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DETERMINING FRICTIONAL BEHAVIOR OF VITAMIN E BLENDED UHMWPE

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Abstract: Frictional behaviors of articulating surfaces have been recognized as critical factors affecting their service life because these behaviors play very important role on wear of ultrahigh molecular weight polyethylene (UHMWPE) which causes failure of artificial joint replacements. The objective of this study is to determine temperature rise as a function of sliding time and maximum load for the articulating surfaces of vitamin E blended UHMWPE acetabular component paired with a cobalt-chromium (CoCrMo) femoral component. Additionally frictional torque between the bearing surfaces was measured and friction coefficient was calculated. Frictional measurements of the joints were carried out on a custom made hip joint friction simulator. The prostheses were in 28 mm diameter. Applied static loads were changed from 200 N to 1500 N. In flexion-extension plane, a simple harmonic oscillatory motion between ±24^o was applied to the UHMWPE acetabular component. The period of motion was 1 Hz and the tests were run up to 11000 cycles. Temperature rise in acetabular and femoral component is recorded with embedded thermocouples. Also the tests are repeated with UHMWPE acetabular component. The results are compared in terms of UHMWPE and vitamin E blended UHMWPE.

Keywords: hip joints, friction, frictional heating, temperature measurement,

1. INTRODUCTION

Total joint replacements have been applied for the patients that affected by osteoarthritis [1]. Although these replacements improve life quality of the patients, their premature failure causes lots of problem for both patients and surgeons. In present days the lifetime of an artificial hip joint is about 15-20 years. This duration is not enough for patients younger than 60 years of age. For articulating surfaces, biotribological behavior like friction, lubrication and wear are the primary failure factors that limiting the service life of the prosthesis [2,3,4].

Tribological behavior of hip joints are effected by many factors including, bearing material, surface hardness and roughness, materials oxidation, number of motion cycle, contact stresses, particles sizes, counts and distribution in lubricant [5]. The wear debris generated from bearing materials could cause adverse tissue reactions, aseptic loosening, osteolysis and at the end implant loss [2,6,7,8,9].

Figure 1. Total Hip Prosthesis

Friction between articulating surfaces cause temperature rise in the acetabular cup and femoral head. This heating may influence the rate of wear, fatigue, creep and oxidative degradation of bearing materials [10,11]. Beside this, temperature rise can damage the surrounding tissue and lubricant around the artificial joint and contribute cup loosening [10]. Lu and McKellop reported that frictional heating may promoted the protein precipitation from the lubricant. This caused property change of lubricant. Thermal precipitation of the proteins may cause depletion of the proteins and incomplete boundary lubrication so may accelerate adhesive wear rate [12]. Bergmann et al. measured the changes of temperature of hip prosthesis in vivo conditions. They measured the temperature of the hip implant in a patient body after one hour walking. The maximum temperature value was 43.1 ^{o}C [13]. In an other study synovial fluid's temperature was found as 46 ^{o}C by 2D and 3D finite element analysis. By considering that the biological defects are occur at 40 ^{0}C, it is clear that frictional heating negatively affects service life of artificial joints [10,14]. So measurement of temperature rise and evaluating frictional behavior of the bearing materials is important for development of new materials and designs for artificial joints with long service life [9].

Different material combinations are used in a total hip replacement. The most cammon combination is metal femoral head- ultra high molecular weigth polyethylene (UHMWPE) cup. Besides ceramic-ceramic, metal-metal, ceramic-UHMWPE combinations of bearing materials are used [15]. UHMWPE has been the most cammonly used acetabular cup material for past four decades because of its excellent biocompatibility, chemical stability, impact load damping properties and low friction coefficient [3,16]. But, the wear debris of UHMWPE is a threatining factor for implant failure. So there was a need for enhangement of UHMWPE properties. Radiation cross-linking of UHMWPE has showed higher wear resistance than conventional UHMWPE but mechanical properties and oxidation resistance has decreased [3,17,18,19]. Delamination commonly occurs when mechanical properties decrease [20]. Oxidation with subsequent embrittlement of UHMWPE decrease abrasive wear resistance of the material [21, 22]. It was reported that addition of vitamin E increases oxidation and delamination resistance of conventional and cross-linked UHMWPE while maintaining the mechanical properties [21,23,24,25].

