Aalto University

Aaltodoc
OPEN ACCESS

This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Author(s): Saikko, Vesa

Title: High frequency circular translation pin-on-disc wear testing of UHMWPE using a ball-on-flat contact along a hypotrochoidal track

Year: 2017

Version: Post print

Please cite the original version:

Saikko, Vesa. 2017. High frequency circular translation pin-on-disc wear testing of UHMWPE using a ball-on-flat contact along a hypotrochoidal track. Polymer Testing. Volume 60. 149-152. ISSN 0142-9418 (printed). DOI: 10.1016/j.polymertesting.2017.03.024.

Rights: © 2017 Elsevier BV. This is the post print version of the following article: Saikko, Vesa. 2017. High frequency circular translation pin-on-disc wear testing of UHMWPE using a ball-on-flat contact along a hypotrochoidal track. Polymer Testing. Volume 60. 149-152. ISSN 0142-9418 (printed). DOI: 10.1016/j.polymertesting.2017.03.024, which has been published in final form at http://www.sciencedirect.com/science/article/pii/S0142941817301824. This post-print is published with permission from Elsevier under CC BY-NC-ND 4.0 license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

All material supplied via Aaltodoc is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

High frequency circular translation pin-on-disc wear testing of UHMWPE using a ball-on-flat contact along a hypotrochoidal track

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
Tel. +358 50 355 1757
E-mail: vesa.saikko@aalto.fi
ORCID ID 0000-0002-0196-0033
RESEARCHER ID I-1675-2016

Abstract

To intensify experimental research within the field of orthopaedic tribology, a three-station, dual motion, high frequency (25.3 Hz) circular translation pin-on-disc wear test device was recently introduced. In the present study, the pins were CoCr with a spherical, polished bearing surface of 28 mm radius, whereas the flat discs were conventional UHMWPE. This configuration was intended to simulate the wear mechanisms of total knee prostheses. The number of wear cycles run was as high as 200 million. The mean wear rate was 0.35 mg per one million cycles (0.77 mg/24 h) which corresponded to a mean wear factor of 3.5×10^{-6} mm^3/Nm. The study provided further proof that a wear test for orthopaedic implant materials can be accelerated by substantially increasing the cycle frequency, provided that the sliding velocity remains close to the values obtained from biomechanical studies. Hence, the moderate frictional heating will not lead to unrealistic wear mechanisms.

Keywords: UHMWPE; Accelerated wear testing; Biotribology; Orthopaedic tribology; Prosthetic joints

1. Introduction

Until recently, wear testing of prosthetic joint materials has been very time-consuming [1,2]. Wear testing cannot be accelerated by excessively increasing the contact pressure or the sliding velocity because the temperature increase is likely to cause thermal effects and lead to wear mechanisms that do not occur clinically. Cooling of the serum lubricant may partly help, but increasing the rate of change of sliding direction has recently been shown to accelerate wear without causing overheating of the contact or other problems [3]. Specifically, the resultant friction vector changed its direction at high rotational velocity (25.3 1/s) relative to the ultrahigh molecular weight polyethylene (UHMWPE) specimen, while the average sliding velocity was 27.4 mm/s, close to typical values found for prosthetic joints [4,5]. One revolution of the resultant friction vector is commonly considered a wear cycle. A dual motion, three-station pin-on-disc device for accelerated wear testing of UHMWPE was designed [3]. The device was called High Frequency Circular Translation Pin-on-Disc (HF-CTPOD). It was first run with the flat-on-flat configuration using cylindrical UHMWPE pins against polished CoCr discs for 22 million cycles. This simulated wear mechanisms occurring in total hip prostheses. It was hypothesized that the wear factor would increase with increasing cycle frequency. The wear factor was indeed found to be 7 times higher than in a single motion CTPOD test of 1 Hz cycle frequency [6].

For the 16-station RandomPOD device [7], a ball-on-flat method was developed to complement the more traditional flat-on-flat test configuration [8]. CoCr pins with a spherical bearing surface of 28 mm radius were manufactured by grinding and polishing. The pins slid against flat UHMWPE discs, the idea being to simulate the contact of non-conforming prostheses, such as the total knee prosthesis. The motivation of the present study was to find out if the ball-on-flat principle is applicable to the HF-CTPOD device as well. Another objective was to utilize the high frequency of the design in order to accumulate an exceptionally large number of cycles, as the device produces 2.2 million cycles in 24 hours.

