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Low wear and friction in alumina/alumina total hip joints

A hip simulator study

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We studied the wear of state-of-the-art alumina/alumina total hip joints with the uniaxial five-station, and the three-axis single-station hip joint simulators of Helsinki University of Technology. The diameters of the joints were 26, 28 and 32 mm. Visual examination and weighing of the components showed no wear. Scanning electron microscopy showed that (a) the wear marks were slight, consisting of removal of grains, multidirectional grooving and mild abrasion, (b) the wear mechanisms were similar to those seen in components removed from patients, and (c) there was no marked difference in the specimens worn in the uniaxial vs. three-axis simulator. The coefficient of friction was measured throughout the 5 million cycle wear test with the three-axis simulator. The average value was 0.007. We conclude that alumina/alumina joints had low wear and friction under the present test conditions. The results are promising, since minimal wear is one of the prerequisites for long-term success in prosthetic joints.

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Suggestions have been made to change the acetabular cup from polyethylene to a material that shows lower wear. One alternative is an acetabular cup made of alumina articulating against a femoral head made of the same material. Such designs have been in clinical use since the early 1970s, but in the early designs, fixation was defective and, although wear was usually low, severe avalanche-like damage of the articulating surfaces sometimes occurred in vivo (Plitz and Hoss 1982, Walter and Plitz 1983, 1984, Walter 1987, Clarke 1992). During recent years, however, both prosthetic design and alumina materials have improved substantially (Sedel and Lerouge 1996, Refior at al. 1997).

We present a wear study of alumina/alumina total hip joints made of Biolox forte alumina, done with the uniaxial five-station, and the three-axis single-station hip joint simulators of Helsinki University of Technology (Saikko et al. 1992, Saikko 1996).

Materials and methods

The specimens, made of Biolox forte alumina, are described in Tables 1, 2 and 3. The clearances of joints 1 to 5 were 0.07, 0.03, 0.05, 0.03 and 0.05 mm in test 1, and 0.07, 0.05, 0.06, 0.04 and 0.05 mm in test 2, respectively. In test 3, the clearance of the test joint was 0.05 mm. The diameters and the roundnesses were measured with a three-dimensional coordinate measuring apparatus. The surface roughness value R_a of the bearing surfaces, measured with a stylus apparatus, was 0.006–0.007 μm. The elastic modulus of Biolox forte is 380 GPa, hardness 2000 HV, and fracture toughness 4 MPa $m^{1/2}$. MgO is used as an additive.

The femoral heads were fixed with 1:10 taper-fit, size 12/14, to holders made of stainless steel 329. The taper-fit interface was sealed with silicone to prevent corrosion at the interface and the exit of possible fretting wear particles from the interface: stainless steel 329 is not an implant alloy. It was used because of its good machinability and high strength. The heads were carefully aligned with the axes of the simulators, using a dial indicator. In the uniaxial simulator, the load was transmitted from the loading arm to the acetabular component via a universal (Hooke) joint that made the acetabular insert self-centering on the femoral head. In the three-axis simulator, the test and the control joints were loaded in series. Therefore, both joints were self-centering, and the only difference between the test conditions in the test and control joints was that there was relative motion in the test joint, but not in the control joint.

The acetabular inserts were fixed with 1:3 taper-fit

Table 1. Comparison of Biolox and Biolox forte alumina

Material	Strength σ_{4P} (MPa)	Microstructure (μm)	Density (mg/mm^3)	Hot isostatically pressed	Proof-tested
Biolox	500	≤ 3.2	3.96	no	no
Biolox forte	580	≤ 1.8	3.98	yes	yes

Table 2. Femoral heads

Test	Head	Nominal dia. (mm)	True dia. (mm)	Departure from roundness (μm)	Neck length
1	1	32	31.99	4	L
	2	28	27.99	4	L
	3	28	28.00	3	L
	4	26	25.99	5	S
	5	26	25.99	3	S
2	1	32	31.99	6	L
	2	28	27.99	4	L
	3	28	27.99	3	L
	4	26	25.99	3	S
	5	26	26.00	5	S
3	Test head	28	28.00	2	M
	Control head	28	28.00	3	M