Although the researches have being done for determining the wear behavior of the total joint replacements in order to improve design, material and manufacturing quality and service life of these joints, it is still unknown phenomena how to design wear resistant artificial joint parts and select ideal material pairs for these kinds of replacements. Therefore examining the friction and wear characteristics of the prosthesis materials pairs both for in vivo clinical applications and in vitro laboratory simulations is still one of the most important topics for researchers [6,16,26,27].

Little literature research is available about frictional heating of vitamin E blended UHMWPE. The objective of this study is to determine temperature rise as a function of sliding time and applied load for the articulating surfaces of vitamin E blended UHMWPE and conventional UHMWPE acetabular component paired with a cobalt-chromium (CoCrMo) femoral component. Additionally frictional torque between the bearing surfaces was measured and friction coefficient was calculated. Frictional temperature rise and frictional torque values of UHMWPE were compared with literature results. So these samples were reference for our experiments. The results for Vitamin E blended UHMWPE were compared with UHMWPE. It is hoped that the results would serve further understand frictional behavior of vitamin E blended UHMWPE.

2. MATERIALS AND METHODS

Acetabular cups were machined from Chirulen 1020 and Chirulen 1020 E rods. (MediTECH Medical Polymers, Vreden, Germany). The inner surface of the samples were machined same as an acetabular cup and in accordance with ISO 7206-2:2011 and ISO 21535 [28,29]. To provide uniform construction for heat dissipation, metal backing or fixing tools were not used except screw to fix the samples. For this reason the outer surfaces of the samples were cylindrical in 40 mm diameter and three screws were used for fixation. The acetabular cup samples were paired with CoCrMo commercially available femoral heads (TST Tibbi Aletler San. Ve Tic. Ltd.Sti. Istanbul, Türkiye). The prostheses were in 28 mm diameter. Surface roughness of acetabular cups was measured by Taylor Hobson Form Talysurf Intra. Surface roughness of, UHMWPE 0.679 µm, vitamin E blended UHMWPE was 0.647 µm. These values are suitable for the reference of ISO 7206-2:2011 [28]. Mechanical and thermal properties of UHMWPE, VE-UHMWPE and CoCrMo can be seen in table 1.

Frictional measurements of the joints are carried out on a custom made hip joint friction simulator. For eliminating experimental inaccuracies the prosthesis are inverted with respect to anatomical position as in previous studies [11,12,30]. Applied static loads are changed from 200 N to 1500 N. In flexion-extension plane, a simple harmonic oscillatory motion between ±24^{o} is applied to the UHMWPE acetabular component. The period of motion is 1 Hz and the tests are run up to 11000 cycles in 5 ml, 25% Bovine Calf (Sigma-Aldrich) lubrication condition. To avoid bacterial contamination 0.3% sodium azide and 5 mM EDTA was added in to the lubricant. The viscosity of the lubricant measured with NDJ-1 Rotary Viscometer as 0.002 Pa.s The experimental setup can be seen in Figure 2.

