ANALYSIS OF WEAR OF THE ACETABULAR COMPONENT OF TOTAL HIP PROSTHESIS: EFFECTS OF MATERIAL AND ORIENTATION

Roberto Dantas Queiroz
Departamento de Ortopedia e Traumatologia – Escola Paulista de Medicina - UNIFESP
robdanqueiroz@globo.com

Taciana Tonetto Castelo Branco
Escola Politécnica – USP
taciana_tcb@yahoo.com

Raúl González Lima
Escola Politécnica – USP
rauglima@usp.br

Luiz Aurélio Mestriner
Departamento de Ortopedia e Traumatologia – Escola Paulista de Medicina - UNIFESP
mestrinerla@terra.com.br

Abstract. *Wear of the hip prosthesis contributes to periprosthetic osteolysis and aseptic loosening after total hip arthroplasty. The reduction of the wear can increase the prosthesis life in younger and more active patients. A finite-element model was used to compute contact stresses during a normal gait cycle and the wear was calculated with the use of the sliding-distance-coupled wear algorithm. In order to study the effect of the acetabular component orientation, this study considers this component with a bearing of UHMWPE and the femoral head of chrome-cobalt. The wear was numerically simulated with the acetabular component being oriented to 30°, 45° and 60° of lateral inclination. To study the effect of materials, four tribologic couples of clinic applied materials were simulated: alumina/alumina, chrome-cobalt/chrome-cobalt, UHMWPE/alumina and UHMWPE/chrome-cobalt, with the lateral inclination of 45°. The results show wear values very similar for inclination of 30° and 45° and 50% greater to 60° of lateral inclination of the acetabular component. The wear, considering the materials, increases in the following order: alumina/alumina, chrome-cobalt/chrome-cobalt, UHMWPE/alumina and UHMWPE/chrome-cobalt.*

Keywords*:* wear, total hip prosthesis, finite element model, material, lateral inclination

1. Introduction

The total hip arthroplasty improves the quality of life of people with arthropathy of the hip and is one of the surgical procedures with the best relationship cost-benefit in medicine. (Garelick *et al*, 1998). The surgical indications have extended to younger patients because of the high confiability and durability of the procedure, with more predictable results on the medium and long periods. However, the greater phisical activity of young people results in mayor wear of the contact surfaces of the prosthesis. The tissue response to wear particles contributes a lot to periprosthetic osteolysis and aseptic loosening, demanding a revision surgery. The reduction of the wear can increase the prosthesis life and, consequently, avoid a revision surgery, with traumatic conducts, high morbidity and high cost.

The clinic study of acetabular wear rates, with radiographs and retrievals, usually takes years to presents scientific results. Mechanical simulators of the hip provide information of good quality, but they are very expensive and the time to complete the tests is long. Alternatively, a computer-based simulation technique, the finite-element mode, is used to investigate and anticipate the clinical results with the advantage of being less expensive and having the capacity to simulate variations of different parameters and its combination.

Several works (Queiroz, 1999; Maxian *et al*, 1996; Patil *et al*, 2003) validate the finite-element method through comparison with clinic data. The cited numeric simulation was used to verify the wear rate of the acetabular component of the total hip prosthesis, with two different approaches, namely, variation of lateral inclination and different couples of clinic applied materials.

2. Materials and Methods

The computer-based model of finite elements of the total hip arthroplasty is divided in the acetabular component and the femoral head, which is programmed to perform flexion-extension movements similar to a normal gait cycle.

The acetabular component, rigidly fixed on a previous determined position, was modeled as a concave hemispheric mesh with internal diameter of 28mm and thickness of 10mm (Fig. 1). The femoral head (Fig. 2) was modeled as a spheric mesh with 28mm. The clearance between the head and the acetabular was 0,1mm. The finite element method consisted of 30217 elements and 5295 nodes in pentahedrical elements. The finite element simulation were performed using the software ANSYS®.

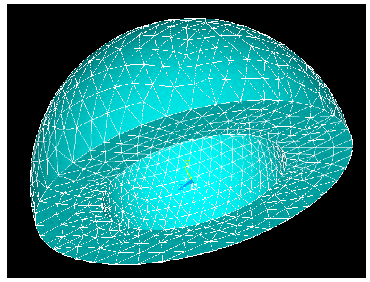

Figure 1. Finite element mesh of the acetabular component

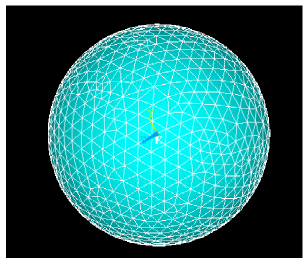

Figure 2. Femoral element mesh of the femoral component

The loads applied to the model in the center of the femoral head corresponded to gait of a patient with a total hip prosthesis, obtained experimentally at 16 discrete instants (Brand, Pedersen and Davy, 1994) of flexion/extension movement. The same study presented the hip flexion angle of the patient which provided the calculation of sliding velocity.