Table 3. Acetabular inserts

Test	Insert	Nominal ID (mm)	True ID (mm)	Departure from roundness (μm)	Rim OD (mm)
1	1	32	32.06	2	44
	2	28	28.02	4	39
	3	28	28.05	5	39
	4	26	26.02	4	35
	5	26	26.04	5	35
2	1	32	32.06	3	44
	2	28	28.04	2	39
	3	28	28.05	3	39
	4	26	26.03	4	35
	5	26	26.05	4	35
3	Test insert	28	28.05	4	37
	Control insert	28	28.05	4	37

to acetabular shells made of titanium alloy. An axial assembly force of 4 kN was used in the fixation of both the heads and the inserts to eliminate the risk of micromotion and fretting wear between the heads and their holders, and between the inserts and their shells during the tests. The assembly force was generated by a blow of a hammer via a plastic piece and a force transducer. The resulting narrow force pulse was saved and checked with a digital oscilloscope. The outside diameters of the hemispheric shells used with 26, 28 and 32 mm ID inserts were 48, 54 and 60 mm, respectively. The shells were fixed to acrylic cup-holders that functioned also as lubricant receptacles, with the help of acrylic bone cement.

The simulators have been described in detail elsewhere (Saikko et al. 1992, Saikko 1996). Basically, they simulated continuous level walking. The uniaxial simulator included 60° flexion-extension, and the vertical component of the joint load was stationary relative to the cup. Five total hip joints were tested simultaneously under identical conditions. The joints were placed in the inverted position to avoid drying out of the articulation during the test. The test frequency was 1.1 Hz. The lengths of extension (stance phase) and flexion (swing phase) were 2/3 and 1/3 of the cycle time, respectively and, during extension, the load was on (3.5 kN), and during flexion, the load was off (zero). The tests were done at 37 °C. The main dif-

Table 4. Weights of the wear test specimens

Test	Component		Weight (g) before test	Weight (g) after		
				1×10^6 cycles	3×10^6 cycles	5×10^6 cycles
1	Head	1	56.2347	56.2345		
		2	35.4382	35.4381		
		3	35.5282	35.5280		
		4	24.0667	24.0667		
		5	24.1107	24.1106		
	Insert	1	57.5210	57.5206		
		2	41.5784	41.5782		
		3	41.6102	41.6098		
		4	31.9726	31.9724		
		5	30.3594	30.3595		
2	Head	1	56.2176	56.2176	56.2174	56.2173
		2	35.2956	35.2958	35.2956	35.2956
		3	35.4857	35.4858	35.4856	35.4833 [a]
		4	24.1594	24.1595	24.1594	24.1594
		5	24.1236	24.1237	24.1237	24.1236
	Insert	1	57.4836	57.4836	57.4828	57.4826
		2	41.8966	41.8968	41.8966	41.8965
		3	41.7817	41.7818	41.7816	41.7815
		4	30.5318	30.5320	30.5319	30.5319
		5	30.6144	30.6146	30.6145	30.6145
3	Test head		33.0403	33.0401	33.0400	33.0400
	Control head		32.9802	32.9803	32.9803	32.9803
	Test insert		34.4443	34.4434	34.4433	34.4432
	Control insert		34.1379	34.1373	34.1372	34.1371

[a] Unfortunately, this value was affected by dismantling after the test, in the process of which some fragments were detached from this head, due to extraction tool malposition, and not all fragments could be retrieved for weighing

ferences between the two simulators were that the three-axis simulator had only one test station, but it had continuous friction measurement and three motion components, 45° flexion-extension, 12° abduction-adduction, and 12° internal-external rotation. The test conditions in the three-axis simulator were identical with those of earlier tests (Saikko 1996).

