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A three-axis knee wear simulator with ball-on-flat contact

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Abstract

A three-axis knee wear simulator with ball-on-flat contact was designed and built for basic wear and friction tests of prosthetic knee materials. The three-axis motion consisted of flexion–extension (FE), anterior–posterior translation (APT) and inward–outward rotation (IOR). Preliminary tests were done with non-irradiated, and with gamma-irradiated, artificially aged ultra-high molecular weight polyethylene disks. The counterface was a 54 mm diameter, polished CoCr ball. The load was static 2 kN, and lubricant diluted calf serum. The wear of non-irradiated polyethylene proved to be insensitive to the disk thickness. Gamma-irradiation and aging resulted in higher wear rates, which further increased with decreasing disk thickness. The steady-state wear rates of the disks varied from 10.7 to 47.1 mg per one million cycles, and the average coefficients of friction from 0.043 to 0.063. The wear zone was burnished in all disks, the dominating wear mechanism being adhesive. Severe delamination occurred only in a disk made from a gamma-irradiated tibial component which had been on the shelf for 10 years. In accordance with clinical findings, the majority of the polyethylene wear particles had a diameter between 0.1 and 1 μm, with an average of 0.7 μm. As the tibial components made of polyethylene are often damaged by oxidation, the effects of aging conditions on polyethylene wear are important subjects of further studies. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Knee joint prosthesis; Wear simulator; Ball-on-flat; Polyethylene

1. Introduction

In knee joint prostheses, the wear of tibial components made from ultra-high molecular weight polyethylene is a significant cause of failure. The tibial component is usually relatively flat, and its thickness may be as low as 4 mm [1,2]. The convex counterface, the femoral component, is most often made from CoCr alloy. The relative motion is a combination of rolling and sliding. The type of motion and the stress levels vary substantially depending on the design of the prosthesis and on the position in which the prosthesis is implanted. In many designs, the tibiofemoral contact is highly non-conforming in order to provide a large range of motion. This causes contact stresses which may exceed the strength of polyethylene. The maximum contact pressures in contemporary prostheses have been measured to be around 20 MPa [3].

The situation is made even worse by the fact that the contact moves cyclically relative to the tibial component, creating the conditions for fatigue wear. In the examination of tibial components removed from patients, typical findings are burnishing, abrasion, scratching, embedded acrylic bone cement particles, pitting, delamination, surface deformation and cracking [4–8]. Delamination has been found to correlate with oxidation [9], which is a consequence of the formation of free radicals in the sterilization by gamma-irradiation. A common feature in the wear of knee and hip prostheses is the production, through the adhesive and abrasive wear mechanisms, of an enormous number of polyethylene wear particles with a size in the biologically harmful micrometre range [10,11]. Particles of this size are known to cause osteolysis, which in many cases leads to the loosening of the prosthetic components, necessitating a reoperation.

Knee joint simulators, sometimes called briefly knee simulators, are intended for wear testing of actual knee prostheses. The available commercial knee joint simulators are complex, difficult to operate and expensive. For basic wear and friction tests of new material candidates, a simple, reliable and easy-to-operate wear test device, which still produces wear mechanisms similar to those occurring clinically in knee prostheses, is more practical. The new knee wear simulator with ball-on-flat contact, described in the present paper together with some preliminary test results, belongs to this latter category. The term knee wear simulator indicates that simplified test specimens and test conditions are used. Contemporary knee prostheses show a large variety of contact geometries. In the present simulator, the test conditions were chosen to reproduce the wear of the most common type, a non-conforming, metal-backed prosthesis with substantial anterior–posterior sliding.