The wear model of this work was proposed by Archard (1953) and modified by Marshek and Chen (1989) and Maxian *et al.* (1996) to determine $W(\theta,\varphi)$, a matrix representing the wear depth distribution during the gait cycle:

$$W(\theta,\varphi) = \int k\sigma(\theta,\phi,t)v(\theta,\phi,t)dt \tag{1}$$

where (θ,φ) is the location of a point on the bearing surface in spherical coordinates; *k* is a wear coefficient, $\sigma(\theta,\phi,t)$ is the distribution of normal contact stress components; and $v(\theta,\phi,t)$ is the sliding velocity at sites of bearing surfaces.

Equation (1) can be re-written in a time discrete approximation, considering the normal stress distribution constant in each time interval:

$$W(\theta,\varphi) = \sum_{i=1}^{16} k\sigma_i(\theta,\phi,t_i)s_i(\theta,\phi,t_i) \tag{2}$$

where $\sigma_i(\theta,\phi,t)$ is the normal stress distribution and $s_i(\theta,\phi,t)$ is the sliding distance:

$$s_i(\theta,\phi,t_i) = \omega(t_i)r(\theta,\phi) \tag{3}$$

where $r(\theta,\phi)$ is the distance to the instantaneous axis of rotation, and $v_i(t)$ is the slope of the hip flexion angle at the 16 discrete instants of the gait cited previously (Brand, Pedersen and Davy, 1994). Our contribution to the Maxian´s model, which considered the change in the flexion/extension angle between successive instants, was to curve fit the discrete angular information and derive the slope from the continuous time curve.

This model was used to evaluate the effect of the materials and the lateral inclination of the acetabular component calculating the wear depth of each node of the contact surface. To compute an one-year period of wear, it was considered 1 million cycles, estimated value of gait cycles per year by Northfield *et al*, 1994.

The maximum wear value found among the wear depth of each node was called “linear wear rate”. The volumetric wear rate of each element the mesh was estimated by the product of contact face’s area of the element and the mean wear depth of the element’s nodes (vertices). This procedure results in 0.8% of accuracy in the volume calculation, according to Maxian *et al*, 1996. The total volumetric wear rate to the acetabular component was the sum of each element volumetric wear.

2.1. Variation of the Acetabular Lateral Inclination

The numerical simulation of the gait cycle was performed with the acetabular component being oriented to 30^o (Fig. 3), 45^o (Fig. 4) and 60^o (Fig. 5) of lateral inclination and neutral anteversion.

The femoral head was considered a chrome-cobalt alloy, with Young´s modulus of 210GPa and the Poisson´s ratio of 0,3 (Wimmer *et al*, 2001). The acetabular bearing was of UHMWPE (Ultra-High Molecular Weight Polyethylene), with Young´s Modulus of 1,4GPa and Poisson´s ratio of 0,35 (Maxian *et al*, 1996).

The wear coefficient was obtained through the CTPOD (Circulary Translating Pin-On-Disc) device developed by Saikko (1998). This laboratory test simulates the realistic wear in a simple way. The value to the chrome-cobalt/UHMWPE couple is 2,50x10^{-6}mm^3/Nm and, bovine serum was utilized as a lubricant (Saikko *et al*, 2001).

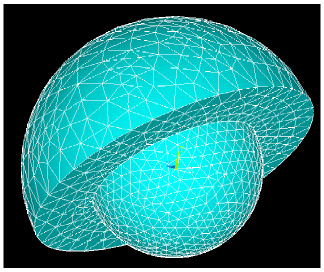

Figure 3. Finite Element Model of the Hip Prosthesis with 30° of Lateral Inclination

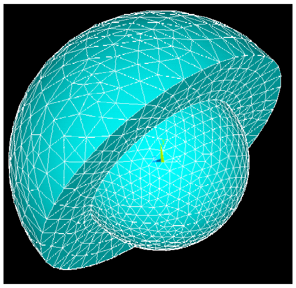

Figure 4. Finite Element Model of the Hip Prosthesis with 45° of Lateral Inclination

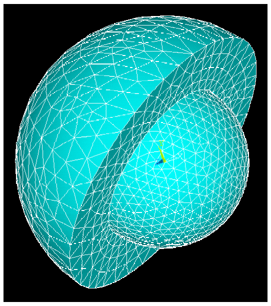

Figure 5. Finite Element Model of the Hip Prosthesis with 60° of Lateral Inclination

2.2. Variation of the Materials

Four tribologic couples were studied: chrome-cobalt/UHMWPE, alumina/UHMWPE, chrome-cobalt/chrome-cobalt, and alumina/alumina, respectively femoral head/acetabular component. The physical properties of the materials are presented in Tab. 1. The lateral inclination angle was 45° and neutral anteversion.