2. Materials and methods

In the three-station, dual motion HF-CTPOD device [3] 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. 1). This high frequency circular translation was thus macroscopic, yet its sliding velocity, 24.8 mm/s, was not excessive from the biomechanical point of view [4,5]. The polished CoCr Protasul-20 (ISO 5832-12, surface roughness R_a value 0.01 μm) pins had a spherical bearing surface with a radius of 28 mm [7]. The discs of 10 mm thickness and 28 mm diameter were made from conventional, non-irradiated UHMWPE (GUR 1050). The type of contact was ball-on-flat. The discs circularly translated counterclockwise so that the circumference of the track was 31.4 mm, at a cycle frequency of 0.517 Hz. This slow circular translation was necessary to bring lubricant to the contact and to convey wear debris away from it. The dual motion resulted in a hypotrochoidal track (length 53.0 mm) of the pin relative to the disc (Fig. 2). The sliding distance per cycle was 1.1 mm. The average relative sliding velocity was 27.4 mm/s (range 9.1 mm/s to 40.5 mm/s in 0.04 s). An additional advantage gained from the slow circular translation was that the contact stress field largely moved relative to the UHMWPE component, as it does in actual knee prostheses in vivo [4].

The load was constant 100 N. The lubricant was HyClone Alpha Calf serum (SH30212.03) diluted 1:1 with ultrapure Milli-Q deionized water [6]. The protein concentration of the lubricant was 20 mg/ml. The amount of lubricant in each chamber was 10 ml. Its temperature was monitored but not controlled. With the dual motion, a 2 224 h wear test of 202.6 million cycles (219 km) was run at room temperature (mean 25 °C). The wear of the discs was measured gravimetrically at intervals of 101 hours (9.2 million cycles) on average using a Mettler AT261 DeltaRange balance with a resolution of 0.01 mg [6]. The wear rate was determined by linear regression using the 22 measurement points for each disc. The wear factor was calculated by dividing the wear rate by the density, 0.935 mg/mm^3 [1], load and sliding distance. The pins were not weighed as their wear was assumed to be negligible due to their high hardness.

3. Results

The wear was highly linear and uniform (Fig. 3). The average wear rate and the standard deviation was 0.35 mg/10^6 cycles ± 0.008 mg/10^6 cycles (0.77 mg/24 h ± 0.017 mg/24 h) which corresponded to a wear factor of 3.47×10^{-6} mm^3/Nm ± 0.08×10^{-6} mm^3/Nm. The standard deviation was only 2.2 per of the mean. The wear mark on the discs had a burnished appearance. No cracking or delamination occurred. Microscopy showed that the extent of the short motion was close to 0.32 mm as intended (Fig. 4). The pattern of such occasional abrasive wear marks also showed that the ratio of the rotational speeds of the two drive cranks was not exactly 48, since the motions were implemented by two separate motors. This further increased the multidirectionality of the test. The lubricant bulk temperature was on the average 5 °C above the environment temperature due to the frictional heat. The polished bearing surface of the CoCr pins was unchanged after the tests. No scratching or other damage occurred. The surface roughness R_a value was 0.01 µm, as before the tests.

4. Discussion

In the ball-on-flat simplification of the contact of the prosthetic knee, it is not sufficient to merely implement a unidirectionally moving or linearly reciprocating contact stress field relative to the UHMWPE disc. It is also essential that the direction of sliding changes continually [8–11]. Otherwise, only minimal wear is produced. In the present study, these requirements were met by the hypotrochoidal track. The rate of change of sliding direction was as high as 9100°/s, so the test was highly accelerated with respect to the number of wear cycles produced per second (25.3). In 2 200 hours, 200 million cycles were produced, which may be the largest number in one wear test with respect to prosthetic joint materials.

However, the average sliding velocity was only 27.4 mm/s. The fact that the increase of the lubricant bulk temperature relative to environment temperature was not higher than 5 °C indicated that the frictional power was moderate and unlikely to cause overheating of the contact. The number of wear cycles clinically may vary from 1 to 10 million per year, and the contemporary prostheses are expected to function without major problems for at least 20 years, preferably 30 years [1]. If the wear rate is high, the vast number of microscopic wear particles produced and accumulated in the periprosthetic tissues cause an inflammatory reaction that lead to the destruction of bone around the implant and loosening of the fixation, that is, to the failure of the arthroplasty [1].