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2. Experimental details

In the new knee wear simulator (Fig. 1), a large CoCr ball represented the femoral component, and a flat polyethylene disk, located horizontally beneath the ball, represented the tibial component. The simulator was built from an old five-station, uniaxial hip joint simulator [12]. The frame, motor and loading system of the hip simulator were utilized. For the present study, one test station was completed. The motions and load were based on biomechanical studies [13–15]. The three-axis motion consisted of flexion–extension (FE), anterior–posterior translation (APT), and inward–outward rotation (IOR). The FE was applied to the ball, and the APT and IOR to the disk (Fig. 2). The motions were implemented by crank mechanisms, and their variations with time were nearly sinusoidal. The cycle time was 0.93 s. A detailed description of the design follows.

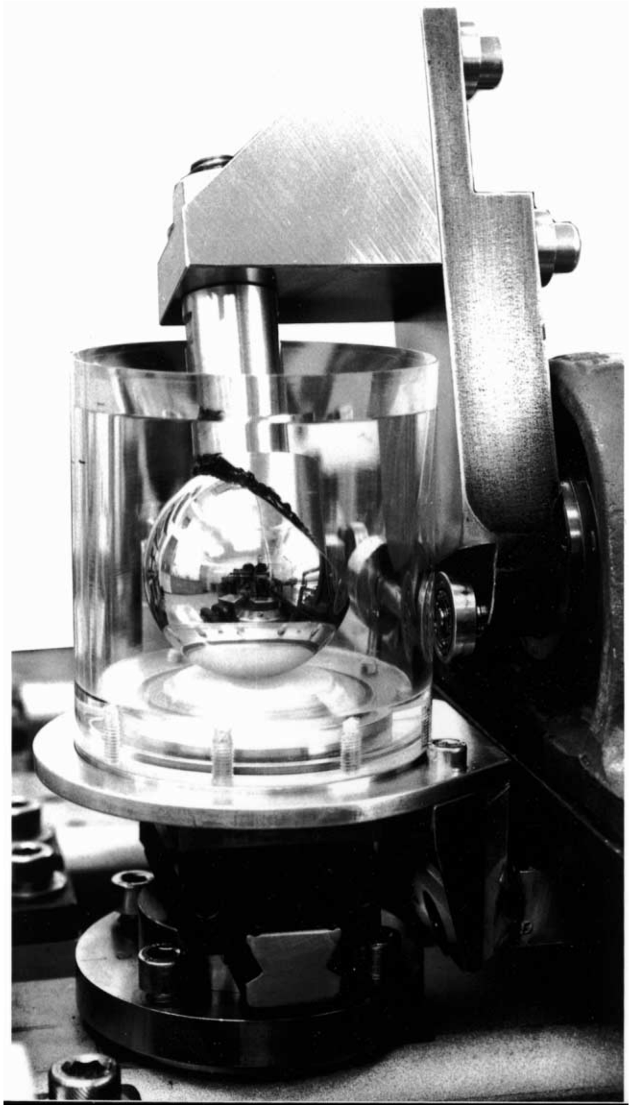

Fig. 1. Close-up of three-axis knee wear simulator with ball-on-flat contact.

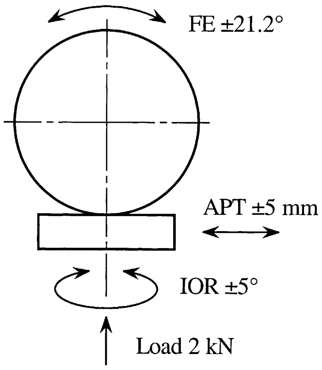

Fig. 2. Principle of the simulator.

The amplitude of the FE motion was 42.4°. Therefore, the sliding distance between the extreme positions would have been 20 mm with the chosen 54 mm ball diameter, if FE was the only motion. However, the APT, which had an amplitude of 10 mm, was synchronized with the FE so that the maximum flexion coincided with the maximum anterior translation of the disk, and maximum extension with the maximum posterior translation. This reduced the sliding distance between the extreme positions to 10 mm, the roll/slide ratio hence being 0.5. Due to the APT, the contact moved cyclically relative to the disk.

