

Wear of the polyethylene acetabular cup

The effect of head material, head diameter, and cup thickness studied with a hip simulator

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Ultra-high molecular weight polyethylene acetabular cups backed by Ti-6Al-4V acetabular shells were articulated against Co-Cr-Mo alloy, ion-implanted Co-Cr-Mo alloy, and zirconia ceramic femoral heads in a hip joint simulator. Three tests of three million walking cycles each were run with five different head-cup combinations. The wear of the cups was measured gravimetrically at half a million cycle intervals. When the thickness of the cup was 10.9 mm, the mean wear rate was 0.14 mm/year against 28 mm dia. Co-Cr-Mo heads and 0.09 mm/year against ion-implanted 28 mm Co-Cr-Mo heads. When the

thickness of the cup was 7.0 mm, the mean wear rate was 0.04 mm/year against 28 mm zirconia heads, but when the thickness was 10.9 mm, no wear occurred against 28 and 32 mm zirconia heads. The results indicate that a significant reduction in the wear of the polyethylene cup can be expected if zirconia is used as the head material, instead of Co-Cr-Mo alloy or ion-implanted Co-Cr-Mo alloy. The diameter of the zirconia head, 28 vs. 32 mm, seems unimportant, but a cup thickness much below 10 mm may be disadvantageous.

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It is widely recognized that the wear products of the total hip prosthesis pose a significant clinical problem by causing adverse tissue reactions, leading to loosening of the implant fixation, pain, restricted function, and eventually to an expensive and complicated revision operation. In recent years, an increasing amount of research has been focused on the wear behavior of prostheses and prosthetic joint materials, after a relatively quiet period in the 80s.

The introduction of ceramic femoral heads has marked a considerable advance in the reduction of the wear of ultra-high molecular weight polyethylene (UHMWPE) acetabular cups. Both clinical and laboratory studies have shown that the wear of UHMWPE cups against alumina ceramic heads is lower than that against metallic heads. Zirconia ceramic has been introduced as a challenger to alumina because of its higher fracture toughness, which is an important material property due to the high tensile stresses caused by the taper-fit attachment of the modular head.

Ion-implantation is a method of surface treatment with which the surface of a metallic head can be made harder and therefore more abrasion-resistant. Scratching of the femoral head in surgery or *in vivo* is extremely dangerous because it can result in rapid wear of the UHMWPE cup.

In the present study, the wear of UHMWPE cups against Co-Cr-Mo alloy, ion-implanted Co-Cr-Mo alloy, and zirconia femoral heads is studied with a hip joint simulator. The components belong to a new total hip design. The variables investigated were head material, head diameter, and cup thickness. The methods were practically identical with those of an earlier study published in this journal (Saikko et al. 1993).

Material and methods

Femoral heads, acetabular cups, and acetabular shells (Tables 1 and 2, Figure 1) were supplied by Industrias Quirúrgicas de Levante S. A. (IQL), Spain. The test scheme was designed so that the comparison of Sets B, C, and E gives information about the effect of head material, C and D about the effect of head diameter, and A and C about the effect of cup thickness on wear of the cup (Table 3). All heads and cups had been manufactured for implantation, except for the experimental nitrogen-ion-implanted Co-Cr-Mo heads, and were received in their sterile packages. Set E heads were identical with Set B heads, with the exception of the ion-implantation treatment. The cups had been sterilized by gamma irradiation. The measurements

Table 1. Femoral heads

Cat. No.	Material	Nominal dia. (mm)
1009-10	Co-Cr-Mo	28
1009-1001	Co-Cr-Mo, N-ion-implanted	28
1010-34	Zirconia	28
1010-20	Zirconia	32

Table 2. Acetabular cups made of UHMWPE

Cat. No.	Nominal ID (mm)	Thickness ^a (mm)	Nominal OD of corresponding Ti-6Al-4V acetabular shell (mm)
1056-50	28	7.0	50
1057-52	28	10.9	52
1054-56	32	10.9	56

^a At the point of loading and in its direction, 45 degrees from the axis of symmetry