3 tests were done. Tests 1 and 2 were done with the uniaxial simulator and test 3 with the three-axis simulator. The length of test 1 was 1 million walking cycles, and the lengths of tests 2 and 3 were 5 million walking cycles. Distilled, deionized water was used as lubricant in all tests. For the quantification of possible wear, the specimens were weighed before and after the test and, in addition, at 1 and 3 million cycles in tests 2 and 3, with a balance that had a resolution of 0.01 mg. Metal transfer was detected at the conical fixation surfaces of heads and inserts after their dismantling. This transfer was found to cause slight weight gain. Most of the metal could be removed, by rubbing with a wad of cotton, soaked in "Sidol" kitchen cleanser that contained clay as an abrasive. The specimens were then washed and allowed to stabilize overnight before the weighings shown in Table 4 were done. The repeatability of the weighings was good, the variation being typically ±0.05 mg, at most. The rubbing of the fixation surface with the cleanser was found to cause a slight weight loss, about 0.3 mg, of a new insert that did not have metal transfer.

The kinetic coefficient of friction was measured with the three-axis simulator throughout the 5 million cycle test 3, exactly as in Saikko (1996).

After the tests, the specimens were sent back to CeramTec AG, where the scanning electron microscopy (SEM) of the articulating surfaces was done to detect possible wear marks and to analyze the wear mechanisms. The specimens had to be sectioned for the SEM.

Results

Visual examination of the heads and inserts showed no signs of wear. The weight changes were so small that the amount of wear was obviously minimal (Table 4). Since the transferred metal could not always be completely removed from the fixation surfaces and since the wear was minimal, net weight gain

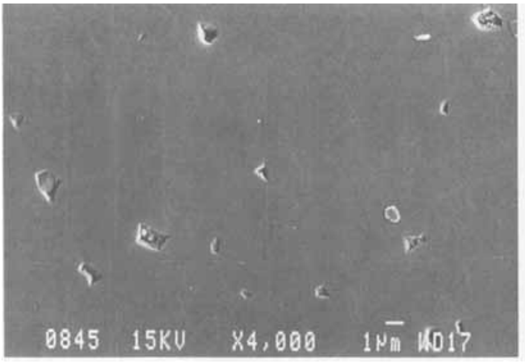

Figure 1. Scanning electron micrograph of holes, where grains have come out: insert 4 after 5 million cycles, test 2. Magnification 4000×. White bar indicates 1 µm.

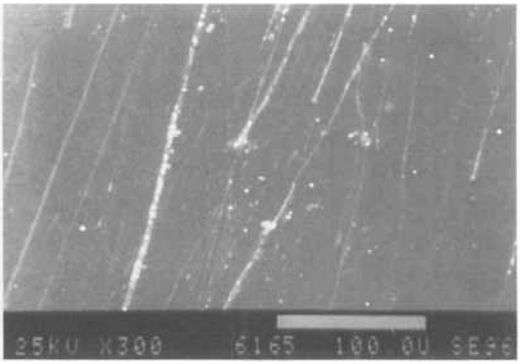

Figure 2. Scanning electron micrograph of a straight grooved surface: head 1 after 1 million cycles, test 1. Magnification 300×. White bar indicates 100 µm.

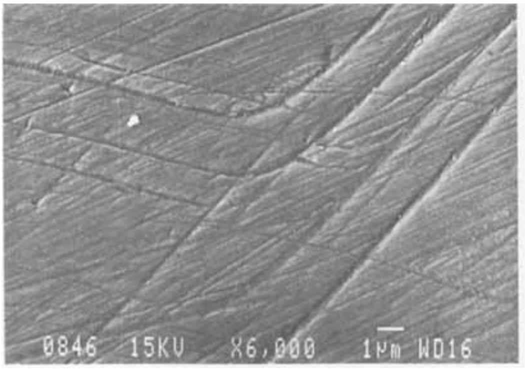

Figure 3. Scanning electron micrograph of curved grooves, generated by freely moving particles: insert 2 after 5 million cycles, test 2. Magnification 6000×. White bar indicates 1 µm.

