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Short communication

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 six 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.

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 two to three 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 $2\pi r\sin 23^\circ$, 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 $2\pi r\sin 11.5^\circ$) 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

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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 three million cycles takes six weeks (Saikko, 2005), whereas in the HF-CTPOD, three days may be sufficient as a test length, as the device produces 2.2 million cycles in 24 h.

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 through 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, through 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 through flexible rods (dia. 2 mm) made

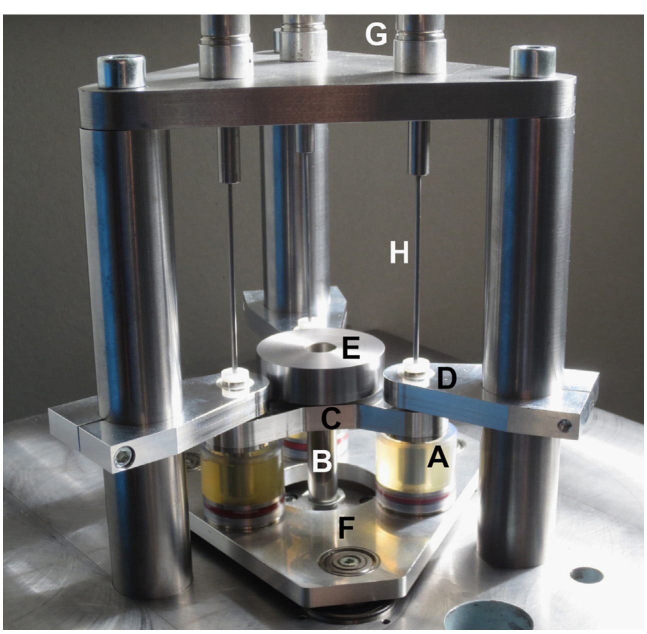

Fig. 1. Three-station, dual motion HF-CTPOD device; (A) test chamber, (B) central drive shaft (eccentricity 0.16 mm, speed 1487 rpm), (C) triple pin holder (short, fast circular translation, track circumference 1.0 mm), (D) guide sleeve (made from polyacetal, diametral clearance 0.32 mm) of pin holder 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.

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

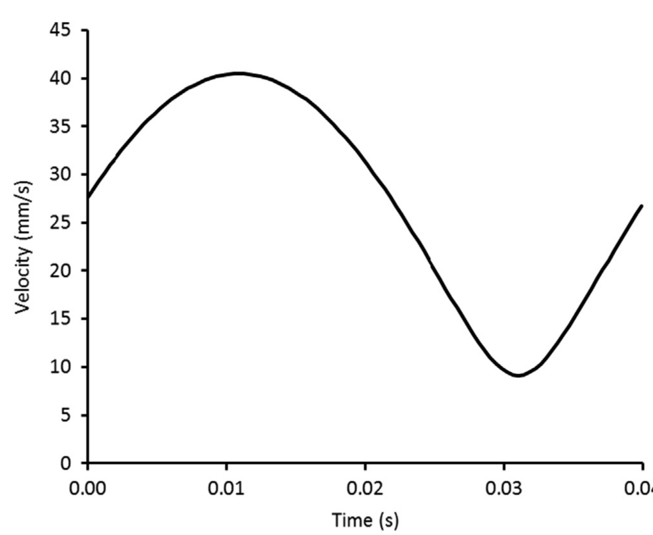

Fig. 3. Variation of relative sliding velocity between UHMWPE pin and CoCr disk with time in dual motion with HF-CTPOD device. In 0.04 s, direction of sliding rotated 360° relative to pin.