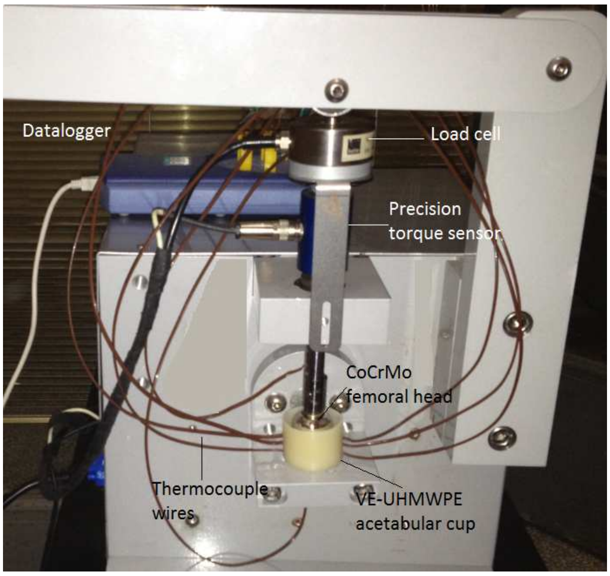

Figure 2. Experimental setup

Table 1. Mechanical and thermal properties of UHMWPE, VE-UHMWPE and CoCrMo

Variable	Unit	UHMWPE	VE-UHMWPE	CoCrMo
		Average	Average	Average
Density	Kg/m^3	936	937	8270
Young's Modulus	MPa	660	683	200
Poisson's Ratio	-	0.46	0.46	0.3
Thermal Conductivity	W/(m*K)	0.4	0.4	12.1

Temperature rise in acetabular and femoral component was recorded with embedded thermocouples as shown in fig.2. For acetabular cup surface temperature measurements were taken from seven points. 3 mm diameter holes were drilled in to backside of the cups to 0.5 mm from the surface. The holes and number of location for each thermocouple can be seen in the cross-sectional view of the sample drawing in Figure 3. After initial calibration of thermocouples, they were adhered in the holes by heat conduction glue. First thermocouple was located at the central axis of the cup, this point was on the normal load axis and center of the sliding surfaces. Second, third, fifth thermocouples were placed right sides of the load axis and sixth, seventh and eighth thermocouples were attached left side of the load axis with 3 mm intervals along the motion direction. For femoral head surface temperature measurement fourth thermocouple was placed inside the bottom center of taper hole of the head. Output signals were collected by a data logger (Pico TC-08) that connected to computer program. Then the temperature values were calculated according to pre-calibration equation.

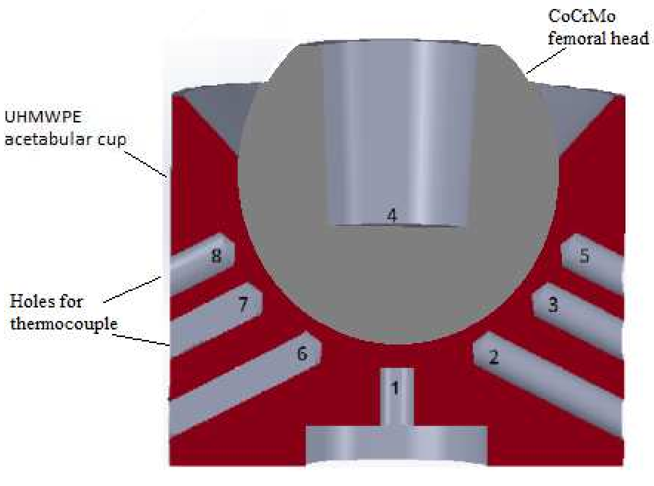

Figure 3. Drawing of acetabular cup and femoral head with thermocouple holes. The numbers on holes, show the location of each thermocouple.

3. RESULTS

Frictional temperature rises, recorded during 11.000 cycle for acetabular cup and femoral head sliding surfaces top points (1. and 4. Locations) under different loading conditions, can be seen in Table 2.

Temperature rise increased by increasing normal loading. VE-UHMWPE cups temperature rises were about 0.12-0.60 ^oC lower than conventional UHMWPE cup samples. Temperature rise in CoCrMo femoral heads, while paired with VE-UHMWPE, were about 1.6-3 ^oC lower than CoCrMo femoral head, while paired with conventional UHMWPE sliding pair.

Table 2. Frictional temperature rise peak values for UHMWPE/VE-UHMWPE acetabular cups (ΔT_1) and CoCrMo femoral heads (ΔT_4) sliding surfaces top points.

