Overview of Metal-on-Polyethylene, Metal-on-Metal, and Ceramic Hip Wear Mechanisms

A Buford [1] and T. Goswami [2]

[1] *Department of Mechanical Engineering, 1815 Coliseum Drive, Russellville, AR 72801*
[2] *Department of Mechanical Engineering, Ohio Northern University, Ada, OH 45810, USA*

ABSTRACT

Premature failure of orthopaedic hip implants caused by multiple wear mechanisms is the primary failure mode of prosthetic hips. Wearing of the implants may lead to aseptic loosening, biological incompatibilities, and mechanical failure of the implant. In order to prevent or restrict the effects of the wear mechanisms, multiple laboratory studies are being conducted in order to determine each mechanism and its contribution to increased wear rates. This paper combines previous laboratory studies related to the wear of metal-on-polyethylene, metal-on-metal, and ceramic materials. The bulk quantity materials discussed include cobalt chromium alloys, stainless steels, zirconium oxide ceramics, and polyethylene materials that are used in biomedical implantation design, and a summary is provided of the test results of the materials subjected to wear mechanisms. The objective of this study is to present the mechanical properties of bulk materials used in implant design to determine how each mechanical or wear mechanism influences the wear rates for the material. The advantages and disadvantages of each material are also discussed.

I. WEAR MECHANISMS

There are many factors that influence the wear rates of implant materials. A wear factor or wear mechanism is classified as any mechanism that causes a change in wear rates. The wear rate is determined by the amount of wear that the implant endures with respect to time, and is commonly measured by volumetric loss. It is important to understand that lower wear rates for a specific variable may have been achieved because of the combination of other factors in the given scenario. In order to determine if a variable is a wear mechanism, testing must be conducted to determine if the variable has a significant effect on the wear rate of the test specimen in a controlled environment.

The three main forms of wear mechanism are adhesion, abrasion, and fatigue. There are multiple factors, separate from design and biomedical factors, in hip implants that have been determined through lab testing to affect a wear mechanism. These factors include: the duration and intensity of articulation, contact stresses, and oxidative wear. These factors are responsible for causing wear modes that are used to classify wear as a function of an implant's life span /1/. Mode 1 refers to the articulation between the primary contact areas of the prosthesis bearing that is considered in the implant design. Mode 2 is classified as the surface abrasion resulting from excessive wear and ultimately penetration of the primary contact areas in Mode 1 that was not considered in the initial design. Mode 3 is particulate wear caused by the suspended wear particles in the articulating zone that increase wear rates because of increased roughness and friction. Mode 4 is the rubbing of non-bearing surfaces together such as fixation pieces that result in fretting. Mode 1 is essential for the implant to function properly; however, the other modes are simply destructive by-products due to cyclic fatigue loading caused by articulation /1/.

2. MATERIAL PROPERTIES

The physical properties of an implant material determine the materials ability to withstand wear. Influential physical properties considered in implant materials include Young's modulus, density, hardness, compressive strength, biocompatibility, and corrosion resistance. Table 1 /2/ displays these properties for the most common implant materials.

From Table 1 a comparative analysis of the different materials can be made. The Biolox ® ceramic material is less dense than the other materials; however, the ceramic material has superior hardness and strengths that contribute to the materials superior wear characteristics. The Biolox ® ceramic material has a hardness 15 times the hardness of steel as well as a Young's modulus that is twice as great, while only half the weight. These properties of the Biolox ® material are comparative amongst most ceramic materials when compared to metal alloys.

2.1 Polyethylene Materials

Ultra high molecular weight polyethylene (UHMWPE) is currently the standard bearing material in hip implant design. There are many factors that influence polyethylene wear; therefore, it is important to understand how each design factor affects the wear of the prosthesis. The polyethylene-on-metal wear mechanisms include: kinematical contact stresses, articulation, oxidation, lubricants and clearances. Various design factors, extracted from Devane *et al.*, (1999) /3/, that influence wear rates are summarized in Table 2.

Ultra high molecular weight polyethylene (UHMWPE) has been the standard type of polyethylene used in design for metal-on-polyethylene implants for several years. This polyethylene has been more wear resistant than other types because UHWMPE has between 45 to 65% less crystalline structure than other types of

Table 1

Physical Properties of Common Implant Materials

Property	Unit	Material			
		Stainless Steel	Co- based Alloys	Titanium Alloys	Biolox ® Al_2O_3
Density	g/cm^3	7.8	8.0	4.5	3.9
Hardness HV	Mpa	1500	3000	900	23000
Compressive Strength	Mpa				5000
Flexural Strength	Mpa	ca. 800	ca. 1000	ca. 600	500
Tensile Strength	Mpa				300
Young's Modulus	Mpa	$200x10^3$	$230x10^3$	$120x10^3$	$380x10^3$
Electrical Resistance	Ω x cm	$7x10^{-5}$	$5x10^{-5}$	$5x10^{-5}$	$5x10^{15}$
Biocompatibility	-	fair	good	good	excellent

Table 2

Summary of Factors Influencing Polyethylene Wear

Factor	Increasing Wear	Decreasing Wear
Age	Younger	Older
Activity level	High	Low
Head size (mm)	32	26 or 28
Fixation	Bone	Cement
Prothesis	Ti	CoCr
Liner Thinkness (mm)	< 8	> 8
Femoral offset	Not restored	Restored
Head type		
Ti	Likely	

polyethylene resulting in a tougher, more ductile material; however, the structure is more susceptible to creep, due to body temperature, and is more fluid absorbent. /4/ Much like the different metal alloys used in implants, there are also many forms of UHMWPE as well as manufacturing processes that affect the properties of the material. These processes include: heat pressing, polishing, gamma radiating, carbon reinforced polymer chains, and pressure crystallization, which have provided both positive and negative results on the materials ability to withstand wear.

UHMWPE has been proven to be a more successful implant material than previous materials; however, UHMWPE has many properties that prevent this material from achieving long-term clinical success. Testing has been done on bulk quantity polyethylene materials to understand its physical properties in order to understand how these properties influence implant behavior /4-8/. R.M. Streicher /4/ reported the following properties of UHMWPE shown in Table 3.