A few trials using two-axis motion, FE and APT, resulted in too low wear rate values, around 1 mg per one million cycles. To solve the problem, the IOR was added. The IOR axis was the vertical symmetry axis of the disk, and the amplitude of the IOR was 10°. The IOR crank mechanism was designed so that the phase difference between the IOR and APT sine waves was $\pi/2$. Hence, the force locus on the disk (the track of the theoretical contact point) was a narrow, symmetric figure of eight with a height of 10 mm and width of 0.22 mm. The length of the force locus was 20.07 mm. This value was used as the sliding distance per cycle in the calculation of the wear factor.

The APT was implemented so that a lever fixed to the FE shaft moved a horizontal, low-friction linear bearing via a force transducer (Fig. 1). The signal of the transducer was proportional to the frictional force between the ball and the disk. Hence, the coefficient of friction, μ, could be calculated. Considering the viscoelastic properties of polyethylene, a better term would be coefficient of total kinetic resistance, because the indentation of the ball into the disk is substantial [16].

The load was vertical, static 2 kN. Earlier hip wear simulations showed that the load need not be dynamic [17]. It was assumed that the same holds true for the knee. Because of the APT, the stresses in the disk changed cyclically even with static load.

The ball was a polished, 54 mm diameter, modular CoCr head of a hip hemiprosthesis, item no. 126–854, manufactured by Waldemar Link, Germany. The axis of the conical part of the ball holder was at an angle of 45° to the main

Table 1
Polyethylene disks, material GUR 1050 Perplas IMP-2000

Test	Thickness (mm)	Gamma-irradiation	Aging
1	10	No	No
2	5	No	No
3	10	2.5 Mrad in air	In air convection oven, 14 days at 100°C
4	10	2.5 Mrad in air	In O_2, 14 days at 70°C, 5 atm pressure
5	5	2.5 Mrad in air	In O_2, 14 days at 70°C, 5 atm pressure

axis of the ball holder (Fig. 1). This made it possible to use the same ball in several tests, by fixing it in a new position. The ball was carefully centred to the FE axis.

The disks were machined from a GUR 1050, Perplas IMP-2000 ultra-high molecular weight polyethylene bar. The diameter of the disks was 40 mm. Five different disks were tested (Table 1). The oxidation was simulated by aging after gamma-irradiation. In the disk holder, the underside of the disk rested against a flat, ground stainless steel backing.

Triple 0.1 μm sterile filtered, low-protein, low-endotoxin HyClone Alpha Calf Fraction serum, cat. no. SH30076.03, diluted 1:1 with Milli-Q grade distilled water, was used as the lubricant, without additives. The amount of lubricant in the acrylic test chamber was 200 ml. The chamber was deliberately made large and open to avoid the overheating of the lubricant, which is known to adversely affect the wear simulation [18]. The capacity of the chamber was 300 ml. The tests were done at room temperature. Once a day, the air temperature near the chamber, within a large covering hood, and the lubricant bulk temperature were measured. At the same time, the value of frictional force was recorded.

The test length was five million cycles. Each test took 8 weeks to run, as the test frequency was 1.08 Hz. The tests were stopped at intervals of ca. 560,000 cycles for wear measurement and lubricant change. During the stop, the specimens and their holders were washed. The disk was vacuum desiccated for 30 min, weighed with a balance having 0.01 mg resolution, and examined with an optical microscope. The maximum contact pressures were calculated assuming that the diameter of the contact was equal to the width of the wear zone, and that the contact pressure distribution was elliptical.

Wear particles were isolated from a sample of used serum taken halfway through test 1. The particles were isolated by NaOH digestion, HCl neutralization, and filtration on a 0.05 μm polycarbonate filter. Sections of filters were examined with a scanning electron microscope. The area of particles was calculated with an image analysis program. The diameters were then calculated using the equivalent circle principle. Particles were identified with infrared spectroscopy.