To make possible a good comparison among the different couples, the wear coefficient had to be obtained in similar conditions. All wear factors (see Tab. 2) with the exception of metal/metal couple, were obtained through CTPOD (Saikko, 1998), with bovine serum as the lubricant. The chrome-cobalt/chrome-cobalt wear coefficient was obtained from a pin-on-ball test, which had comparable dynamics.

Table 1. Physical Properties of the Simulated Materials

Materials	Young´s Modulus (GPa)	Poisson´s Ratio
Alumina	375	0,22
Chrome-Cobalt	210	0,30
UHMWPE	1,4	0,35

Table 2. Wear Coefficients of the Studied Tribologic Couples

Tribologic Couple	Wear Coefficient[1] (mm^3/Nm)	Reference
Alumina/ Alumina	$5{,}10 \times 10^{-8}$	Saikko and Karänen, 2002
Alumina/ UHMWPE	$1{,}55 \times 10^{-6}$	Saikko and Ahlroos, 2000
Chrome-Cobalt/ Chrome-Cobalt	$2{,}06 \times 10^{-7}$	Wimmer *et al*, 2001
Chrome-Cobalt/ UHMWPE	$2{,}50 \times 10^{-6}$	Saikko, Colonius and Keränen, 2001

(1): measured at 25°C

3. Results

From the contact stress on the acetabular component in each of the 16 instants of the gait cycle and flexion-extension angle information, the wear depth was calculated for each node, and then the linear wear rate and the total volumetric wear rate were calculated.

3.1. Variation of the Acetabular Lateral Inclination

Figure 6 shows the results of tension to the first five instants of the gait cycle discretized considering the acetabular lateral inclination for 30, 45 and 60 degrees.

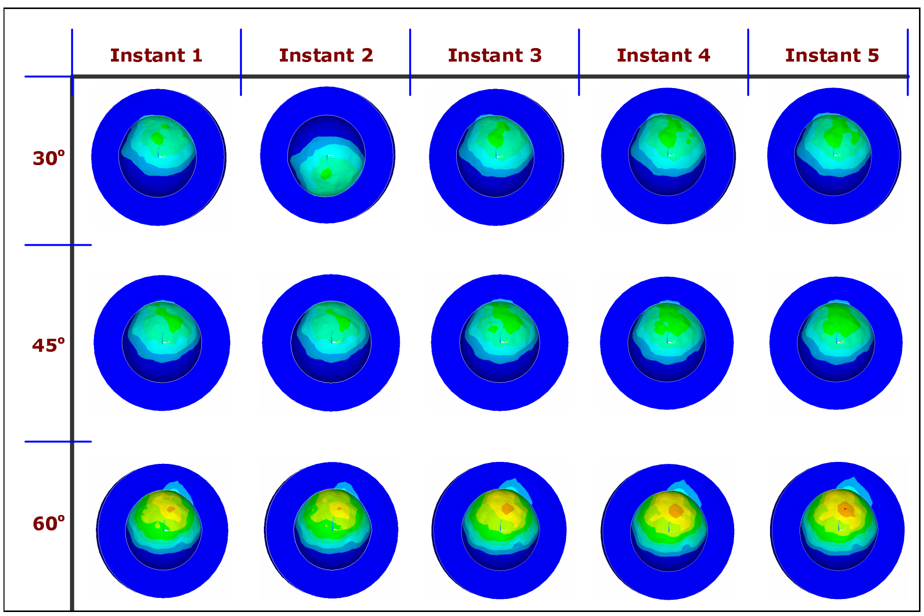

Figure 6. Results for the Contact Stress of the Finite Element Model Simulation Considering the Acetabular Lateral Inclination for the First Five Instants of the Gait Cycle

Table 3 presents the numerical simulation results with different angles of lateral inclination of the acetabular component. Figure 7 shows the amount of total volumetric wear rate for the three positions.

