect to the wear studies of the total disc arthroplasty, in which multidirectional motion is a necessity [21,22], quite as it is with the hip and the knee [12]. Note that the RandomPOD can easily be programmed to produce virtually any slide track shape, and any dynamic load profile, if certain types of fixed tracks and profiles are considered practicable. The random features of the machine actually are its extreme and unique characteristics, standing out as functions never before implemented by any other tribosimulator.

5. Conclusions

With conventional, gamma-sterilized UHMWPE, the complex, yet biomechanically realistic non-cyclic motion and load resulted in a mean wear factor significantly higher than that produced by a fixed slide track and load. The standard deviations of the wear factors (n = 16) were low. Under both test conditions, the wear mechanisms were similar to those observed clinically. In the field of orthopaedic tribology, fixed conditions are commonly used in wear testing, but there is a growing interest in using more diverse motion and load input to further improve the wear simulation. The findings of the present study indicate that this trend is well justified.

Conflict of interest statement

The authors do not have any conflicts of interest to disclose.

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Table 1. Randomization of component location and position in each reassembly.

Variable	No. of possibilities	Note
Location of pin in the device	16	equals to no. of test stations
Location of disc	16	
Location of lubricant chamber, and o-ring	16	
Rotational position of pin within its holder	unlimited	rotationally symmetric pin
Rotational position of disc on the motion plate	2	equals to no. of locking pins
Rotational position of pin guide module in the device	4	equals to no. of support poles

Table 2. Wear rate and wear factor with two different test conditions. Mean ± standard deviation. Test duration 880 hours, six wear measurement points, n = 16.

Type of motion	Type of load	Wear rate (mg/km)	Correlation coefficient of linear regression R^2	Wear factor (10^{-6} mm^3/Nm)
Random	Random	0.265 ± 0.017	0.9983 ± 0.0011	3.92 ± 0.26
Circular translation	Static	0.214 ± 0.024	0.9927 ± 0.0030	3.19 ± 0.36

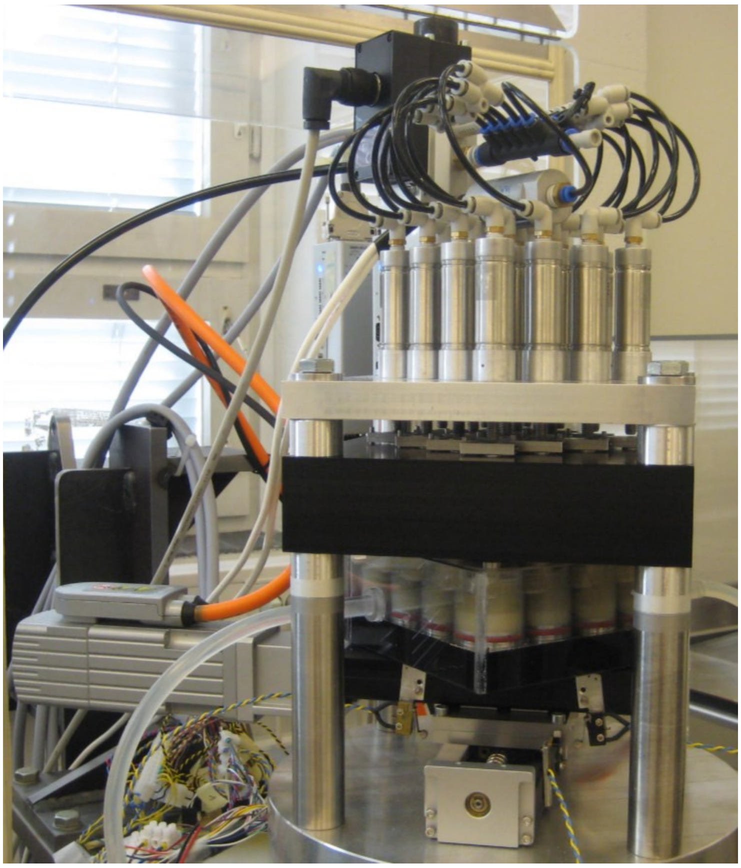


Figure 1. RandomPOD wear test device with 16 test stations. Note servo-electric x-y-table for translation of discs, and proportional-pneumatic, vertical loading of pins. Test chambers are surrounded by circulating cooling water.