3. Results

The simulator proved to be easy to operate and reliable, needing minimal maintenance. The test results are summarized in Fig. 3 and Table 2. The wear rates of the

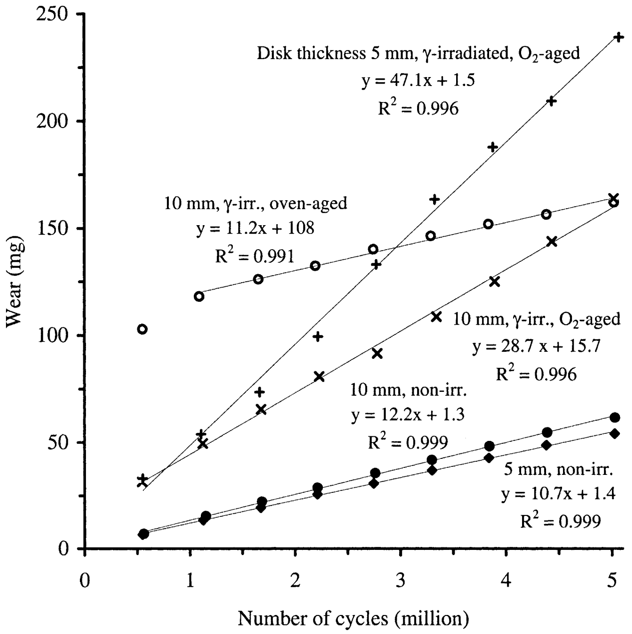

Fig. 3. Variation of gravimetric wear of polyethylene disks with number of cycles.

Table 2
Wear of polyethylene disks, and average coefficient of friction

Test	Wear rate (mg/10^6 cycles)	Wear factor (10^{-6} mm^3/Nm)	Wear pit dimensions (mm)			μ
			Length	Width	Depth	
1	12.2	0.33	23.6	14.7	0.5	0.045
2	10.7	0.29	23.3	14.8	0.6	0.047
3	11.2	0.30	25.8	17.1	0.9	0.043
4	28.7	0.77	24.9	16.8	1.0	0.058
5	47.1	1.27	26.0	17.6	1.3	0.063

Fig. 4. Optical micrograph from wear zone of polyethylene disk, test 1.

non-irradiated disks were almost identical, and moderate. The wear rate of the gamma-irradiated disk which was aged in an air convection oven was high in the beginning, but later the wear rate decreased and settled to a value between those of the non-irradiated disks. The wear rate of the gamma-irradiated, O_2-aged disk of 10 mm thickness was 2.4 times higher than that of the non-irradiated disk of the same thickness, and the wear rate of the gamma-irradiated, O_2-aged disk of 5 mm thickness was 64% higher than that of similarly treated disk of 10 mm thickness. In visual

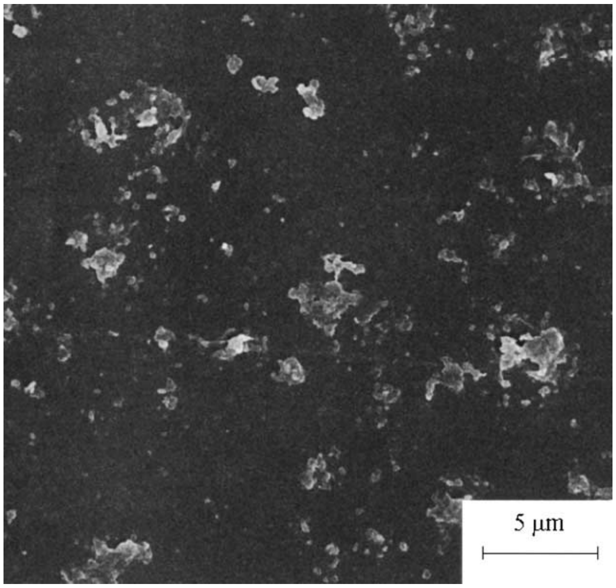

Fig. 5. Scanning electron micrograph of small polyethylene wear particles, test 1.