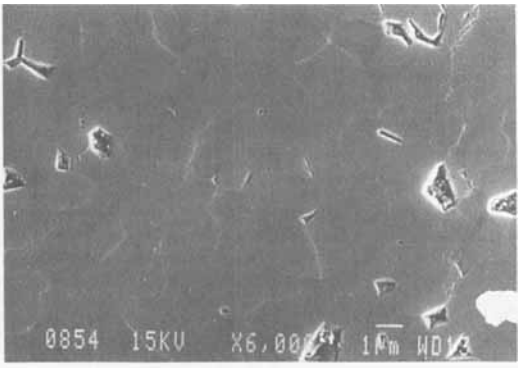

Figure 4. Scanning electron micrograph of a mild abrasion area, showing a relief surface: head 3 after 5 million cycles, test 2. Magnification 6000×. White bar indicates 1 µm.

sometimes occurred. Test 3 showed that the weight changes measured were caused primarily by the metal transfer and its removal. The average value of the coefficient of friction during the 5 million cycle test 3 was 0.007 ± 0.003 (SD).

Characterization of the surfaces with SEM

The surface defects were single defects or phenomena in very small areas. The wear-marks were caused by wear mechanisms typically occurring in alumina/alumina joints. The primary wear mechanism was the removal of grains due to contact pressure (Figure 1).

The size of the holes showed that only smaller grains were removed. A loose grain may have stayed in its place and grooved the counterface until it was transported due to the kinematics and change in the gap between the counterfaces. Grains that remained in place grooved the counterface in a linear way in tests 1 and 2, due to the uniaxial motion (Figure 2).

When the particle was free to move between the counterfaces, both surfaces were grooved. The shape of such grooves was not linear, not even in tests 1 and 2. The shape was determined by the interaction of the gap geometry, relative motion and the force vector at the cutting edge of the particle, the direction of which changed randomly. Thus no correlation to the movements of the simulators could be seen. These grooves were present in several specimens (Figure 3).

The grooving process removed secondary wear particles with an estimated size of one or more magnitudes smaller than the size of the primary wear particles.

In the present simulators, since the prostheses were in the inverted position, the wear debris tended to remain between the counterfaces. When the wear particles had a very small grain size, the wear mechanisms changed from a grooving type to a mild abrasion type, revealing a relief surface (Figure 4). In the mild abrasion, the wear resistance of alumina depended on the crystalline axis, therefore the shape of the grains was visible in the mild abrasion area.

There was no marked difference in the specimens worn in the uniaxial vs. three-axis simulator (Figure 5). Moreover, there was no evidence that the 5 million cycle test 2 produced larger or more wear-marks than

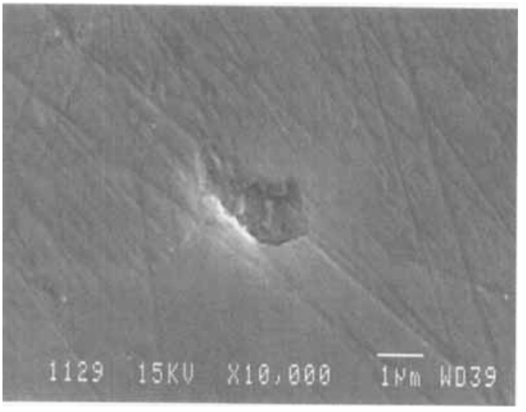

Figure 5. Scanning electron micrograph of hole where grain has come out, and criss-cross grooves: test insert after 5 million cycles, test 3. Magnification 10 000×. White bar indicates 1 μm.

the 1 million cycle test 1. The wear rate was obviously negligible after initial wear during the running-in period.