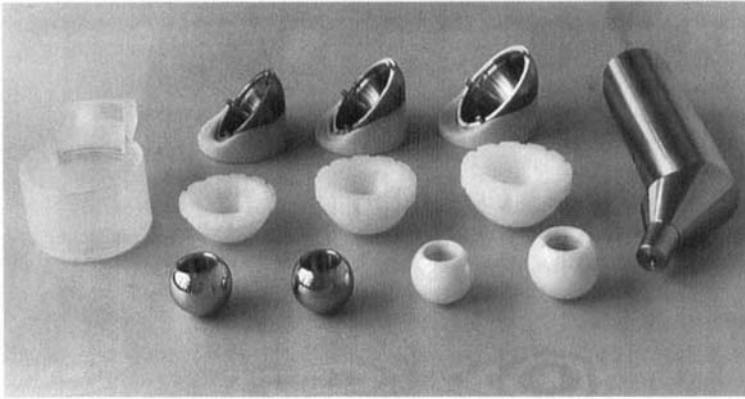


Figure 1. Examples of femoral heads, acetabular cups, and acetabular shells included in tests. Shells are embedded in acrylic bone cement. Cup-holder made of acrylic (left), and head-holder made of stainless steel 329 (right).

Table 3. Test sets

Set	Head diameter (mm) and material	Cup thickness (mm)
A	28, zirconia	7.0
B	28, Co-Cr-Mo	10.9
C	28, zirconia	10.9
D	32, zirconia	10.9
E	28, ion-implanted Co-Cr-Mo	10.9

of diameter, roundness and surface roughness of the femoral heads, and internal radius of the acetabular cups are presented in Table 4.

The basic idea in this study was to do the tests, measurements, and calculations the same way as in the earlier study (Saikko et al. 1993), using the five-station hip joint simulator from Helsinki University of Technology (Saikko et al. 1992). Hence, detailed descriptions of the methods can be found in those papers. The deviations were as follows:

1. The roundness of the heads was measured in two planes, instead of only one, the angle between these two planes being 30 degrees (Figure 2). Plane I was the 'equator' plane of the head relative to its axis of

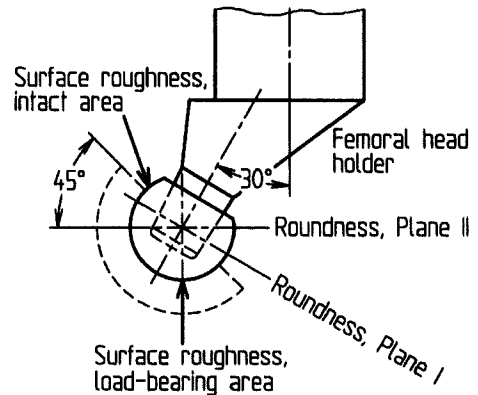


Figure 2. Diagram showing roundness measurement planes and surface roughness measurement areas of femoral head. Broken line indicates position of acetabular cup in simulator. Head and its holder are shown in a position corresponding to the neutral position of the flexion-extension cradle. Loading direction is vertical.

symmetry, and Plane II was the horizontal plane through the center of the head, when the head was mounted in its holder and the flexion-extension cradle of the simulator was in the neutral position.

Table 4. Size, form, and surface finish measurement of heads, and radius of cups

Set	Head	Dia. (mm)	Departure from roundness (μm) ^a		Surface roughness R_a (μm) ^b		Internal radius of corresponding cup, intact area (mm)
			Plane I	Plane II	Intact area	Load-bearing area after test	
A	1	27.98	0.5	0.5	0.008	0.010	14.08
	2	27.97	0.3	0.3	0.007	0.012	14.06
	3	27.98	0.2	0.2	0.008	0.009	14.07
B	1	27.99	0.4	0.3	0.016	0.12	14.06
	2	27.97	0.5	0.7	0.012	0.28	14.07
	3	27.98	0.5	0.3	0.016	0.17	14.24
C	1	27.98	0.2	0.2	0.008	0.009	14.05
	2	27.98	0.5	0.5	0.008	0.012	14.01
	3	27.97	0.2	0.3	0.008	0.009	14.25
D	1	31.97	0.7	0.8	0.008	0.012	16.24
	2	31.97	0.9	1.1	0.008	0.009	16.22
	3	31.98	0.9	0.7	0.009	0.010	16.20
E	1	27.98	0.8	0.9	0.013	0.20	14.08
	2	27.98	0.6	0.5	0.014	0.28	14.15
	3	27.98	0.6	0.5	0.011	0.08	14.23

^a The planes of measurement are shown in Figure 2.