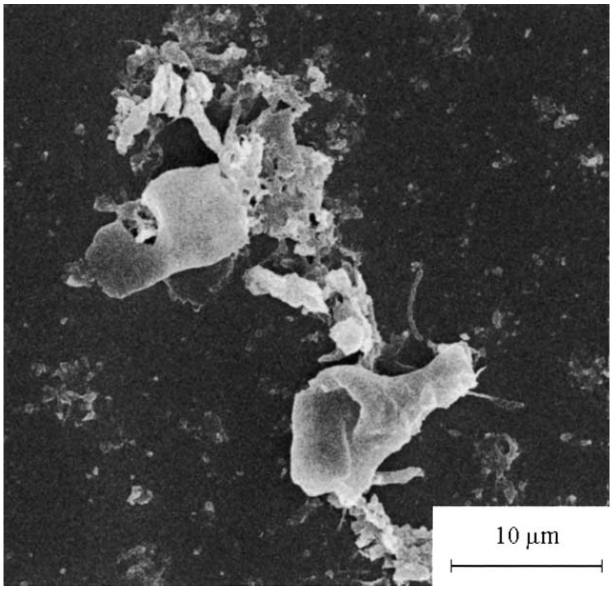

Fig. 6. Scanning electron micrograph of large polyethylene wear particles, test 1.

examination, the wear zone was burnished in all tests. In optical microscopy, smoothness was the dominating feature (Fig. 4). In test 5, the disk showed macroscopic cracks and signs of starting delamination after four million cycles. The majority of the wear particles had a diameter between 0.1 and 1 μm (Fig. 5). The average diameter of the 96 particles distinguished in Fig. 5, a typical scanning electron micrograph, was $0.7 \pm 0.5\,\mu$m. In addition, there were some larger flakes with a diameter of the order of 10 μm (Fig. 6). The friction signal was serrated in shape. Therefore, the rms value was used in the calculation of μ. The bulk temperature of the lubricant was close to the air temperature near the test chamber, which was ca. 29°C, the difference being usually a few tenths of a degree. The calculated maximum contact pressures at five million cycles in tests 1–5 were 17.7, 17.4, 13.1, 13.5 and 12.3 MPa, respectively.

4. Discussion

The quantification of clinical wear of prosthetic knees is difficult. The measurement of linear wear is confused by the substantial creep of polyethylene. The wear factor is also problematic, because the volume of material removed, the load and the sliding distance are very difficult to estimate with precision. Therefore, the validation of a knee wear simulator must rely on qualitative methods. In practice, the most important method is the evaluation of wear mechanisms by the microscopy of worn surfaces and of wear particles.

The burnishing of the polyethylene surface was a macroscopic sign of adhesive wear producing wear particles in the clinically relevant micrometre size range. It was encouraging to discover that the particles produced in the present simulator were similar to those isolated from tissues around failed total knee prostheses [10,11], having the same average diameter, 0.7 μm. As in earlier hip wear simulations [17], an essential factor in the burnishing proved to be that the direction of sliding constantly changed relative to the polyethylene specimen. In the present simulator, this was arranged so that the track of the contact point on the disk formed a figure of eight. Abrasion and scratching did not occur in the present tests because abrasives, such as acrylic particles, were not added to the lubricant. This may be done in later tests.

The wear of the gamma-irradiated, oven-aged disk (test 3) was rapid in the beginning because the surface of the disk was very brittle. However, the wear rate of this disk decreased substantially during the first million cycles, as the ball penetrated through the brittle surface layer and reached the ductile, undamaged core of the disk. The steady-state wear rate was between those of the non-irradiated disks (Fig. 3). These values, 10.7–12.2 mg per one million cycles, corresponding to wear factors of 0.29×10^{-6} to $0.33 \times 10^{-6}\,\mathrm{mm^3/N\,m}$, may be considered moderate. Apparently, the parameters of the oven aging were not optimal because pitting or delamination did not occur, and because in retrieved and shelf-aged polyethylene components, the maximum embrittlement caused by oxidation does not occur on the surface, but below the surface. Clinically, delamination correlates with oxidation [9], and the risk of severe wear and fragmentation increases with decreasing thickness of the polyethylene tibial component [4,5,19–23].