Table 3

Properties of UHMWPE

Property	SI Units	UH-RCH Chirulen	UH-HI Himont 1900	Requirements according to ISO/DIS 5834 Type A = RCH	Type B = HI
Density	g/cm^3	0.94	0.94	0.935-0.944	0.93-0.944
Tensile Stress					
@ yield 23^0 C	N/mm^2	25.60	25.60	min 21	min 21
Tensile Stress					
@ break 23^0 C	N/mm^2	40.00	51.00	min 35	min 35
120^0 C	N/mm^2	19.80	22.70	min 18	min 18
Elongation					
@ break 23^0 C	N/mm^2	373.00	321.00	min 350	min 350
120^0 C	N/mm^2	860.00	920.00	min 600	min 600
Notched Impact Strengh	mJ/mm^2	122 no break	45 no break	min 140 no break	min 140
Ball indentation hardness	N/mm^2	48.80	46.50	-	-
Hardness HV 0.1/30	N/mm^2	51.00	51.00	-	-
Flow Value	N/mm^2	0.33	0.45	min 0.2	min 0.2
Molecular Weight	10^{6}g/mol	2.00	2.90	-	-
Water absorption 1 Month	ppm	82.00	78.00	-	-
Ash	ppm	123.00	233.00	max 150	max 300
Foreign particles	N/mm2	1.00	4.00	max 10	max 10
Manufacturers: Hilmont, Wilmington (UH-HI) and Ruhrchemie, Oberhausen (UH-RCH)					

At the time of Streicher's study there were only two manufacturers of medical grade polyethylene. The companies, Hilmont, Wilmington, U.S.A. and Ruhrchemie, Oberhausen, use different processes to synthesize the polymer powders, and therefore each brand of UHMWPE has different properties that influence performance. These properties include particle size and distribution. When forming the polyethylene, the polymer powder is heated at 200 0C into sheets, rods, or finial mold design.

After the polymer material is formed there are still catalyst residue, corrosion products, and dirt from the various base materials that the UHMWPE is formed from. Table 4 displays the trace elements that are still present extracted from Streicher's study. Alterations of polyethylene's physical properties can be achieved through various treatment and manufacturing techniques. Alterations were implemented into design in hopes of making a more wear resistant material. These processes include gamma irradiation, heat pressing, polishing, high-pressure crystallization, and carbon reinforcement of polymer chains.

Table 4

Trace Elements in UHMWPE

EDAX CHIRULEN	Analysis (ppm) CHIRULEN	HIFAX 1900
Aluminuim	6	64
Chlorine	2	5
Chromium	0.3	0.1
Iron	3	4
Calcium	39	11
Silicium	1	2
Titanium	9	27
Molybdenum	not determined	
Nickel	not determined	
Potassium	not determined	
Sulphur	not determined	

2.2 Gamma Irradiating Polyethylene

Gamma irradiation is now being tested to determine if this process will beneficially alter the properties of polyethylene. Some of the prospective benefits of gamma irradiating polyethylene include a more effective cross linking, and eliminating the effects of oxidation on the polyethylene /9-12/. One form of gamma irradiating polyethylene treatment is Thin Layer Activation (TLA). TLA uses high-energy charged particle beams to manipulate polyethylene resulting in the creation of radiotracers to a precise surface layer of the polyethylene /13-16/. "The advantages of (TLA) include higher sensitivity, speed, and area selectivity." Stroosnijder *et al.*'s (2002) /13/ study concluded that the TLA treatment of polyethylene was beneficial in preventing material loss in polyethylene.

2.3 High Pressure Crystallization of Polyethylene

High pressure crystallization was implemented into design producing higher resistance to fatigue crack growth and increase creep resistance, but the high pressure crystallization did not provide significant results to prove this process decreases wear rate of polyethylene /17-23/. Increasing the crystallinity of polyethylene causes an increase in the polyethylene's modulus of elasticity resulting in more intense contact stresses. If the contact stresses are unevenly dispersed the wear rate of the polyethylene will increase /24, 25/. Subsurface delamination has been determined as a detrimental byproduct of the heat pressing of the polyethylene surfaces /3/. This delamination has been determined to lead to premature cracking of the surface.

2.4 Carbon Reinforcement of Polyethylene

The addition of carbon reinforced polymer chains is used as a method to use to make the material stronger and tougher; however, The carbon reinforced polymers cause increased wear due to less conformed articulating surfaces and higher contact stresses /3/. The carbon fibers blended with polyethylene produce a material with higher resistance to creep, but a decrease in resistance to fatigue resulting in no overall improvement to wear resistance.

2.5 Alloy Properties

Cobalt chromium alloys are the standard material for metal-on-metal implants. However, each type of cobalt chromium alloy has different properties that affect the wear rates of the implant. These properties include percent carbon and manufacturing process.

2.6 Manufacturing Processes

The type of manufacturing process also has an effect on the wear rates. Medley *et al.* (1996) /26/ determined that the casting technique was superior to the wrought technique. The average linear wear value for casting was 0.43 mm^3 as compared to the wrought value of 0.61 mm^3. The difference in wear rates for the two manufacturing processes was small, but the casting technique was superior /26/.

2.7 Ceramic Materials

The most common type of ceramic material used for biomedical prosthesis and design is aluminum oxide /27/. Zirconium oxide is also considered as a second-generation material that has potential as a material for design. Other types of ceramic materials being considered but not clinically emphasized include titanium oxide (TiO_2) and zirconium oxide (ZrO_2) /28-30/. Ceramics are considered to be a superior implant material as compared to other alloys due their ideal biocompatibility and mechanical properties. Over the last twenty years ceramics mechanical properties such as flexural and tensile strengths have increased significantly; however, the impact strengths and fracture resistance have still remained relatively low. Beneficial properties of ceramics as an implant material include their chemical inertness, lack of solubility, smooth surfaces, and high wettability. The smooth wettable surface of the ceramic surfaces produces lower coefficients of friction as compared to conventional implant metals. Reported cases conclude that the ceramic material has produced 4000 times lesser wear products than cobalt chromium alloys compared with polyethylene /27/. The ceramic-polyethylene results, shown in Table 5 /31/, conclude that ceramic materials showed a superior wear resistance as compared to metal alloys.