Load (N)	UHMWPE	VE-UHMWPE
200	$\Delta T_1 = 6.01\ ^oC$ $\Delta T_4 = 9.48\ ^oC$	$\Delta T_1 = 5.89\ ^oC$ $\Delta T_4 = 7.88\ ^oC$
750	$\Delta T_1 = 10.19\ ^oC$ $\Delta T_4 = 17.86\ ^oC$	$\Delta T_1 = 9.89\ ^oC$ $\Delta T_4 = 16.50\ ^oC$
1000	$\Delta T_1 = 11.22\ ^oC$ $\Delta T_4 = 20.76\ ^oC$	$\Delta T_1 = 10.87\ ^oC$ $\Delta T_4 = 19.31\ ^oC$
1500	$\Delta T_1 = 13.63\ ^oC$ $\Delta T_4 = 29.02\ ^oC$	$\Delta T_1 = 13.03\ ^oC$ $\Delta T_4 = 26.03\ ^oC$

The temperature rises for both VE-UHMWPE and UHMWPE cups taken from top contact points (location 1) for different loading conditions can be seen in fig.5.

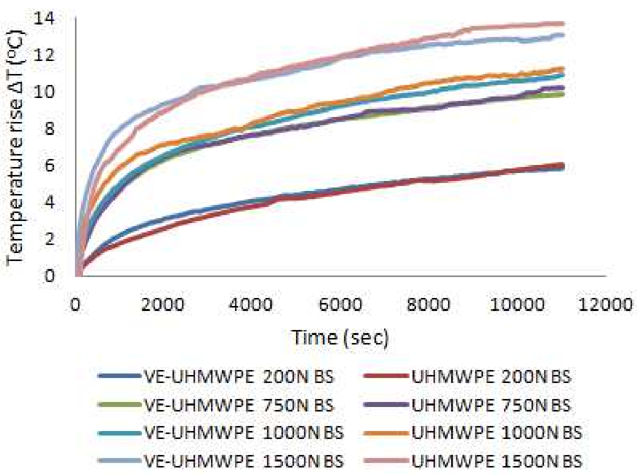

Figure 4. The temperature rises for both VE-UHMWPE and UHMWPE cups taken from top contact points (location 1) for different loading conditions.

The temperature rises for CoCrMo femoral heads paired with both VE-UHMWPE and UHMWPE cups can be seen in fig.6. The temperatures were taken from top contact points (location 4) for different loading conditions.

For each loading conditions and each material pairs, temperature rise curve showed similar characteristics as shown in fig.5 and fig.6. It is important to note that these recorded temperatures are for the thermocouple location points. So the surface temperatures must be higher than measured values.

The temperature distribution in VE-UHMWPE and conventional UHMWPE paired with CoCrMo femoral heads under 1000 N static load can be seen in fig. 7 and in fig. 8 respectively.

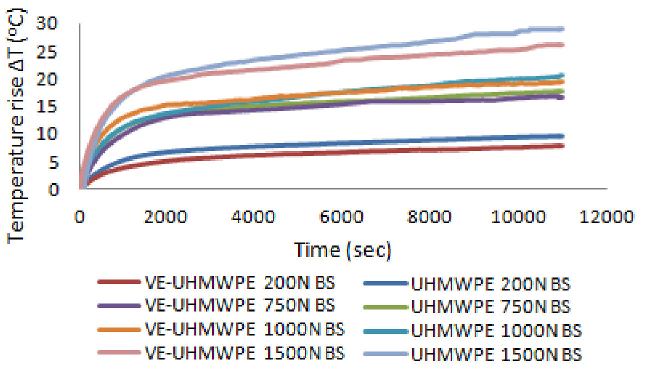

Figure 5. The temperature rises for CoCrMo femoral heads paired with both VE-UHMWPE and UHMWPE cups. The temperatures were taken from top contact points (location 4) for different loading conditions.

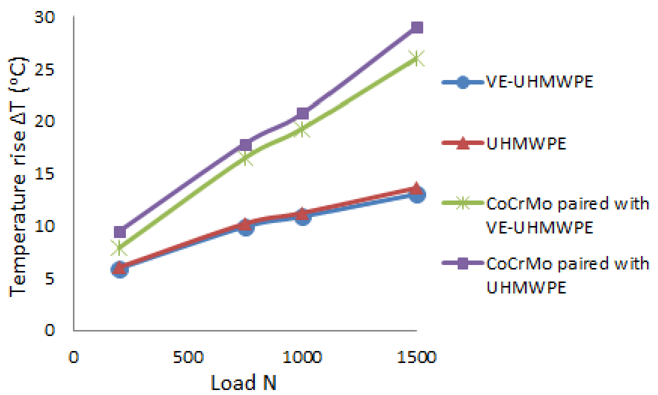

Figure 6. Temperature rise as a function of applied static load, in location 1 and location 4 at the end of 11.000 cycle.