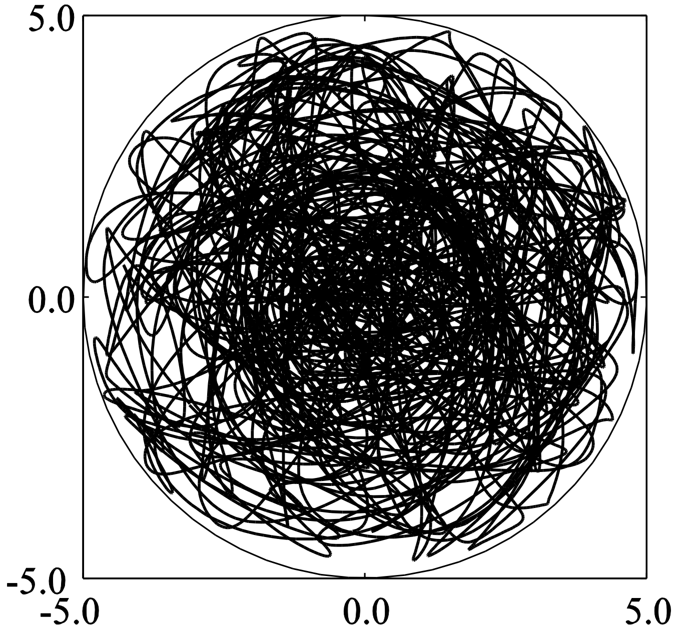


Figure 2. Example of random track after 2 min of sliding. Track never crosses boundary circle of 10 mm diameter.