Basic requirements for ceramic materials have been set in order to produce acceptable clinical results. These results are a function of purity, grain size, density, and mechanical strengths of the ceramic materials

Table 5

Wear Rates from Studies of Ceramic-on-Polyethylene Total Hip Replacements

Study	Acetabular Bearing	Femoral Bearing	Femoral Head Diameter *(mm)*	Average Liner Wear Rate *(mm/yr)*
Saito et al (1992)*	Polyethylene	Alumina	28	0.10
Sugano et al (1995)*	Polyethylene	Alumina	28	0.10
Okumura et al (1989)	Polyethylene	Alumina	28	0.08
Schuller and Marti (1990)	Polyethylene	Alumina	32	0.03
Ohashi et al (1989)	Polyethylene	Alumina	28	0.03
Wroblewski et al (1996)	Crossed-Linked Poly	Alumina	22	0.03

* Same group of patients

/32/. The suggested consistencies of alumina ceramic are 99.7% with no more than 0.1% consistency of alkaline oxides and silicon oxides. It is also suggested that, in order to maintain the average grain size of 4 μm for ceramic materials, 2 - 25% of the ceramic consist of magnesium oxide. The wear rates produced for ceramic materials are a function of the grain size and density; therefore, it is suggested that the minimum density of 3.96 g/cm^3.

3. MATERIALS PAIRED WITH POLYETHYLENE

Analyses of laboratory results conclude which materials are superior in multiple scenarios and provide crucial information on how materials affect wear rates. Brummitt *et al.* (1996) /33/ conducted a study on retrieved implants consisting of both titanium and cobalt chromium alloys. The cobalt-chromium alloys showed superior wear resistance after a time period of twelve years as compared to the titanium alloys that were significantly damaged after a time period well under twelve years. Both metal alloys were combined with the same Ultra High Molecular Weight Polyethylene (UHMWPE) components. The cobalt-chromium alloy surface finish was maintained uniformly over the articulation zones; however, the titanium implants were uniformly damaged. The roughness measurements, R_a for both types of alloys are shown in Table 6 /33/. The average roughness values from the three tests conducted on the specimens are shown in Figure 1

Table 6

Comparison of R_a Value with Instruments

Material	Interferometer	Mechanical profilometer	Laser profilometer	Average of three Test
Worn Ti alloy	0.101	0.081	0.273	0.152
Worn Ti alloy	0.091	0.093	0.448	0.211
Worn Co-Cr	0.016	0.034	0.152	0.067
Worn Co-Cr	0.006	0.021	0.108	0.045

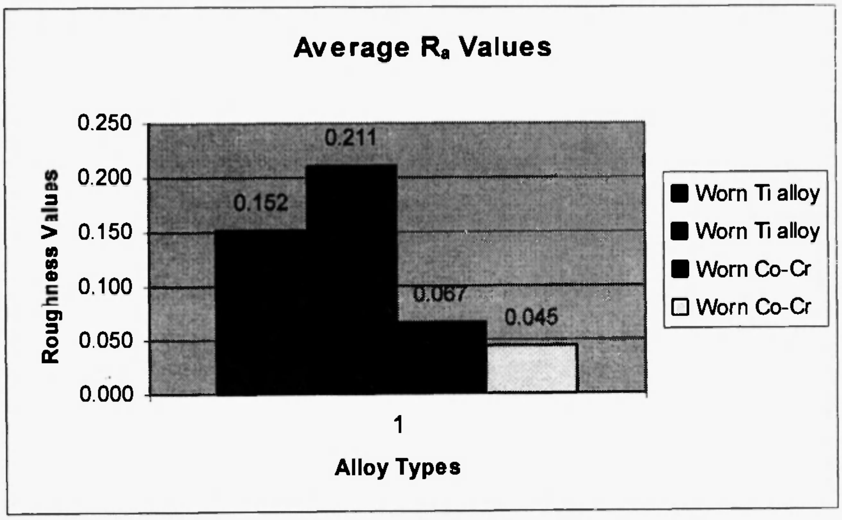

Fig. 1: Average R_a Values

Table 7

The Effect of Bone Debris Resulting from Pin Reciprocating Abrasion on the Surface Roughness of Various Metals

Material	Surface Hardness *(DPH)*	Wear Depth (μm)	Increase in R_a (μm)	Number of wear Cycles
316L S.S.	230	48	0.74	10^6
Ti-6AL-4V	330	28	4.09	10^6
Nitrogen ion Implanted Ti-6Al-4V	700	31	3.25	10^6
Co-Cr-Mo	400	1	0.1	10^6
ZrO_2	1430	0	0	10^7

Ra - Roughness Value

/33/. Although the implants were removed from different patients with different life styles that affected the wear rates, the cobalt-chromium alloys were significantly lower than the titanium alloys in both cases.

Davidson *et al.* (1993) /34/ concluded the same results as the previously mentioned study, where Co-Cr-Mo was the superior alloy. The experiment dealt with many types of alloys and provided data on the material properties and how these properties affected the amount of wear on the metal-polyethylene implants. The results of the experiment are shown in Table 7 /34/. The Co-Cr-Mo had the highest resistance to bone debris formation out of all the metal-polyethylene combinations as shown in Figure 2 /34/.

Urban *et al.* (2001) /31/ revealed how different materials affected the wear of hip implants over a period between 17 to 21 years. The materials, combined with polyethylene, that were evaluated in this study include

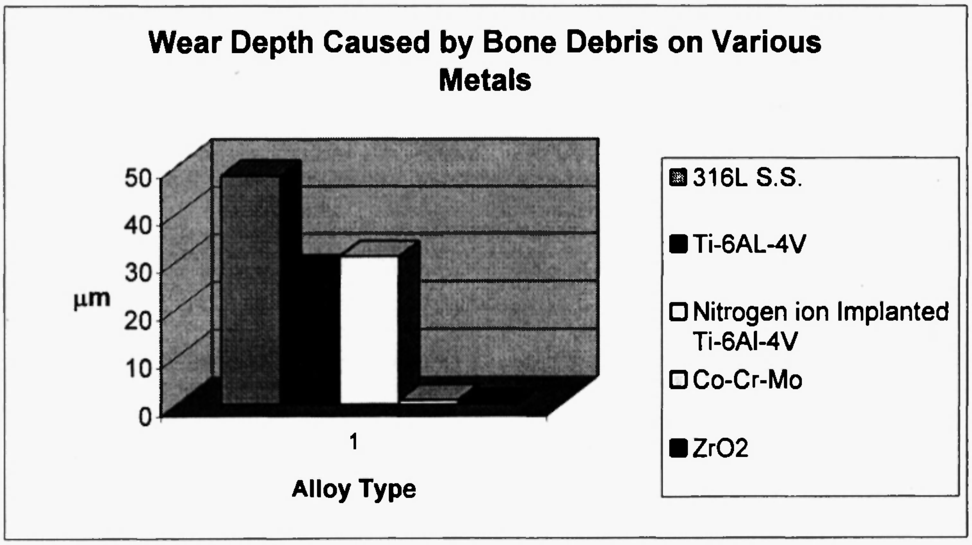

Fig. 2: Wear Depth Caused by Bone Debris on Various Metals

stainless steel, cobalt chromium alloys, and ceramics. The metal-on-polyethylene results are shown in Table 8 /31/. There were no significant differences in the average wear per year between the stainless steels and the cobalt-chromium alloys.