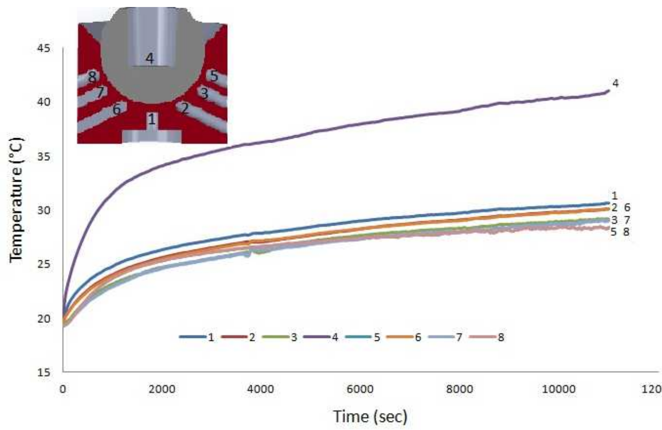

Figure 7. The temperature rise of the VE-UHMWPE acetabular cup and CoCrMo femoral head for 1000N loading condition taken from 8 different location points.

For each thermocouple location points, the rate of the temperature rise was high up to 2000 seconds then the rate was decreasing. Temperature values for location 1 and location 4 which were in contact points and located on the center of normal load axis are highest for both VE-UHMWPE/CoCrMo and UHMWPE/CoCrMo sample groups. For VE-UHMWPE/CoCrMo sliding pairs temperature at location 1 was 29.92 °C and at location 4 was 39.11. Temperatures for the locations 2,3,5,6,7,8 were decreasing while moving away from top contact surface of the materials. The values for these locations were 29.14 °C, 28.90 °C, 26.88°C, 28.73 °C, 28.11 °C and 26.79 °C respectively.

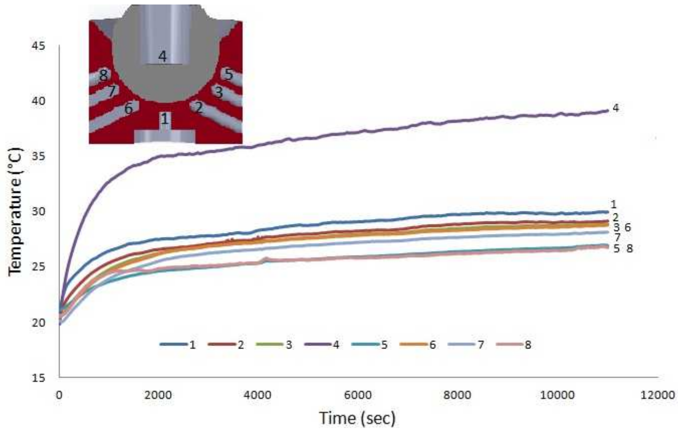

Figure 8. The temperature rise of the conventional UHMWPE acetabular cup and CoCrMo femoral head for 1000N loading condition taken from 8 different location points.

Because of the ball-in-cup configuration of the hip joint the pressure distribution within the contact area cannot be determined precisely. So the friction coefficient μ, cannot be calculated accurately. Instead of friction coefficient μ, a dimensionless parameter called friction factor was determined by using the equation (1).

$$f = \frac{T}{RL} \qquad (1)$$

Here, f is the friction factor, T is the measured torque (Nm), r is the radius of femoral head (m), L is the load (N) [31].

In present study the measured average torque under 1000 N loading and end of 11.000 cycle was 1.2 Nm and 1.7 Nm for VE-UHMWPE and conventional UHMWPE respectively. So the friction factors, calculated by using equation (1) 0.085 for VE-UHMWPE and 0.12 for UHMWPE.

4. DISCUSSION

The results indicate that a significant temperature rise was occurred in UHMWPE and VE-UHMWPE acetabular cup samples sliding against CoCrMo femoral heads.