^b The areas of measurement are shown in Figure 2.

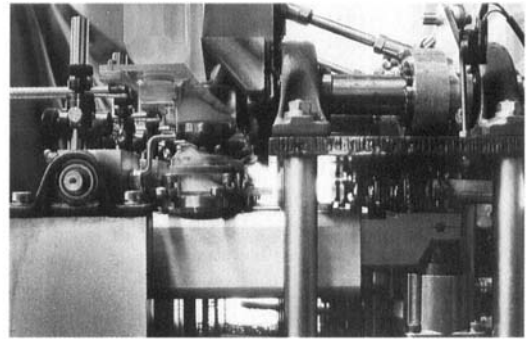
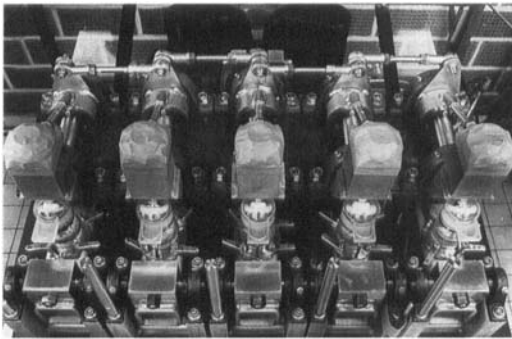


Figure 3. Top view (left) of simulator with specimens installed. Specimens are, from left to right, Sets A, B, C, D, and E. Side view (right) of simulator showing Set E test and control joints, loading arm and pneumatic loading cylinder (below) and flexion-extension cradle (above).

2. The internal radius of the cups was measured with a three-dimensional CNC coordinate measuring apparatus, instead of the simple three-ball method, using five points at a maximum distance of c. 10 mm from each other.

3. Femoral head-holders machined of stainless steel 329 (Figure 1) were used, instead of femoral stems, to attach the heads to the simulator. The 1:10 taper-fit interface between the head and the holder was sealed with a layer of silicone sealant, preventing the corrosion of the interface and the possible exit of corrosion products from the interface (Saikko 1994).

In the present walking simulator, flexion-extension motion with a range of 60 degrees, and the vertical component of the joint load were included. The duration of extension was 2/3 of the gait cycle. During extension, the load was 3.5 kN and during flexion the load was zero. The test frequency was 65 walking

cycles per minute. The test environment temperature was maintained at 37 °C and distilled water was used as lubricant. For the assessment of wear, the test was periodically stopped and the cups were removed for vacuum desiccation and weighing. The effect of water absorption on weight change was determined by the use of loaded soak control cups that were similar to the test cups. Three tests of three million walking cycles each were run with the five different head-cup combinations. The simulator is shown in Figure 3.

All the measurements presented in Table 4 were made after the simulator tests. The roundness of all the heads and smoothness of the ceramic heads were very good. The variation in the internal radius of the cups is noteworthy, but this is probably attributable to the distortion of shape caused by the tests.