Sychterz *et al.* (1996) /35/ conducted a statistical study on 19 retrieved implants. The statistical analysis was used to determine if cobalt-chromium heads were significantly superior to ceramic femoral heads when paired with a polyethylene cup. The study concluded that there was no correlation to wear rates between the cobalt-chromium and ceramics, nor was there a direct relationship to wear caused by the sex of the patient or

Table 8

Wear Rates from Studies of Metal-on-Polyethylene Total Hip Replacements

Study	Acetabular Bearing	Femoral Bearing	Femoral Head Diameter (*mm*)	Average Liner Wear Rate (*mm/yr*)
Woolson and Murphy (1995)	Polyethylene*	Cobalt-Chromium	28	0.14
Okumura et al (1989)	Polyethylene	Stainless Steel	22	0.14
Livermore et al (1990)	Polyethylene	Stainless Steel	22	0.13
	Polyethylene	Cobalt-Chromium	32	0.10
	Polyethylene	Stainless Steel	28	0.08
Madey et al (1997)	Polyethylene*	Stainless Steel	22	0.09
Bankston et al (1995)	Polyethylene*	Cobalt-Chromium	28	0.05
Ohashi et al (1989)	Polyethylene	Cobalt-Chromium	32	0.04
	Polyethylene	Stainless Steel	28	0.04

* Cemented all-polyethylene Component

the head type, modular or non-modular /35/. The physical properties of the retrieved implants are shown in Table 9 /35/. The wear rates for the retrieved implants are shown in Table 10 /35/.

The different types of materials combined with the different types of polyethylene result in varied wear rates. The cobalt chromium alloys and ceramic materials, used in polyethylene-on-metal implants, have proved superior in wear resistance as compared to previous metals used in total hip arthroplasty design as verified by the studies researched.

3.1 Metal-on-metal Compared with Polyethylene-on-metal

Multiple tests show that the metal-on-metal implants are superior against wear as compared to polyethylene-on-metal implants. The metal-on-metal implants do not form particulate as fast or in as great a quantity as polyethylene. The metal-on-metal implants experience an accelerated wear rate that eventually

Table 9

Data on the Patients and Components

Specimen #	Gender, Age of Patient *(Yrs)*	Weight of Patient at time of Op. *(kg)*	Duration that Implant was *in Situ* *(Mos.)*	Femoral Head	Modular Head
1R	M, 69	81.6	62	Ceramic	Yes
2L	M, 62	74.8	112	Cobalt-Chromium	No
2R	62	74.8	110	Cobalt-Chromium	No
3L	F, 71	61.2	92	Cobalt-Chromium	No
4R	M, 71	73.0	45	Cobalt-Chromium	Yes
5L	F, 77	86.2	66	Cobalt-Chromium	No
5R	75	79.4	91	Cobalt-Chromium	No
6R	F, 87	60.8	75	Cobalt-Chromium	No
7L	M, 50	88.4	116	Cobalt-Chromium	No
8L	F, 66	54.9	51	Ceramic	Yes
9R	M, 79	81.6	151	Cobalt-Chromium	No
10L	F, 39	45.4	97	Cobalt-Chromium	No
10R	43	45.4	56	Ceramic	Yes
11L	M, 78	76.2	42	Cobalt-Chromium	Yes
12L	F, 62	59	52	Cobalt-Chromium	No
12R	63	62.6	44	Cobalt-Chromium	No
13R	F, 77	65.8	132	Cobalt-Chromium	No
14L	M, 70	86.6	206	Cobalt-Chromium	No
14R	69	83.9	123	Cobalt-Chromium	No
15R	F, 76	47.2	33	Cobalt-Chromium	Yes
16L	F, 84	56.7	144	Cobalt-Chromium	No
16R	83	56.7	156	Cobalt-Chromium	No
17R	M, 73	107.5	75	Ceramic	Yes
18R	F, 81	69.8	83	Cobalt-Chromium	No
19L	M, 76	74.8	53	Cobalt-Chromium	Yes
19R	73	75.7	88	Ceramic	Yes

Table 10

Data on Wear

Specimen #	Linear Wear (mm)	Volumetric Wear (mm^3)	Rate of Linear Wear (mm/yr.)	Rate of Volumetric (mm^3 /yr.)	Angle from Face of Cup*	Angle from Superior Point#
1R	0.32	216.1	0.06	41.8	34.8	-97.1
2L	0.41	300.1	0.04	32.2	43.4	168.0
2R	0.80	561.7	0.09	61.3	39.3	81.5
3L	0.40	238.6	0.05	31.1	22.7	58.1
4R	0.63	492.5	0.17	131.3	59.7	21.4
5L	0.36	232.1	0.07	42.2	29.3	0.1
5R	0.18	116.1	0.02	15.3	28.0	-4.0
6R	0.24	183.5	0.04	29.4	57.0	42.8
7L	0.30	199.0	0.03	20.6	31.7	31.0
8L	0.30	176.9	0.07	41.6	21.0	-139.4
9R	0.28	13.0	0.02	1.0	-52.0	-82.0
10L	0.82	24.6	0.10	3.0	-57.2	-16.4
10R	0.26	149.9	0.05	32.1	21.6	-47.5
11L	0.32	119.4	0.09	34.1	-2.9	143.3
12L	0.40	259.3	0.09	59.8	29.2	-53.7
12R	0.41	211.6	0.11	57.7	13.5	48.2
13R	0.74	484.6	0.07	44.1	31.6	62.2
14L	0.78	305.1	0.05	17.8	-1.5	66.3
14R	0.21	111.2	0.02	10.9	15.4	25.6
15R	0.49	189.6	0.18	68.9	-2.1	12.2
16L	0.47	281.2	0.04	23.4	22.6	80.1
16R	0.39	34.9	0.03	2.7	-41.6	-130.4
17R	1.07	779.1	0.17	124.7	43.7	35.5
18R	0.58	412.7	0.08	59.7	40.5	13.0
19L	0.17	106.6	0.04	24.1	29.2	25.1
19R	0.24	179.6	0.03	24.5	45.7	12.4

* A negative angle indicates a lateral wear vector.