In the non-irradiated disks, the wear rate and contact pressure were insensitive to the disk thickness. The wear rates of gamma-irradiated, O_2-aged disks were not only much higher than those of the non-irradiated disks, but the wear rate of the disk of 5 mm thickness, 47.1 mg per one million cycles, was clearly higher than that of the disk of 10 mm thickness, 28.7 mg per one million cycles. On the basis of the present tests, it appears that the thickness dependence of wear seen in vivo is caused by gamma-irradiation in air. Naturally, more tests are needed to verify this finding. It was interesting, however, to note that the microtomed cross-sections of the disks did not show any embrittlement, except for the surface of the oven-aged disk. To elucidate this point, an additional test was done with a disk machined from a Townley tibial component, which had been gamma-irradiated in air and had been on the shelf for 10 years. This disk delaminated and cracked within minutes after the start of the test, and the test had to be stopped after 500 cycles only. Microtomed cross-sections showed severe subsurface embrittlement (“white band”). Obviously, more research is needed to optimize the aging conditions of polyethylene wear test specimens with regard to the prosthetic knee.

The open lubricant chamber, which was capable of holding a large amount of fluid, proved to be an effective way of avoiding excessive heating of the lubricant. Although the friction power was ca. 2 W, the average increase of the lubricant bulk temperature relative to the environment temperature was a few tenths of a degree only. Excessive heating of serum is known to cause misleading wear for polyethylene [18].

The fact that the addition of the IOR increased the wear rate agrees with the observation made using the Stanmore pin-on-flat knee wear simulator [24]. The difference was, however, more pronounced in the present simulator. The test conditions in these two studies were fairly similar. The main difference between the simulators is in the direction of APT motion of the disk relative to the direction of sliding of the counterface. In the present simulator, the directions are always the same, whereas in the Stanmore simulator, which does not have the FE, they are always opposite to each other, as in a tyre-road contact when the vehicle accelerates so that the wheel slips (present simulator), or brakes so that the wheel is locked (Stanmore simulator).

As the prosthetic components made of polyethylene are often damaged by oxidation, it is important that wear tests are done not only with undamaged specimens but also with specimens which are aged so that their properties correspond to those of real, damaged components. Therefore, the aging conditions need to be carefully optimized, and explicitly so that the feedback in the iteration procedure comes from wear tests. This work will be continued with the present simulator, which is currently being completed by making it into a more efficient, five-station device facilitating the repetition of the tests.

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References

[1] K.J. Chillag, E. Barth, An analysis of polyethylene thickness in modular total knee components, Clin. Orthop. 273 (1991) 261–263.

[2] D.L. Bartel, J.J. Rawlinson, A.H. Burstein, C.S. Ranawat, W.F. Flynn Jr., Stresses in polyethylene components of contemporary total knee replacements, Clin. Orthop. 317 (1995) 76–82.

[3] T. Stewart, Z.M. Jin, D. Shaw, D.D. Auger, M. Stone, J. Fisher, Experimental and theoretical study of the contact mechanics of five total knee joint replacements, J. Eng. Med. 209 (1995) 225–231.

[4] T.M. Wright, D.L. Bartel, The problem of surface damage in polyethylene total knee components, Clin. Orthop. 205 (1986) 67–74.

[5] J.P. Collier, M.B. Mayor, J.L. McNamara, V.A. Surprenant, R.E. Jensen, Analysis of the failure of 122 polyethylene inserts from uncemented tibial knee components, Clin. Orthop. 273 (1991) 232–242.

[6] R.C. Wasielewski, J.O. Galante, R.M. Leighty, R.N. Natarajan, A.G. Rosenberg, Wear patterns on retrieved polyethylene tibial inserts and their relationship to technical considerations during total knee arthroplasty, Clin. Orthop. 299 (1994) 31–43.