Because of the differences in thermal conductivity of the sample materials, the temperature rise in CoCrMo femoral head was higher than acetabular cup samples. So, significant portion of the frictional heat conducted through the femoral head. For each loading conditions the temperature rise values listed in table 2. The peak temperature values for VE-UHMWPE and UHMWPE acetabular cups at location 1 were 31.08 °C and 31.72 °C respectively for 1500 N loading condition and 3 hours test duration. Lu and McKELLOP [12] found 40.4 °C for 2030 N loading condition and 6 hours test duration. The peak temperature values for CoCrMo femoral heads at location 4 were 43.93 °C and 46.90 °C while paired with VE-UHMWPE and UHMWPE acetabular cups respectively. In previous study [12] Lu and McKELLOP measured the CoCrMo femoral head temperature as 40 ^{o}C while Liao et al. measured 41 ^{o}C [11]. In an in vivo study Bergmann et al. [13] measured the temperature of femoral head as 43 ^{o}C. All of these studies CoCrMo femoral heads were paired with conventional UHMWPE acetabular cups.

The results in different studies may differ according to the used materials properties or test conditions and parameters. For example, in friction simulator studies 5 ml of lubricant was used [30] while in wear simulator studies about 500 ml lubricant was used [11,12]. In the present study, by considering the small volume of synovial fluid in an articular capsule, 5 ml lubricant was used. It is obvious that if larger volume of lubricant used, the lower temperature values would be recorded. With regard to differences in test conditions, it can be said that the results in present study for conventional UHMWPE and CoCrMo sliding pairs are comparable with the results reported in literature. With the difference of previous studies, in present study CoCrMo femoral head paired with VE-UHMWPE acetabular cup. Although thermal conductivity of the VE-UHMWPE and conventional UHMWPE are same the temperature rise in femoral head for conventional UHMWPE/CoCrMo sliding pairs were a small amount of higher than in femoral head for VE-UHMWPE/CoCrMo sliding pairs. Differences in structural properties and elastic modulus of the materials may cause a small amount of difference in measured temperature values. For example, as explained in reference [12], while a material with higher elastic modulus is used, the contact area would be smaller, so a larger area would be exposed to the lubricant for each cycle providing more cooling. As a result of this, the temperature rise would be low. It is reported in references [32,33] that addition of vitamin E reduces subsurface crack or gap formation and so prevent delamination of the material. Prevention of delamination may serve protection of surface quality and occurrence of lower frictional heating in sliding materials.

It is clear that frictional heating of sliding materials is vital important for service life of artificial joints. 6 ^{o}C temperature increase with in the hip joint can cause formation of fibrous tissue, possibly periprosthetic pain or prosthetic loosening. 5 ^{o}C temperature rise in lubricant can cause precipitation of proteins in simulation tests. In vitro studies use calf serum instead of synovial fluid and simulated conditions rather than natural ones [34]. The measurement values may differ in vivo conditions but the results of in vitro studies give beneficial ideas about behavior of materials.

5. CONCLUSION

The aim of this study was to determine temperature rise as a function of sliding time and maximum load for the articulating surfaces of vitamin E blended UHMWPE acetabular component paired with a cobalt-chromium (CoCrMo) femoral component. Because, a few literature results are available about frictional heating of VE-UHMWPE, conventional UHMWPE was used as control material. The results for conventional UHMWPE were comparable with literature results. Temperature rise in VE-UHMWPE asetabular cup was about 0.5-2.0 ^{o}C lower than conventional UHMWPE for different location of thermocouples. Temperature rise in CoCrMo femoral head paired with VE-UHMWPE acetabular cup was about 1.5-3.0 ^{o}C lower than CoCrMo femoral head paired with UHMWPE acetabular cup. Measured torque value and calculated frictional factor were lower for VE-UHMWPE than conventional UHMWPE.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] W. Shibo, G. Shirong, L. Hongtao and X. Huang, “Wear behaviour and wear debris characterization of UHMWPE on alumina ceramic, stainless steel, CoCrMo and Ti6Al4V hip prostheses in a hip joint simulator,” Journal of Biomimetics, Biomaterials and Tissue Engineering, 7, pp. 7-25, 2010.