The diameter of primary wear particles was approximately 1–5 μm, whereas the diameter of the secondary wear particles was less than 1 μm. Particles generated by mild abrasion were estimated to be in the nanometer range.

Discussion

The wear of alumina/alumina total hip joints of 26, 28 and 32 mm diameter, made of Biolox forte alumina, was studied on two different hip joint simulators. The wear and friction proved to be minimal. Visual examination and weighing of the components showed no wear. Scanning electron microscopy showed that the wear marks were slight, consisting of removal of grains, multidirectional grooving and mild abrasion. The low wear is consistent with clinical experience (Sedel and Lerouge 1996), and with the hip simulator studies by the Munich group (Refior et al. 1997). The appearance of the bearing surfaces was similar to that of normal retrievals (Dorlot 1992).

The retrieval studies of alumina/alumina total hip prostheses found in the literature pertain to older designs and materials. The early alumina/alumina designs have been fairly successful (Nevelös et al. 1993, Sedel and Lerouge 1996), and their wear is usually low (Dorlot 1992). Alumina particles are biologically well tolerated (Gualtieri et al. 1987). However, severe avalanche-like damage of the articulating surfaces has sometimes occurred in vivo (Plitz and Hoss 1982, Walter and Plitz 1983, 1984, Walter 1987). The malposition of the acetabular cup is the major cause of severe wear (Dorlot 1992, Walter 1992, Nevelös et al 1993, Refior et al. 1997).

The microstructure of the new Biolox forte alumina is better than that of the older alumina grades that have been used in prosthetic hip joints since the early 1970s. The contemporary prosthetic designs further reduce the risk of the avalanche-like damage by reducing the possibility of fragments being detached from the rim of the cup.

Too low assembly force is one possible, but overlooked cause of problems in the conical head-stem interface. The recommended minimum value of axial assembly force in Biolox heads and inserts is 1–2 kN. In the present study, 4 kN was used to ensure firm fixation. Since the in vivo joint forces are not axial, sufficient axial assembly force is needed to avoid micromotion and fretting wear between the head and the stem, which could damage the taper-fit surfaces, and eventually even cause a fracture. It is usual to avoid hitting the head with a hammer during surgery because it is thought that this may cause a fracture. However, state-of-the-art alumina heads can sustain an axial force of at least 40 kN (Heimke 1994). A brisk blow of a hammer via a plastic piece, which means a force hardly above 4 kN in the assembly situation, may well reduce the risk of head-stem interface problems.

The average coefficient of friction of the 28 mm alumina/alumina joint, 0.007, was lower than that measured earlier with the same three-axis simulator for CoCr/PE joints, 0.011 (Saikko 1996). A low value of 0.007 suggests hydrodynamic squeeze film lubrication, and supports the view that simplified sphere-on-flat tests underestimate the hydrodynamic effect (Zhou et al. 1997). The coefficient of friction of alumina against alumina can be up to two orders of magnitude higher than the above value in a ring-on-disk test (Walter 1987), and in disk-on-disk and pin-on-disk tests (Chevalier et al. 1997), in which no hydrodynamic effect is found.

There is a common belief that if a hip joint simulator is uniaxial—that is, includes the chief motion component, flexion-extension only, as the present five-station simulator does—it cannot reproduce the in vivo wear mechanisms, since any grooving would take place in a single direction. In retrieved total hip components, the directions of grooves are typically random. The scanning electron microscopy of the present specimens showed that grooves were not produced in a single direction in any of the tests, and there was no marked difference in the specimens worn in the uniaxial vs. three-axis simulator. Therefore, the belief that a uniaxial simulator produces only unidirectional grooves has now proved wrong. Another common belief is that the inverted position of the prosthesis in a simulator would automatically lead to abnormally high wear because the wear particles would tend to stay as abrasives between the articulating surfaces. Our study does not confirm that view either since the tests were done so that the joints were in the inverted position and the wear was still low.

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