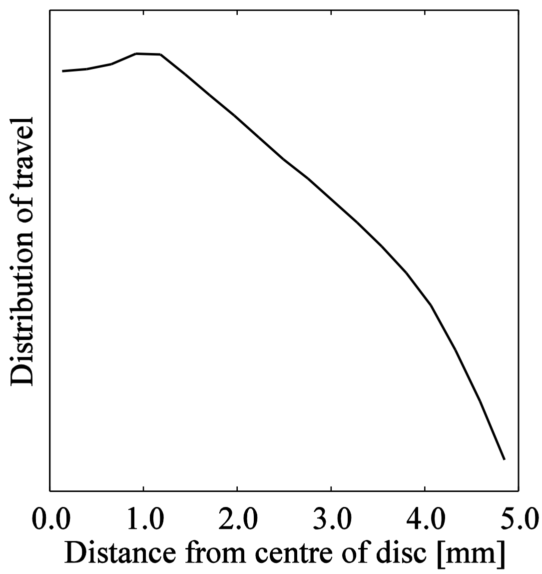
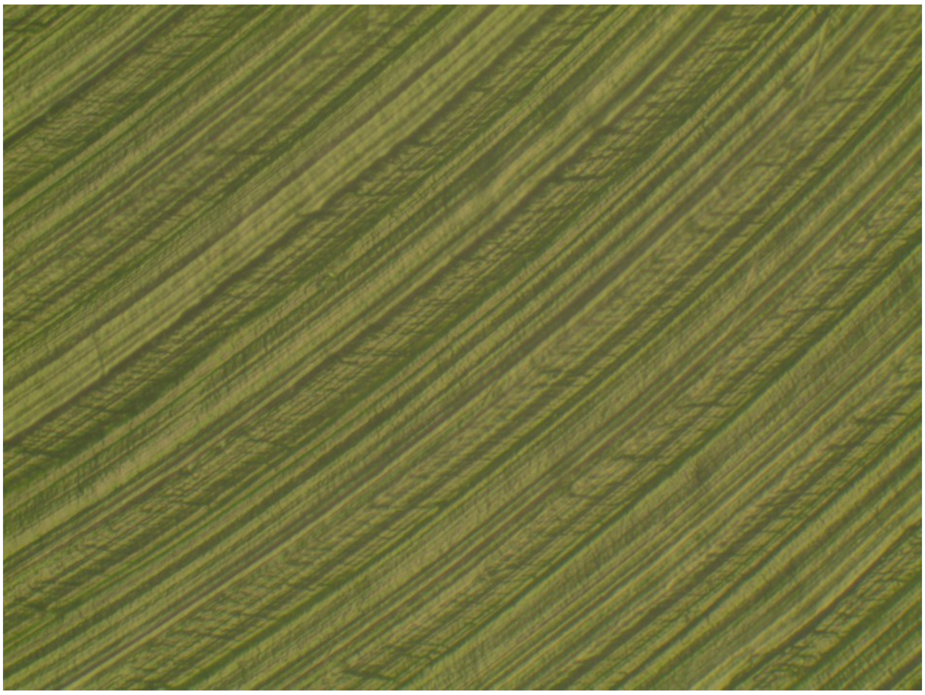
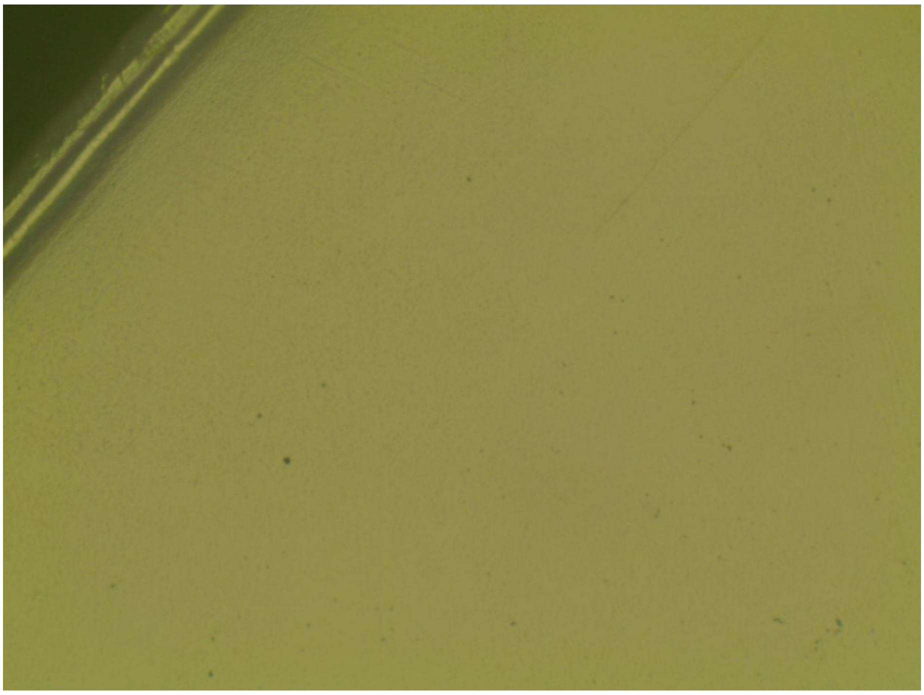


Figure 3. Distribution of random travel on disc. A total of 360 000 points were computed, time interval being 0.01 s, corresponding to 60 min of sliding. In computation, disc was divided into 0.1 mm wide concentric rings, and total length of travel on each ring was divided by area of ring.



(a)



(b)

Figure 4. Optical micrographs from UHMWPE wear surface, (a) original machined, (b) worn under conditions of random motion/random load. Note flatness and smoothness in (b), in which pin edge is seen top left. In both, picture width corresponds to 0.33 mm.

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