Nevertheless, as the present ball-on-flat contact with static load and the hypotrochoidal track, implemented by biaxial translations of the pins and of the discs, were naturally not intended to mimic the in vivo kinematics of the prosthetic knee in the way that full-scale knee joint simulations are [12–16], they admittedly were also limitations of the study. However, simplifications of the contact mechanics and of the type of relative motion are common for all pin-on-disc wear testing. This fact should not be used as a reason to underrate the possibilities of pin-on-disc testing in the basic research within the field of orthopaedic tribology. For instance, in the development of a new type of implant polymer, there may be dozens of material variants that need to be wear tested. With validated high-capacity [6] or accelerated pin-on-disc methods [3], the variants possessing the best wear resistance can quickly be distinguished. The next logical step then is full-scale joint simulator studies with the most promising material candidates, from which acetabular liners and tibial insert are manufactured. The wear testing of dozens of material variants with contemporary 3 to 12-station joint simulators is virtually impossible, as one test takes at least 6 to 8 weeks with 1 Hz cycle frequency to reach 3 to 5 million cycles, the minimum test length for the evaluation of wear behaviour of orthopaedic implants [1]. This is the principal justification of pin-on-disc wear screening. Another limitation of the present study was that the roughening of the

CoCr surface, which is known to sometimes take place in vivo and lead to the increase of the UHMWPE wear, was not included in the tests.

In the RandomPOD ball-on-flat tests in which the rate of change of sliding direction was 500°/s on average, the UHMWPE wear factor was 2.04×10^{-6} $mm^3/Nm \pm 0.06 \times 10^{-6}$ mm^3/Nm ($n = 16$) [8]. The mean value of the present test was 70 per cent higher. In a ball-on-flat test with a narrow figure-of-eight track (rate of change of sliding direction 380°/s, track length 20 mm) at 1 Hz, the UHMWPE wear factor was 0.39×10^{-6} $mm^3/Nm \pm 0.04 \times 10^{-6}$ mm^3/Nm ($n = 5$) [11], i.e., an order of magnitude lower than that of the present study. This indicates that increasing the rate of change of sliding direction indeed substantially accelerates the wear test. If this is done without increasing the sliding velocity to unrealistic values, say, above 50 mm/s [4,5], no overheating of the contact, which is likely to lead to wear mechanisms not seen clinically, takes place. In the earlier HF-CTPOD study with a flat-on-flat contact (prosthetic hip wear simulation), the mean wear rate was 0.82 $mg/10^6$ cycles [3], i.e., 2.3 times higher than the present ball-on-flat wear rate, 0.35 $mg/10^6$ cycles. Interestingly, this ratio was in agreement with a retrieval study in which it was found out that the mean wear rate of conventional UHMWPE acetabular hip liners (44 mm^3/year) was twice that of conventional UHMWPE tibial knee inserts (22 mm^3/year) in well-functioning prostheses that were free from oxidative damage, retrieved postmortem [17]. Clinical wear factors for tibial inserts are not available, so a comparison with the wear factor value obtained in the present study, 3.5×10^{-6} mm^3/Nm, is unfortunately not possible. The wear behaviour of the present UHMWPE discs was ductile, that is, there was no pitting, surface cracking or delamination, since the discs were not irradiated and, therefore, they did not have oxidative damage as a result of gamma-irradiation sterilization (in air) that has been shown to cause fatigue and serious delamination wear of tibial inserts clinically in the 1990s [18]. The polished appearance of the wear mark together with fine scratches observed in microscopy (Fig. 4) were in agreement with a retrieval study regarding well-functioning knee prostheses, free from oxidative damage [17].

Conflict of interest statement

The author has nothing to declare

Acknowledgments

The study was funded by the Aalto University

References

[1] S.M. Kurtz, 2009, UHMWPE Biomaterials Handbook, 2nd ed., Elsevier, Amsterdam. xix + 543 pp.

[2] D. Baykal, R.S Siskey, H. Haider, V. Saikko, T. Ahlroos, S.M. Kurtz, Advances in tribological testing of artificial joint biomaterials using multidirectional pin-on-disk testers, J. Mech. Behav. Biomed. Mater. 31 (2014) 117–134. http://dx.doi.org/10.1016/j.jmbbm.2013.05.020

[3] V. Saikko, 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, J. Biomech. 48 (2015) 401–404. http://dx.doi.org/10.1016/j.jbiomech.2014.11.035

[4] J.D. DesJardins, S.A. Banks, L.C. Benson, T. Pace, M. LaBerge, A direct comparison of patient and force-controlled simulator total knee replacement kinematics, J. Biomech. 40 (2007) 3458–3466. http://dx.doi.org/10.1016/j.jbiomech.2007.05.022

[5] V. Saikko, O. Calonius, Slide track analysis of the relative motion between femoral head and acetabular cup in walking and in hip simulators, J. Biomech. 35 (2002) 455–464. http://dx.doi.org/10.1016/S0021-9290(01)00224-X

[6] V. Saikko, A hip wear simulator with 100 test stations, Proc. Inst. Mech. Eng. H. J. Eng. Med. 219 (2005) 309–318. DOI: 10.1243/095441105X34301