\# Negative angles are directed anteriorly and positive angles are directed posteriorly.

ceases as compared to polyethylene-on-metal implants that continuously wear. The results from the Anissian *et al.* (1999) /36/ test comparing polyethylene-on-metal, metal-on-metal, and ceramic-on-metal roughness and wear values are shown in Table 11 /36/. Table 12 compares the wear particulate count for the combination of the materials in the Anissian *et al.* study /36/.

4. DURATION AND INTENSITY OF ARTICULATION

Considering that a hip implant endures numerous cycles of articulation, implant materials must be capable of withstanding fatigue due to cyclic loading. Therefore, duration and intensity are two important factors that

Table 11

Total Number of Particles Generated During Mechanical Testing

Head/ Taper	Number of Cycles (Mean +or- SD x 10^6)			
	1M Saline	5M Saline	10M Saline	10M Total
Co-Cr(W)/Ti(S)	0.71+or- 0.30	1.58 +or- 0.51	2.39 +or- 0.83	4.04 +or- 1.61
Co-Cr(W)Co-CrS)	11.39 +or- 1.27	3.07 +or- 1.21	6.25 +or- 1.04	4.43 +or- 1.63
Co-Cr(W)/T(r)	0.50 +or- 0.19	1.56 +or- 0.13	2.06 +or- 0.30	3.25 +or- 0.38
Co-Cr(W)Co-Cr[R]	1.09 +or- 0.49	3.10 +or- 1.43	3.78 +or- 1.58	5.31 +or- 1.16
Zr/Ti [R]	1.30 +or- 0.41	1.71 +or- 0.39	2.09 +or- 0.30	5.02 +or- 1.33
Zr/Co-Cr[R]	1.82 +or- 0.87	2.28 +or- 0.90	3.09 +or- 1.42	4.00 +or- 1.29
Co-Cr(W)[+10]/Ti(S)	1.84 +or- 0.90	2.49 +or- 0.82	2.99 +or- 0.87	4.25 +or- 1.58
Co-Cr(W)[+10]/Co-Cr(S)	1.40 +or- 1.06	1.89 +or- 1.37	2.79 +or- 1.22	3.47 +or- 1.34
Co-Cr(W)/Ti(N)	0.97 +or- 0.36	1.49 +or- 0.38	1.66 +or- 0.31	2.27 +or- 0.51
Co-Cr(W)/Co-Cr(N)	07.0 +or- 0.25	1.34 +or- 0.43	2.02 +or- 1.05	2.53 +or- 1.10

(W) wrought materials: [C] Cast materials: (S) small surface: [R] rough surface : (N) nitrogen implanted

Table 12

Total Number of Particles Generated During Mechanical Testing

Dimensional Mismatch	Number of Cycles (x 10^6 Particles)			
Degrees	1M Saline	5M Saline	10M Saline	10M Total
Cobalt-Chromium Alloy Head (wrought)/ Titanium Alloy Taper (smooth)				
-0.045	0.92	1.96	3.39	4.31
-0.033	1.04	1.68	2.58	5.96
-0.011	0.36	0.83	1.47	2.06
0.011	0.79	2.08	2.91	3.82
Cobalt-Chromium Alloy Head (wrought)/ Titanium Alloy Taper (rough)				
0.010	0.30	1.64	2.05	2.68
0.027	0.34	1.41	2.04	3.48
-0.019	0.73	1.73	2.55	3.43
0.072	0.66	1.47	1.96	3.40
Cobalt-Chromium Alloy Head (wrought)/ Cobalt-Chromium Alloy Taper (smooth)				
0.054	2.27	5.36	6.92	7.52
-0.015	3.08	6.50	7.65	8.69
-0.001	1.27	5.09	7.07	7.97
0.170	2.62	5.95	7.54	8.40
Cobalt-Chromium Alloy Head (wrought)/ Cobalt-Chromium Alloy Taper (rough)				
0.006	0.56	2.92	3.54	4.62
-0.015	1.07	3.11	3.71	4.12
-0.018	1.21	4.38	5.29	6.68
-0.007	1.84	4.28	5.04	5.82

are related to articulation between implant materials and the corresponding affect on wear rates. Bowsher *et al.* (2001) /37/ conducted a study on different types of movements that a hip implant would perform, and the wear rates that were produced were analyzed. These motions included walking, stumbling, and jogging. Each motion was conducted in both a smooth and rough condition /37-42/.

The results concluded that the increased speed of running motion resulted in an increased wear rate. The rougher condition also increased the wear rates as compared to the smooth conditions. The stumbling motion produced the highest frictional torques on the implant, up to 64% higher than walking. The stumbling motion also increased the wear rate 11%-60% higher than the wear rates for walking motion /37/.

4.1 Contact Stresses

Contact stresses are an important factor that influence wear rates on an implant material. Many tests have been performed on implant materials to evaluate the articulating contact area in hope to develop design techniques to decrease wear rates /43-51/. Contact stresses are produced by different types of articulating motions and can be divided into three basic categories: sliding, gliding, and rolling.

Sliding is classified as a motion caused by the relative contact position of the polymer that remains stationary. Gliding is where the contact position in the polymer reciprocates. Rolling occurs when the contact position on the polymer varies and the relative velocities of both components are equal /43/. Often more than one type of kinematic contact stress occurs in an implant design, and therefore it is necessary to understand each type and how they influence wear rates.

The Cornwall *et al.* (2001) /43/ study was conducted on each type of kinematic contact stress and the results are shown in Table 13 /43/. The materials involved in the testing were Co-Cr alloys paired with ultra high molecular weight polyethylene. There were two sliding tests conducted that produced two very different results. The Sliding A test was recommended by ASTM, and used a flat pin in the contact area unlike the spherical pin used in the Sliding B test that resulted in a significantly lower wear rate. A comparison of the average wear rates for the types of kinematic contact stresses is shown in Figure 3 /43/. From the data collected in the experiment it is evident that the sliding contact stress was dominant in both test cases.