Table 3. Wear Simulation Results Considering the Acetabular Lateral Inclination Variation

Lateral Inclination	Linear Wear Rate[1] (mm/yr)	Total Volumetric Wear Rate (mm^3/yr)
30°	0,189	30,854
45°	0,173	30,966
60°	0,257	47,413

(1) : the maximum wear depth found in the mesh

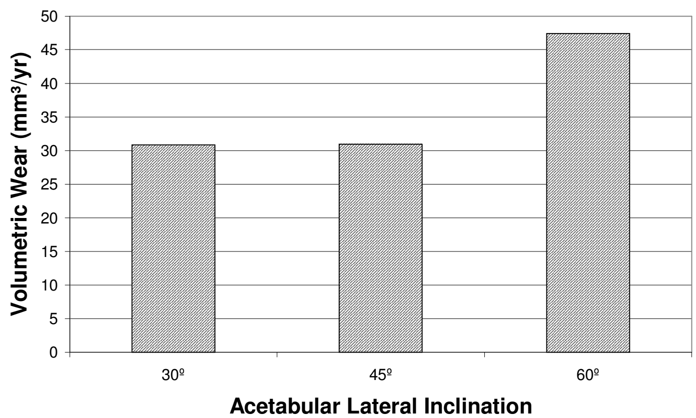

Figure 7. Volumetric Wear Rate Considering the Acetabular Lateral Inclination

3.2. Variation of the Materials

For each studied tribologic couple, Tab. 4 presents the linear wear rate and the total volumetric wear rate. The Figure 8 presents the Volumetric Wear Rate considering the Variation of Materials.

Table 4. Wear Simulation Results Considering Materials Variation

Tribological Couples	Linear Wear Rate[1] (mm/yr)	Total Volumetric Wear Rate (mm^3/yr)
Alumina/Alumina	0,002	0,198
Alumina/UHMWPE	0,050	6,333
Chrome-Cobalt/Chrome-Cobalt	0,007	0,941
Chrome-Cobalt/UHMWPE	0,173	30,966

(1) : the maximum wear depth found in the mesh

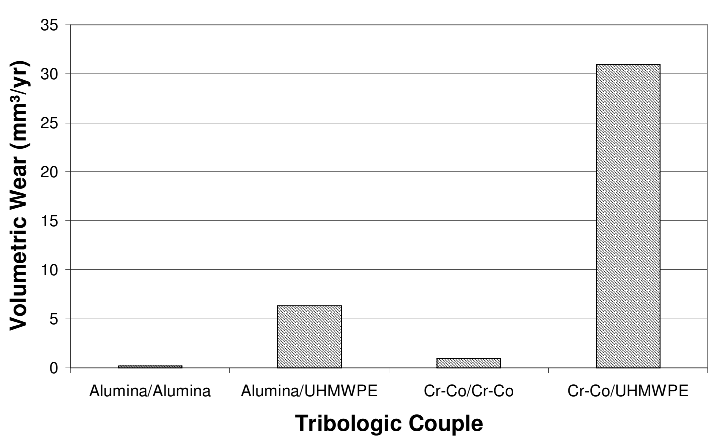

Figure 8. Volumetric Wear Rate Considering Materials Variation

4. Discussion

The wear of the contact surfaces results on gradual removal of material between the femoral and component head acetabular with the particle generation that occurs, a consequence of the cyclical movement between two opposing surfaces, under tension. The wear particles unchain a cell response that promotes the septic loosening of the total hip prostheses and revision surgery.

The wear in total hip arthroplasty is complex and multifactorial. During the surgery, the positioning of the acetabular component and the lateral inclination may modify the wear rate (Chen *et al*, 1998; Hirakawa *et al,* 2001; Patil *et al*, 2003).

The results found in the wear simulation with the acetabular inclination in 30°, 45° and 60º (Tab. 1) demonstrate that it did not have relevant alteration of the linear or total volumetric wear rate with the variation of 30° to 45° of the angle of lateral inclination. Nevertheless, the acetabular position in 60° of lateral inclination presented an increase of approximately 40% for linear wear rate and of approximately 50% for the total volumetric wear rate comparing to the other two cases. The clinical radiographic study developed by Patil *et al* (2003) shows that hip prostheses with lateral inclination angles bigger than 45° present an increase of 40% for the linear wear rate comparing to smaller angles, in agreement to this work.

Research on alternative contact surfaces to total hip arthroplasty has the objective to reduce the wear rate and then increase the life prosthesis, two approaches are being lead: the improvement of UHMWPE with sterilization techniques (cross-linked types) and the substitution of polyethylene forming new tribological couples. However, the comparison between the cross-linked UHMWPE types is difficult because there is not a standard to the processing and sterilization methods, resulting in similar materials but with different properties.