[2] M.R Widmer, “Modified Molecular Friction in Artificial Hip Joints,” Ph.D. Thesis, Swiss Federal Institute of Technology Zurich, 2002.

[3] H. Bhatt and T. Goswami, “Implant wear mechanisms—basic approach,” Biomedical Materials 3, 9, pp.1-9, 2008.

[4] J.M. Martell, E. Berkson, R. Berger, J. Jacobs “Comparison of two and three-dimensional computerized polyethylene wear analysis after total hip arthroplasty,” Journal of Bone and Joint Surgery American, 85A, pp.1111–1117, 2003.

[5] A. Buford, T. Goswami, “Review of wear mechanisms in hip implants: Paper I – General,” Materials and Design, 25, pp. 385–393, 2004.

[6] L. Mattei, F. DiPuccio, B. Piccigallo, E.Ciulli, “Lubrication and wear modelling of artificial hip joints: A review,” Tribology International, 44, pp. 532–549, 2011.

[7] H.J. Cho, W.J. Wei, H.C. Kao, C.K. Cheng, “Wear behavior of UHMWPE sliding on artificial hip arthroplasty materials,” Materials Chemistry and Physics, Volume 88, Issue 1, pp. 9-16, 15 November 2004.

[8] S. Affatato, M. Spinelli, M. Zavalloni, C. Mazzega-Fabbro, M. Viceconti, “Tribology and total hip joint replacement: current concepts in mechanical simulation,” Medical Engineering & Physics 30, pp.1305–1317, 2008.

[9] G.N. Dong, M. Hua, J. Li, K.B. Chuah, “Temperature field and wear prediction for UHMWPE acetabular cup with assumed rectangular surface texture,” Materials and Design 28, pp. 2402–2416, 2007.