[7] V. Saikko, J. Kostamo, RandomPOD—A new method and device for advanced wear simulation of orthopaedic biomaterials, J. Biomech. 44 (2011) 810–814. doi:10.1016/j.jbiomech.2010.12.024

[8] V. Saikko, In vitro wear simulation on the RandomPOD wear testing system as a screening method for bearing materials intended for total knee arthroplasty, J. Biomech. 47 (2014) 2774–2778. http://dx.doi.org/10.1016/j.jbiomech.2014.04.039

[9] A. Wang, C. Stark, J.H. Dumbleton, Mechanistic and morphological origins of ultra-high molecular weight polyethylene wear debris in total joint replacemant prostheses, Proc. Inst. Mech. Eng. H. J. Eng. Med. 210 (1996) 141–155.

[10] M.R. Gevaert, M. LaBerge, J.M. Gordon, J.D., DesJardins, The quantification of physiologically relevant cross-shear wear phenomena on orthopaedic bearing materials using the MAX-Shear wear testing system, J. Tribol. 127 (2005) 740–749. doi:10.1115/1.2000272

[11] V. Saikko, Calonius, O, Simulation of wear rates and mechanisms in total knee prostheses by ball-on-flat contact in a five-station, three-axis test rig, Wear 253/4, (2002) 424–429. http://dx.doi.org/10.1016/S0043-1648(02)00154-0

[12] A.G. Wang, S.-S. Yau, A. Essner, L. Herrera, M. Manley, J.H. Dumbleton, A highly crosslinked UHMWPE for CR and PS total knee arthroplasties, J. Arthroplasty 23 (2008) 559–566. DOI: 10.1016/j.arth.2007.05.007

[13] T.M. Grupp, S. Utzschneider, C. Schröder, J. Schwiesau, B. Fritz, A. Maas, W. Blömer, V. Jansson, Biotribology of alternative bearing materials for unicompartmental knee arthroplasty, Acta Biomat. 6 (2010) 3601–3610. doi:10.1016/j.actbio.2010.04.003

[14] J.D. DesJardins, R.J. Rusly, Single flexion-axis selection influences femoral component alignment and kinematics during knee simulation, Proc. Inst. Mech. Eng. H. J. Eng. Med. 225 (2011) 762–768. DOI: 10.1177/0954411911400534

[15] B.R. Micheli, K.K. Wannomae, A.J. Lozynsky, Christensen, S.D. Christensen, O.K. Muratoglu, Knee simulator wear of vitamin E stabilized irradiated ultrahigh molecular weight polyethylene, J. Arthroplasty 27 (2012) 95–104.
DOI: 10.1016/j.arth.2011.03.006

[16] M.E. Roy, L.A. Whiteside, D.S. Tilden, O.F. Noel, Reduced UHMWPE wear using magnesia-stabilized zirconia instead of CoCr femoral components in a knee simulator, J. Arthroplasty 30 (2015) 468–474. http://dx.doi.org/10.1016/j.arth.2014.09.027

[17] R. Pourzal, C.B. Knowlton, D.J. Hall, M.P. Laurent, R.M. Urban, M.A. Wimmer, How does wear rate compare in well-functioning total hip and knee replacements? A postmortem polyethylene liner study, Clin. Orthop. Relat. Res. 474 (2016) 1867–1875.
DOI 10.1007/s11999-016-4749-8

[18] G.W. Blunn, A.B. Joshi, R.J. Minns, L. Lidgren, P. Lilley, L. Ryd, E. Engelbrecht, P.S. Walker, Wear in retrieved condylar knee arthroplasties. A comparison of wear in different designs of 280 retrieved condylar knee prostheses, J. Arthroplasty 12 (1997) 281–290. http://dx.doi.org/10.1016/S0883-5403(97)90024-3

Figure captions

Figure 1. Triple pin holder, shown upside down, UHMWPE test disc and lubricant chamber. CoCr pins had spherical, polished bearing surface of 28 mm radius and of 9 mm diameter. Pins were press fit into polytetrafluroethylene bushings.

Figure 2. Hypotrochoidal track, with 48 loops, of pin relative to disc in HF-CTPOD. Relative motion consisted of large counterclockwise circular translation of disc at 0.517 Hz, and short clockwise circular translation of pin at 24.8 Hz. Direction of sliding changed 9100°/s, yet average sliding velocity was 27.4 mm/s only. Hypotrochoid parameters were R = 5.1064 mm, r = 0.1064 mm, and d = 0.16 mm. Hence, track length was 53.0 mm, and period was 1.94 s.