Table 13

Mean Wear Loss, Wear Rate, and Wear Factor for the Different Test Configurations after 3×10^6 Cycles of Testing

Testing configuration	*n*	Contact Stress *(Mpa)*	Mass loss *(mg)* Average	SD	Wear rate *(mm³/10⁶* Average	SD	Wear Factor *(mm³/N m)* Average	SD
Sliding A (ASTM)	5	3	1.452	1.571	0.523	0.573	6.811×10^{-8}	7.0886×10^{-8}
Sliding B	3	32	0.101	0.058	0.036	0.021	5.289×10^{-9}	3.3651×10^{-9}
Gliding C	3	32	3.390	0.546	1.217	0.203	1.867×10^{-7}	3.2107×10^{-8}
Rolling D	3	22-32	4.589	3.227	1.643	1.152	2.515×10^{-7}	1.7603×10^{-7}

SD - Standard Deviation
n - number of test

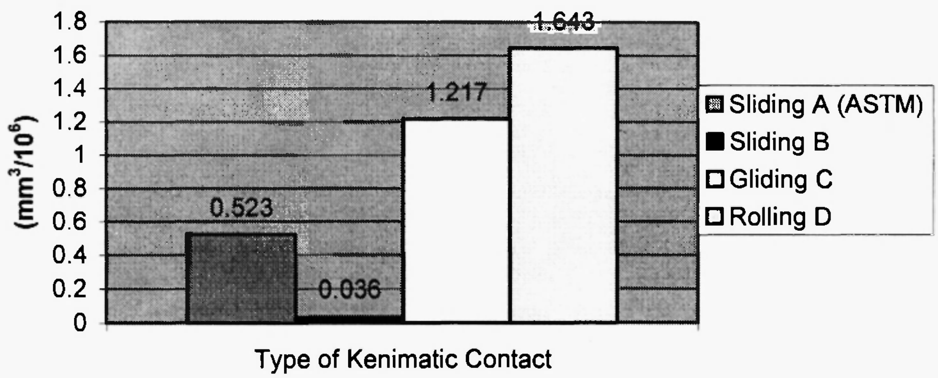

Fig. 3: Kinematic Contact vs Average Wear Rate

High contact stresses are generally thought to be detrimental to the prosthesis, but in some documented cases these stresses were tested and found to be complimentary to the prosthesis. Wang *et al.*'s (2001) /52/ study concluded that an increase in maximum contact stress resulted in lower coefficients of friction and a decrease in wear rates. These results were contradictive to many previous theoretical studies /53,54/.

The effects of improper contact stresses are burnishing, pitting, fretting, and scratching. Burnishing is the most common type of polyethylene wear and is classified by a rubbing, polishing motion /1/. The other forms of polyethylene wear are very similar and all result in the detrimental deformation of the prosthesis joint.

4.2 Oxidative Wear

Metals. unlike ceramics, react with the oxygen rich biological environment, and form a protective oxidative coating that prevents corrosion. The thin, transparent coating is generally 2-5 nm thick /31/. The oxidative film forms instantly once exposed to the *in vivo* conditions, but is not permanently fixated on the metals. The coatings are capable of being scratched or rubbed off when undergoing surface contact. Once the coating is dissipated, the implant metals are susceptible to releasing metal ions and particulates are released. The presence of the particulate and ions creates third body wear that dramatically increases wear rates due to the substantial increase in roughness. This detrimental cycle of destruction of the coating, releasing of the metal ions, and the reformation of new coatings is referred to as oxidative wear /34/. Davidson *et al.*'s (1993) laboratory study was conducted to determine the material consistency of particulate caused by oxidative wear for the most commonly used implant materials. The particulate formations of various types of implant materials used in design are shown in Table 14 /34/. The metal levels contained in the serum, simulating the biological fluids contained around the bearing surfaces of the hip joint, were also measured and shown in Table 15 /34/.

Table 14

Metal Levels Produce After 1.1 × 10^5 Articulation Cycles of Various Femoral Heads Against UHMWPE

Material	*Condition*	*Fe*	*Ni*	*Co*	*Cr*	*Ti*	*Al*	*Zr*
316 S.S.	Plain	830	190	-	100	-	-	-
	Nitrogen ion implanted	250	95	-	50	-	-	-
CO-Cr-Mo	Plain	-	-	80	25	-	-	-
	Nitrogen ion implanted	-	-	130	65	-	-	-
Ti-6Al-4V	Plain	-	-	-	-	160	30	-
	Nitrogen ion implanted	-	-	-	-	185	35	-
Al_2O_3	BIOLOX* (Feldmuhle)	-	-	-	-	-	0	-
ZrO_2	Yttria stabilized	-	-	-	-	-	-	0
	PROZYR**	-	-	-	-	-	-	-
ZrO_2	Monoclinic	-	-	-	-	-	-	0

-Units in (ng/ml)

* Cerasir GmbH, Plochingen, Germany

** Ceramiques Techniques Desmarquest, Evrenx, France.

Table 15

Metal Levels From Various Articulation Combinations in Serum After 1 × 105 Cycles

Head Material	*Cup*	*Fe*	*Ni*	*Cr*	*Co*	*Ti*	*Al*
316 S.S.	UHMWPE	236*	54	30*	-	-	-
Co-Cr-Mo	UHMWPE	-	-	47	154	-	-
Co-Cr-Mo	Co-Cr-Mo	-	-	2420	11,110	-	-
Ti-6Al-4V	UHMWPE	-	-	-	-	<330**	<2.5**

-Units in (ng/ml)

* Estimated based on Fe/Ni and Cr/Ni ratios in Table xx1.

** Detection limit.

5. SUMMARY

From the information on wear mechanisms in biomedical implant materials, particularly hip joints, the following conclusions were determined for the following variables: type of materials, combinations of materials, articulation due to motion, number of cycles, type of contact stresses, susceptibility to oxidative wear, polyethylene altercations, surface conditions, and alloy properties.

The combination of implant materials used in the prosthesis determines how the material will respond to wear mechanisms. Each material has unique physical properties such as hardness, strength and other resistance properties that influence its ability to withstand fatigue. There are many treatment processes to implant materials such as gamma-irradiation, heat pressurizing, and carbon reinforcement of polymers that can manipulate materials properties having either positive or negative effects on the materials performance.

The different types of kinematic contact stresses produced different wear rates. Rolling contact stresses received higher wear rates in testing compared to gliding, and sliding contact stresses produced the lowest wear rate. Higher contact stresses result in lower coefficients of friction and therefore decreasing wear rates. The type of articulation due to motion has a direct effect on wear rates. For example, a faster, running motion produces a higher wear rate than a slower, walking motion. The stumbling motion produced the highest frictional torques on the implant, up to 64% higher than walking. Oxidative wear will increase the wear rates of the bearing materials with the exception of ceramic materials, which are not subject to oxidation. Irregular conjunctions between materials at the surface interface result in higher wear rates as compared to smooth conjunctions. Gamma irradiation treatment of polyethylene has proven to be beneficial in higher sensitivity, speed, and area selectivity of polyethylene resulting in prevention of material loss. High-pressure crystallization did not provide significant results to prove that this process decreases the wear rate of polyethylene. The carbon-reinforced polymers cause increased wear due to less conformed articulating surfaces and higher contact stresses. The high percent carbon alloys showed superior wear resistance as compared to the low percent carbon alloys.