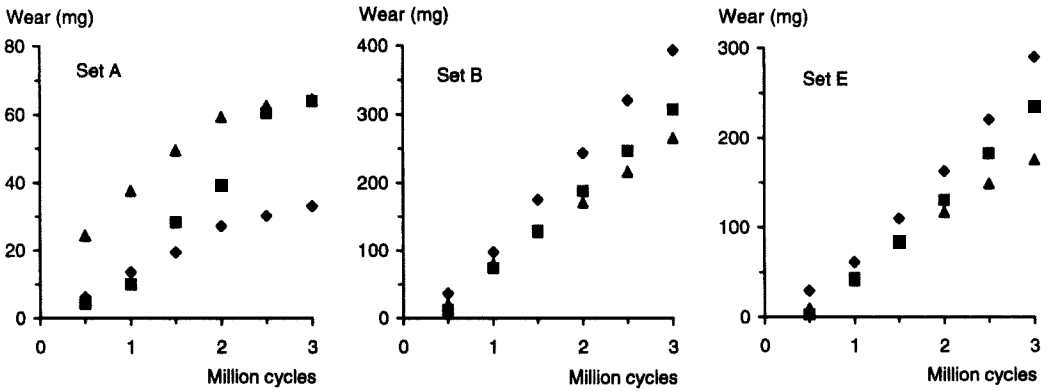


Figure 4. Variation in wear of acetabular cups with number of simulated level walking cycles, (A) Set A, (B) Set B, (C) Set E. Symbols ■ refer to test 1, ◆ to test 2, and ▲ to test 3. Sets C and D are excluded because no wear occurred in them. Note differences in scales for wear.

Results

The wear of Sets A, B, and E cups is shown in Figure 4. Sets C and D are not included in Figure 4 because no wear occurred in them. The wear rates were calculated by linear regression (Table 5). The values of yearly wear were calculated by dividing the mg/10⁶ cycles values by the density of polyethylene (0.94 mg/mm³) and the projected area of the head. One million cycles was estimated to correspond to one year in vivo. The wear factor indicates how much polyethylene (mm³) is removed for every newton of load and meter of sliding distance. In comparing the mean wear rates, the t-test was used (Table 6). All the differences in means were significant.

When the head diameter was 28 mm and cup thickness 10.9 mm, the mean polyethylene wear against ion-implanted Co-Cr-Mo was somewhat lower than that against non-ion-implanted Co-Cr-Mo, 0.09 and 0.14 mm/year, respectively, whereas no wear occurred against zirconia. When the head material

was zirconia and cup thickness 10.9 mm, the polyethylene wear was zero, not only against ø28 heads but also against ø32 heads. When the head material was zirconia and diameter 28 mm, the mean polyethylene wear was 0.04 mm/year with a 7.0 mm cup thickness, whereas it was zero with a 10.9 mm cup thickness, as stated above.

The surface roughness in the load-bearing area of the metallic heads, Sets B and E, increased substantially during the tests, due to polyethylene transfer (Table 4). The load-bearing area of Set E heads turned dark. The rougher the head, the higher was the wear rate of the cup in Sets B and E. During the tests, the temperature of the lubricant in Sets B and E articulations was generally a couple of degrees higher than that in the others, which was obviously due to increased surface roughness of the heads causing a higher coefficient of friction and therefore a greater frictional heat. The greater friction could be detected also from the fact that the worn area in the cup, the wear ‘pit’, moved substantially in the posterior direc-

Table 5. Linear regression parameters for variation in wear of acetabular cups with number of cycles: intercept (mg), slope (mg/10⁶ cycles), and correlation coefficient *r*; wear rate and mean wear rate (mg/10⁶ cycles), mean yearly wear (mm/year), and mean wear factor (10⁻⁶ mm³ N⁻¹ m⁻¹). Sets C and D are not included because no wear occurred in them

Set	Test	Intercept	Slope	Correlation coefficient <i>r</i>	Wear rate	Mean		
						Wear rate	Yearly wear	Wear factor
A	1	-11.7	26.4	0.99	14.7	21.8	0.04	0.48
	2	2.4	11.0	0.99	13.4			
	3	21.1	16.3	0.96	37.5			
B	1	-46.2	118	1.00	71.4	83.0	0.14	1.81
	2	-41.2	144	1.00	103			
	3	-21.8	96.2	1.00	74.4			
E	1	-49.8	92.9	1.00	43.3	51.9	0.09	1.13
	2	-37.8	105	0.99	67.2			
	3	-23.0	68.1	1.00	45.1			

Table 6. Comparison of mean wear rates

Sets compared	Difference in means (mg/10 ⁶ cycles)	γ	t	p	At 95% confidence level, the difference in means is between (mg/10 ⁶ cycles)
B - C	83.0	2	8.21	0.01	55 - 111
B - D	83.0	2	8.21	0.01	55 - 111
B - A	61.2	3	4.79	0.01	26 - 97
E - C	51.9	2	6.76	0.01	31 - 73
E - D	51.9	2	6.76	0.01	31 - 73
B - E	31.2	3	2.46	0.05	-4 - 66
E - A	30.0	4	2.74	0.03	0 - 60
A - C	21.8	2	2.79	0.05	0 - 44
A - D	21.8	2	2.79	0.05	0 - 44
C - D	0				

tion. On the zirconia heads, no damage could be seen, not even on Set A heads, although moderate wear occurred in Set A cups. However, the wear of Set A cups was clearly less than the wear of Sets B and E cups. The femoral heads were examined with a light microscope.