[7] P. Lewis, C.H. Rorabeck, R.B. Bourne, P. Devane, Posteromedial tibial polyethylene failure in total knee replacements, Clin. Orthop. 299 (1994) 11–17.

[8] G.W. Blunn, A.B. Joshi, P.A. Lilley, E. Engelbrecht, L. Ryd, L. Lindgren, K. Hardinge, E. Nieder, P.S. Walker, Polyethylene wear in unicondylar knee prostheses, Acta Orthop. Scand. 63 (1992) 247–255.

[9] C.J. Bell, P.S. Walker, M.R. Abeysundera, J.M.H. Simmons, P.M. King, G.W. Blunn, Effect of oxidation on delamination of ultrahigh-molecular-weight polyethylene tibial components, J. Arthroplasty 13 (1998) 280–290.

[10] K. Hirakawa, T.W. Bauer, B.N. Stulberg, A.H. Wilde, Comparison and quantitation of wear debris of failed total hip and total knee arthroplasty, J. Biomed. Mater. Res. 31 (1996) 257–263.

[11] A. Kobayashi, W. Bonfield, Y. Kadoya, T. Yamac, M.A.R. Freeman, G. Scott, P.A. Revell, The size and shape of particulate polyethylene wear debris in total joint replacements, J. Eng. Med. 211 (1997) 11–15.

[12] V. Saikko, P. Paavolainen, M. Kleimola, P. Slätis, A five-station hip joint simulator for wear rate studies, J. Eng. Med. 206 (1992) 195–200.

[13] B. Kummer, Biomechanics of the hip and knee joint, in: M. Schaldach, D. Hohmann (Eds.), Advances in Artificial Hip and Knee Joint Technology, Springer, Berlin, 1976, 525 pp.

[14] A. Seireg, R.J. Arvikar, The prediction of muscular load sharing and joint forces in the lower extremities during walking, J. Biomech. 8 (1975) 89–102.

[15] M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten, Measurement of lower extremity kinematics during level walking, J. Orthop. Res. 8 (1990) 383–392.

[16] S.D. Waldman, J.T. Bryant, Dynamic contact stress and rolling resistance model for total knee arthroplasties, J. Biomech. Eng. 119 (1997) 254–260.

[17] V. Saikko, T. Ahlroos, Type of motion and lubricant in wear simulation of polyethylene acetabular cup, J. Eng. Med. 213 (1999) 301–310.

[18] A. Wang, V.K. Polineni, A. Essner, C. Stark, J.H. Dumbleton, Quantitative analysis of serum degradation and its effect on the outcome of hip joint simulator wear testing on UHMWPE, in: 45th Annual Meeting, Orthopaedic Research Society, Anaheim, California, February 1999.

[19] G.A. Engh, K.A. Dwyer, C.K. Hanes, Polyethylene wear of metal-backed tibial components in total and unicompartmental knee prostheses, J. Bone Joint Surg. 74B (1992) 9–17.

[20] S.H. Palmer, P.J.M. Morrison, A.C. Ross, Early catastrophic tibial component wear after unicompartmental knee arthroplasty, Clin. Orthop. 350 (1998) 143–148.

[21] R.E. Bartley, S.D. Stulberg, W.J. Robb III, H.J. Sweeney, Polyethylene wear in unicompartmental knee arthroplasty, Clin. Orthop. 299 (1994) 18–24.

[22] D.J. Kilgus, J.R. Moreland, G.A.M. Finerman, T.T. Funahashi, J.S. Tipton, Catastrophic wear of tibial polyethylene inserts, Clin. Orthop. 273 (1991) 223–231.

[23] S.M.G. Jones, I.M. Pinder, C.G. Moran, A.J. Malcolm, Polyethylene wear in uncemented knee replacements, J. Bone Joint Surg. 74B (1992) 18–22.

[24] P.S. Walker, G.W. Blunn, P.A. Lilley, Wear testing of materials and surfaces for total knee replacement, J. Biomed. Mater. Res. Appl. Biomater. 33 (1996) 159–175.