REFERENCES

1. McKellop, H.A., Campbell, P.C., Park, S.H., Schmalzried, T.P., Grigoris, P.G., Amstutz, H.C., Sarmiento, A. (1995) The Origin of Submicron Polyethylene Wear Debris in Total Hip Arthroplasty, *Clinical Orthropaedics and Related Research*, Vol. 311, pp.3-20
2. Dorre, E., *Safety of Ceramic Components for Total Hip Endoprostheses*, pp.102-107
3. Devane, P. A. and Horne J.G. (1999) Assessment of Polyethylene Wear in Total Hip Replacement, *Clinical Orthopaedics and Related Research*, Vol. 369, pp. 59-72
4. Streicher, R.M. Testing of PE-UHMW as a Material for Implants: Results and Conclusions.
5. Truss, R.W. et al. (1980). *Pol. Eng. and Sci.* 20 (11): pp.747-755.
6. Halldin, G.W. and Kamel, I.L. (1997) *Pol. Eng. and Sci.* 17 (1): pp.21-26
7. Halldin, G.W. and Kamel, I.L. (1997). Paper, 25th ANTEC.
8. Halldin, G.W. and Metha, S.D. (1983). Paper 31st ANTEC.
9. Gomez-Barrena, E., Li, S., Furman, B. S., Masri, B.A., Wright, T.M., Salvati, E.A. (1998) Role of Polyethylene Oxidation and Consolidation Defects in Cup Performance, *Clinical Orthopaedics and Related Research*, Vol. 352, pp. 105-117.
10. Grobbelaar, C.J., Du Plessis, T.A., and Marais, F., The radiation improvement of polyethylene prostheses. *Journal of Bone and Joint Surgery* (1978) 60**B**: 370-374.
11. Orthopaedics Today: Consumer guide to total knee systems. (1996) *Orthopaedics Today* Vol. 16: pp.17-21.

12. Rimnac, C.M., Klein, R.W., Betts, F., and Wright, T.M. (1994) Post irradiation ageing of ultra high molecular weight polyethylene. *Journal of Bone and Joint Surgery*. Vol.76A: pp. 1053-1056.
13. Stroosnijder, M.F., Hoffmann. M., Sauvage, T., Londiaux G.B. (2002) *Wear Evaluation of Cross-linked UHMWPE by Thin Layer Activation Compared to Gravimetry*, European Commission, Institute for Health and Consumer Protection, Society for Biomaterials 28th Annual Meeting Transactions.
14. Stroosnijder, M.F., *Application of Particle and Laser Beams in Materials Technology*. (P. Misaelidis, ed.) Kluwer (1995) pp. 399-413.
15. Oonishi, H., Ishimaru, H., Tsuji, E., *et al.* (1996) Effect of Cross-Linkage by Gamma-Radiation-Heavy Doses to Low-Wear Polyethylene in Total Hip Prostheses, *Journal of Mat Sci: Mat Med*. Vol. 7: pp.753— 763, 1996.
16. Oonishi, H., Kuno, M., Tsuji, E. *et al.*, The Optimum Dose of Gamma-Radiation-Heavy Doses to Low-Wear Polyethylene in Total Hip Prostheses, *Journal of Mat Sci: Mat Med*, Vol.8(11): pp.11-18.
17. Clarke IC, Good V, Williams P *et al.*, (1997) Simulator Wear Study of High-Dose Gamma-Irradiated UHMWPE Cips, in *Transactions of the Society for Biomaterials Annual Meeting*, Minneapolis, Society for Biomaterials, p.71.
18. Bajaria, S.H. and Bellare, A., (1998) Deformation, Morphology, and Wear Behavior of Polyethylene Used in Orthopedic Implants, *Medical Plastics and Biomaterials Magazine*, http://www.devicelink.com/mpb/archive/98/03/003
19. Li S, and Howard EG Jr, Process of manufacturing ultra high molecular weight polyethylene shaped articles, U.S. Pat. 5,037,928, 1991.
20. McKellop H, Lu B, and Li S, (1992) Wear of Acetabular Cups of Conventional and Modified UHMW Polyethylenes Compared on a Hip Joint Simulator, *Trans Orthop Res Soc*, Rosemont, IL, Orthopaedic Research Society, pp. 356.
21. Champion AR, Li S, Saum K *et al.* (1994) The Effect of Crystallinity on the Physical Properties of UHMWPE, *Trans Orthop Res Soc*, Rosemont, IL, Orthopaedic Research Society, PP. 585.
22. Chmell MJ, Poss R, Thomas WH *et al.* (1996) Early Failure of Hylamer Acetabular Inserts Due to Eccentric Wear, *J Arthroplasty*, Vol:11, pp. 351–353.
23. Livingston BJ, Chmell MJ, Spector M *et al.* (1997) Complications of Total Hip Arthroplasty Associated with the Use of Hylamer Acetabular Components, *J Bone Joint Surg*, October 1997.
24. Biomet, Inc., Warsaw, IN (1994) Addressing Osteolysis in Total Hip Arthroplasty, Form No. Y-BEM-052/071594/HP
25. Bartel, D.L., Rimnac, C.M., Wright, T.M. (1991) *Evaluation and Design of the Articular Surface. Controversies of Total Knee Arthroplasty*, Edited by V.M. Goldberg, Raven Press Ltd., New York.
26. Medley, J.B., Chan, F.W., Krygier, J.J., Bobyn, J.D. (1996) Comparison of Alloys and Design in a Hip Simulator Study of Metal on Metal Implants, *Clinical Orthopaedics*, 1996 Supplement, Vol. 39, pp. S148-S159.
27. Fraser, J., (1999) Knee and hip joint replacements. Longer lasting prosthesis, *Australian Family Physician*, Vol.28, No:11, pp.1109-1115.