Figure 3. Variation of wear of UHMWPE discs with number of cycles in dual motion HF-CTPOD test.

Figure 4. Optical micrograph from worn UHMWPE disc showing occasional abrasive wear marks.

Figure 1.

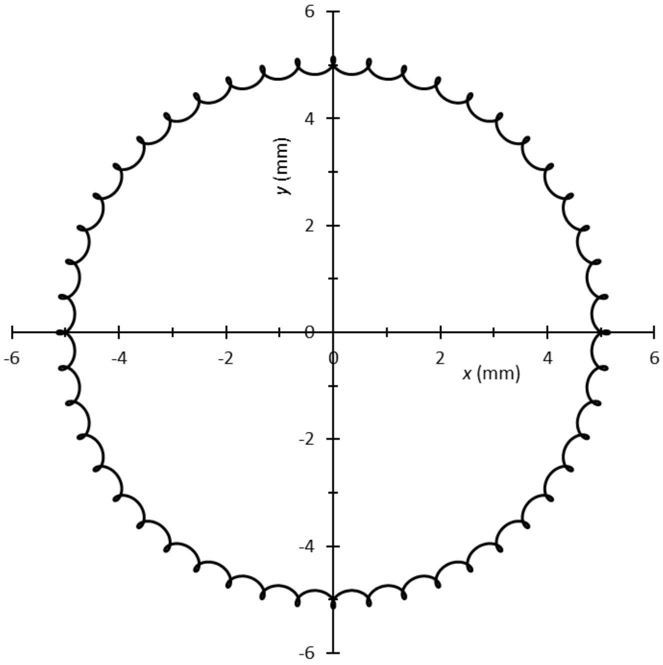

Figure 2.

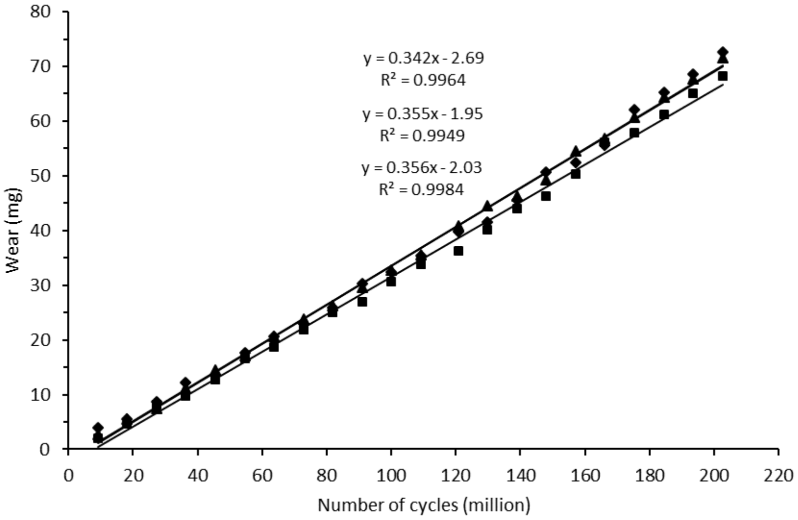

Figure 3.

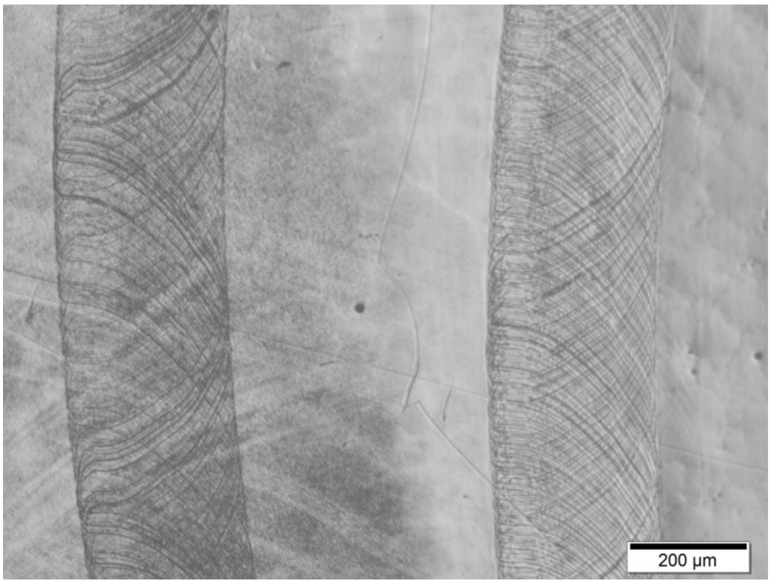

Figure 4.