The appearances of the load-bearing area and removed polyethylene of Sets A, B, and E cups were similar to those of designs in which substantial wear occurred in the earlier study (Saikko et al. 1993). In Sets C and D cups, the principal change in appearance of the load-bearing area was polishing: the machining grooves were flattened, and the load-bearing area was more reflective than the intact area.

Discussion

The wear rates of Sets B and E cups, expressed as mm/year, were lower than those of cups worn against stainless steel heads in the earlier study (Saikko et al. 1993), but higher than those of cups worn against Co-Cr-Mo heads. There are, however, essential differences in the specimens between these two studies—e.g., in the backing and thickness of the cup, and in the diameter of the head—so a straightforward comparison is not possible.

Clinically, the radiographically measured penetration rate of $\varnothing 32$ Co-Cr-Mo heads into UHMWPE cups in the Müller design has been found to be 0.5 mm/year in the beginning and 0.15–0.2 mm/year after 5 years, creep deformation predominating in the beginning (Buchhorn et al. 1984). These values are fairly similar to those measured for $\varnothing 28$ Co-Cr-Mo heads in the present study.

The reduction in the wear of the UHMWPE cup achieved by the ion-implantation of the Co-Cr-Mo head was significant, but the results suggest that it is still modest compared to the advantage that could be

gained by changing to the zirconia head. In regard to the reduction in UHMWPE wear, zirconia really appears to be an excellent head material. Its behavior was similar to that of alumina in the earlier studies (Saikko 1993, Saikko et al. 1993).

The fact that the wear of the cup against the zirconia head was zero with 10.9 mm cup thickness, whereas the wear was substantial with 7.0 mm cup thickness, is surprising. Zero wear was observed in only 5.6 mm thick metal-backed UHMWPE cups against $\varnothing 32$ alumina heads (Saikko 1993, Saikko et al. 1993), and very little wear against experimental $\varnothing 32$ zirconia heads (Saikko 1994), whose deviations from roundness were clearly greater than those in the present commercial heads, and against $\varnothing 32$ Co-Cr-Mo Vitallium heads (Saikko et al. 1993). The effect of cup thickness on contact stresses in metal-backed polyethylene cups was calculated by Bartel et al. (1985). According to their analysis, an only minimal increase in contact stresses occurs when the cup thickness decreases, if the radial clearance is 0.1 mm or lower. Only when the cup thickness decreases below 4 mm and the radial clearance is around 0.5 mm or more, can a noteworthy increase in contact stresses be expected. Hence, the explanation of the difference in wear between Sets A and C is apparently not the elastic contact stresses. However, the analysis by Bartel et al. did not take creep into account. Since the creep resistance of UHMWPE is low, it is possible that in the 10.9 mm thick cup the creep deformation renders the contact pressure distribution broader and flatter and therefore more benign in regard to wear. The magnitude of the creep deformation in the 10.9 mm thick cup during the wear tests was clearly greater than that in the 7.0 mm thick cup. Unfortunately, this theory does not explain the difference in wear between the 7.0 mm thick cup and the 5.6 mm thick cup against $\varnothing 32$ zirconia heads (Saikko 1994) since the mean wear rates were 0.04 and 0.005

mm/year, respectively. Moreover, it is interesting to note that, according to calculations by Bartel et al., the contact stresses with 28 and 32 mm heads are practically equal if the outside diameter of the cup is constant, 42 mm. On the other hand, it is possible that the properties of the polyethylene of the present cups, e.g., the elastic modulus and creep resistance, differ from those of the cups in the earlier studies, resulting in different contact stresses after all.

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