28. Lemons, J.E. (1994) Mechanical Properties of Ceramics, *Tech Prin Des Safety Joint Implants*, Hogrefe & Huber, publishers, pp.60-61.
29. *Transactions, Society for Biomaterials Annual Meetings*, Volumes IX and X, 1986 and 1987.
30. McKinney, R. V. Jr and Lemons, J. E. ,Eds. (1985). *The Dental Implant.* PSG Pub Co. Littleton, MA.
31. Urban, J.A., Garvin, K.L., Boese, C.K., Bryson, L., Pedersen, D.R., Callaghan, J. J., Miller, R.K., (2001) Ceramic-on-Polyethylene Bearing Surfaces in Total Hip Arthroplasty, *The Journal of Bone and Joint Surgery*, Vol. 83-A, No. 11, pp.1688-1694.
32. Semlitsch, M. and Dawihl, W. *Basic Requirements for Alumina Ceramic in Artificial Hip Joint Balls in Articulation with Polyethylene Cups*, pp.99-101.
33. Brummitt, K., Hardaker, C.S., McCullagh, P.J., Drabu, K.J., Smith, R.A. (1996) Effect of counterface material on the characteristics of retrieved titanium alloy total hip replacements, *Journal of Engineering in Medicine.* Vol. 210, No. 3, pp.191-195.
34. Davidson J. (1993) Characteristics of Metal and Ceramic Total Hip Bearing Surfaces and Their Effect on Long-Term Ultra High Molecular Weight Polyethylene Wear, *Clinical Orthopaedics and Related Research*, Vol. 294, pp. 361-378.
35. Sychterz, C., Moon, K., Hashimoto, Y., Terefenko, K., Anderson, C., Bauer, T. (1996) Wear of Polyethylene Cups in Total Hip Arthroplasty, *Journal of Bone and Joint Surgery*, Vol. 78-A, No. 8, pp.1193-2000.
36. Anissian, L.H., Stark, A., Gustafson, A., Good, V., Clarke, I.C. (1999) Metal-on-metal Bearing in Hip Prosthesis Generates 100-fold Less Wear Debris than Metal-on-polyethylene, *Acta Orthop Scand,* Vol. 70, No. 6, pp. 578-582.
37. Bowsher, J.G. and Shelton, J.C. (2001) A Hip Simulator Study of Patient Activity Level on the Wear of Cross Linked Polyethylene Under Smooth and Roughened Femoral Conditions, *Wear*, Vol. 250-251, No. 1, pp. 167-179.
38. McKellop, H.A., Clarke, I.C., Degradation and wear of ultra-high-molecular-weight polyethylene, in: Fraker, A.C., Griffin, C.D. (Eds.) *Corrosion and Degradation of Implant Materials: Second Symposium,* ASTM STP 859, American Society for Testing Materials, Philadelphia, 1985, pp.251-368
39. Wang, A., Sun, D.C., Yau, S.S, Edwards, Essner, M., Polineni, V.K., Stark. C., Dumbleton, J.H., Orientation softening in the deformation and wear of ultra-high molecular weight polyethylene, *J. Wear* 203/204 (1997) pp.230-241
40. Bragdon, C.R., O'Connor, D.O., Lowenstein, J.D., Jasty, M., Syniuta, W.D., The importance of multidirectional motion on the wear of polyethylene, *Proc. Inst. Mech. Eng.* 210 (H) (1996) pp. 157-165
41. Saikko, V., Ahlroos, T. (1999) Type of motion and lubricant in wear simulation of polyethylene acetabular cup, *Proc. Inst. Mech. Eng.* (Part H) 213 (4): pp.301-310
42. Barbour, P.S.M., Stone, M.H., Fisher, J. (1999) A hip joint simulatorstudy using simplified loading and motion cycles generating physiological wear paths and rates, *Proc. Inst. Mech. Eng.* (Part H) 213 (6): pp.455-467

43. Cornwall, G.B., Bryant, J.T., Hansson, C.M. (2001) *The Effect of Kinematic Conditions on the Wear of Ultra High Molecular Weight Polyethylene (UHMWPE) in Orthopeadic Bearing Applications*, Department of Mechanical Engineering Queens University, Kingston, Ontario, Canada, Vol. 215, pp. 95-105
44. Rose, R.M., Cimino, W.R., Ellis, E., and Crugnola, A.N. (1982) Exploratory investigations on the structure dependence of the wear resistance of polyethylene. *Wear*, 77, pp.89-104.
45. Cooper, J.R., Dowson, D., and Fisher, J. (1993) The effect of transfer film and surface roughness on the wear if lubricated ultra-high-molecular-weight-polyethylene acetabular prostheses. *Clin. Mater.*, **14**, pp.295-302.
46. McKellop, H., Clarke, I.C., Markolf, K.L. and Amstutz, H.C. (1978) Wear characteristics of UHMW polyethylene: a method for accurately measuring extreme low wear rates. *Journal of Biomedical Materials. Res.*, **12**, pp.895-927.
47. Poggie, R.A., Wert, J.J., Mishra, A.K. and Davidson, J.A. (1992) Friction and wear characterization of UHMWPE in reciprocating sliding contact with Co-Cr, Ti-6Al-4V and zirconia implant bearing surfaces. In *Wear and Friction of Elastomers* ASTM STP1145 (Eds: R. Denton and M.K. Keshavan), American Society for Testing and Materials, Philadelphia, Pennsylvania.)
48. Saikko, V.O. (1993) Wear and friction properties of prosthetic joint materials evaluated on a reciprocating pin-on-flat apparatus. *Wear*, **166**: pp.169-178
49. Streicher, R.M. (1988) Tribology in medicine: testing and optimization of material combinations for endoprostheses. *Med. Orthop. Technol.*, **08**, pp.1-12.
50. Weightman, B., and Light, D. (1985) A comparison of RCH 1000 and Hi-Fax 1900 ultra-high-molecular-weight-polyethylenes. *Biomaterials*, **6**, pp.177-183
51. Wright, K.W., Dobbs, H.S. and Scales, J.T. (1982) Wear studies on prosthetic materials using the pin-on-disc machine. *Biomaterials*, **3**, pp.41-48.
52. Wang, A., Essner, A. and Klein, R. (2001) Effects of contact stress on friction and wear of ultra high molecular weight polyethylene in total hip replacement, *Journal of Engineering in Medicine*, Vol. 215, No. 2, pp.133-139.
53. Jin, Z.M., Dowson, D., and Fisher, J. (1994) A parametric analysis of the contact stresses in ultras-high molecular weight polyethylene acetabular cups. *Med. Engng Physics*, **16**, pp. 398-405
54. Jin, Z.M., Dowson, D., and Fisher, J. (1997) Analysis of fluid film lubrication in artificial hip joint replacements with surfaces of high elastic modulus. *Proc. Instn. Mech, Engrs. Part H, Journal of Engineering in Medicine,* **211** (H3)