[10] C.C. Hu, J.J. Liau, C.Y. Lung, C.H. Huang, C.K. Cheng, " A twodimensional finite element model for frictional heating analysis of total hip prosthesis," Materials Science and Engineering C 17, pp. 11–18, (2001).
[11] Y.-S. Liao, H. McKellop, Z. Lu, P. Campbell, P. Benya, "The effect of frictional heating and forced cooling on the serum lubricant and wear of UHMW polyethylene cups against cobalt–chromium and zirconia balls," Biomaterials 24, pp. 3047–3059, 2003.
[12] Z.Lu and H. McKellop, "Frictional heating of bearing materials tested in a hip joint wear simulator," Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine. Part H 211, pp. 101-108, 1 January 1997.
[13] G. Bergmann, F. Graichen, A. Rohlmann, N. Verdonschot, G.H. Van Lenthe, "Frictional heating of total hip implants. Part 1: measurements in patients," Journal of Biomechanics, 34 pp. 421–428, 2001.
[14] G. Bergmann, F. Graichen, A. Rohlmann, N. Verdonschot, G.H. Van Lenthe, "Frictional heating of total hip implants. Part 2: Finite element study," Journal of Biomechanics 34, pp. 429–435, 2001.
[15] R. Pietrabissa, M. Raimondi, E. Martino, "Wear of polyethylene cups in total hip arthroplasty: a parametric mathematical model," Medical Engineering & Physics 20, pp. 199–210, 1998.
[16] D. Xiong, S. Ge. "Friction and wear properties of UHMWPE/Al2O3 ceramic under different lubricating conditions", Wear, 250, pp.242–245, 2011.
[17] C.A. Jacobs, C.P. Christensen, A.S. Greenwald, H. McKellop, "Clinical Performance of Highly Cross-Linked Polyethylenes in Total Hip Arthroplasty," J Bone Joint Surg Am., 89, pp. 2779-2786, 2007.
[18] L. Bradford, D.A. Baker, J. Graham, A. Chawan, , M.D. Ries, L.A. Pruitt, "Wear and Surface Cracking in Early Retrieved Highly Cross-Linked Polyethylene Acetabular Liners," The Journal of Bone & Joınt Surgery, 86-A, no:6, pp.1271-1282, 2004.
[19] J. Furmanski, S. Gupta, A. Chawan, A. Kohm, J. Lannutti, B. Jewett, L.A. Pruitt, M.D. Ries, "Aspherical femoral head with highly cross-linked ultra-high molecular weight polyethylene surface cracking," The Journal of Bone and Joint Surgery, 89, pp.2266-2270, 2007.
[20] B. R. Micheli, K. K. Wannomae, A. J. Lozynsky, S. D. Christensen, O. K. Muratoglu, "Knee Simulator Wear of Vitamin E Stabilized Irradiated Ultrahigh Molecular Weight Polyethylene", The Journal of Arthroplasty Vol. 27,1, pp.95-104, 2012.
[21] P. Bracco, E. Oral, "Vitamin E-stabilized UHMWPE for Total Joint Implants", Clinical Orthopaedics and Related Research, 469, pp. 2286–2293, 2011.
[22] G. Blunn, E. M. Brach del Preva, L. Costa, J. Fisher, M. A. R. Freeman, "Ultra high Molecular-weight polyethylene (UHMWPE) in total knee replacement: fabrication, sterilisation and wear", Journal of Bone Joint Surgery Br,84, pp.946–949, 2002.
[23] E. Oral, S.L. Rowell, O.K. Muratoglu, "The effect of α-tocopherol on the oxidation and free radical decay in irradiated UHMWPE", Biomaterials, 27, pp. 5580-5587, 2006.
[24] E. Oral, K.K. Wannomae, N.E. Hawkins, W.H. Harris, O.K. Muratoglu, "α-Tocopherol doped irradiated UHMWPE for high fatigue resistance and low wear", Biomaterials, 25, pp. 5515-5522, 2004.
[25] E. Oral, S. D. Christensen, A.S. Malhi, K.K. Wannomae, O.K. Muratoglu, "Wear Resistance and Mechanical Properties of Highly Cross-linked, Ultrahigh–Molecular Weight Polyethylene Doped With Vitamin E", The Journal of Arthroplasty Vol. 21 No. 4, pp.580-591, 2006.
[26] 23E.P.J. Watters, P.L. Spedding, J. Grimshaw, J.M. Duffy, R.L. Spedding, "Wear of artificial hip joint material," Chemical Engineering Journal, 112, pp.137–144, 2005.
[27] 24S. Ge, S. Wang, N. Gitis, M. Vinogradov, J. Xiao, "Wear behavior and wear debris distribution of UHMWPE against Si3N4 ball in bi-directional sliding," Wear, 264, pp. 571–578, 2008.
[28] ISO 7206-2:2011, Implants for surgery-Partial and total hip joint prostheses Part 2: Articulating surfaces made of metallic, ceramic and plastics materials.
[29] ISO 21535:2001 Non-active surgical implants -- Joint replacement implants -- Specific requirements for hip-joint replacement implants.
[30] Y. Yan, A. Neville, D. Dowson, S. Williams, J. Fisher, "Effect of metallic nanoparticles on the biotribocorrosion behaviour of Metal-on-Metal hip prostheses", Wear 267, pp. 683–688, 2009.
[31] Z.M. Jin, M. Stone, E. Ingham, J. Fisher, "(v) Biotribology", Current Orthopaedics, 20, pp. 32–40, 2006.
[32] S. Teramura, H. Sakoda, T. Terao, M. M. Endo, K. Fujiwara, N. Tomita, "Reduction of Wear Volume from Ultrahigh Molecular Weight Polyethylene Knee Components by the Addition of Vitamin E", Journal of Orthopaedic Research, Volume 26, Issue 4, pp. 460-464, 2008.
[33] N. Tomita, T. Kitakura, N. Onmori, Y. Ikada, E. Aoyama, "Prevention of fatigue cracks in ultrahigh molecular weight polyethylene joint components by the addition of vitamin E", Journal of Biomedical Materials Research, Volume 48, Issue 4, pp. 474–478, 1999.
[34] J. W. Pritchett, "Heat Generated by Hip Resurfacing Prostheses: An in Vivo Pilot Study", Journal of Long-Term Eff ects of Medical Implants, 21(1), pp. 55–62, 2011.