The metal/metal couple is not a new idea, being utilized in early prosthesis. The high wear rates result in the development of UHMWPE bearings, but scientists attribute now the high wear rates to design and not to material properties. The improvement in the processing of ceramics became possible its usage in hip prosthesis, in despite of being a fragile material and with great risks yet, especially in more active patients.

Our study concentrated in chrome-cobalt alloy and alumina against UHMWPE and itself, representing the tribological couples used in hip prosthesis: metal/metal, metal/UHMWPE, ceramic/ceramic and ceramic/UHMWPE. The authors do not acknowledge other studies, clinical radiographic studies or laboratory studies, that congregates all combinations addressed here.

To the chrome-cobalt/UHMWPE alloy, the linear wear rate was 0,173 mm/yr and the total volumetric wear rate was 30,966 mm^3/yr, values inside the possible clinic variation (Livermore *et al*, 1990).

The combination alumina/UHMWPE presented linear wear rate of 0,050mm/yr and total volumetric year of 6,333mm/yr. Urban *et al* (2001) had described a medium linear wear rate of 0,034mm/yr in a clinic-radiographic study, comparable to our value.

In the clinic comparison between the chrome-cobalt and the alumina femoral head, performed by Urban *et al* (2001), the linear wear rate for the first one was three times superior of the alumina and a similar proportion was found in this study.

There is not clinical radiographic study *in vivo* to metal/metal couple, studies of wear are performed after the revision surgery, presenting linear wear rates from 0,006 to 0,008 mm/yr (Schmidt *et al*, 1996; McKellop *et al*, 1996), in agreement to this numeric simulation that obtained 0,007mm/yr to chrome-cobalt/chrome-cobalt couple.

Similar to the metal couples, alumina studies are performed only after the withdrawal of the hip prosthesis. Skinner (1999) presented in his study the linear wear rate of 0,003mm/yr, 30% superior to our study (0,002mm/yr). Our total volumetric wear rate was 0,198mm^3/yr, inside the range of clinic values presented by Walter *et al* (2004) – from 0,02 to 1,15 mm^3/yr.

5. Conclusion

1 – The wear rate of the acetabular component increase with lateral inclination above 45°.

2 – In decreasing wear rate order, the tribological couples are: chrome-cobalt/UHMWPE, alumina/UHMWPE, chrome-cobalt/chrome-cobalt and alumina/alumina.

6. Acknowledgements

The authors gratefully acknowledge the contributions from Dr. José Augusto Lopes and Flávio Celso Trigo for the development of the Finite Element Model and computation of the normal contact stress.

7. References

Archard, J.F., 1953, "Contact and Rubbing of Flat Surfaces", J. Appl. Phys., Vol.24, pp. 981-988

Brand, R. A., Pedersen, D.R. and Davy, D.T., 1994, "Comparasion of Hip Force Calculations and Measurements in the Same Patient", J. Arthroplasty, Vol.9, pp. 45-51.

Chen, F.S., Di, C., Kale, A.A., Lee, J. F., Frankel, V.H., Stuchin,S.A. and Zuckerman, J.D., 1998, "Results of Cemented Metal-Backed Acetabular Components: a 10-year-average Follow-up Study", J. Arthoplasty, Vol.13(8), pp. 867-873.

Garellick, G., Malchau, H., Herberts, P., Hansson, E., Axelsson, H. and Hansson, T., 1998, "Life Expectancy and Cost Utility After Total Hip Replacement", Clin. Orthop., Vol. 346, pp.141-151.

Hirakawa, K., Mitsugi, N., Koshino, T., Saito, T., Hirasawa, Y. and Kubo, T., 2001, "Effect of Acetabular Cup Position and Orientation in Cemented Total Hip Arthroplasty", Clin. Orthop., Vol. 388, pp. 135-142.

Livermore, J., Ilstrup, D. and Morrey, B., 1990, "Effect of Femoral Head Size on Wear of the Polyethylene Acetabular Component." J. Bone Joint Surg. [Am], Vol.72, pp. 518-528.

Marshek, K.M and Chen, H.H., 1989, "Discretization Pressure-Wear Theory for Bodies in Sliding Contact". J. Tribology, Vol.111, pp. 95-100.

Maxian, T.A., Brown, T.D., Pedersen, D.R. and Callaghan, J.J, 1996, "A Sliding-Distance-Coupled Finite Element Formulation for Polyethylene Wear in Total Hip Arthorplasty", J. Biomech., Vol.29, pp. 687-692.

Mc Kellop, H., Park, S.H., Chiesa, R., Doorn, P., Lu, B., Normand, P., Grigoris, P. and Amstutz, H., 1996, "In Vivo Wear of Three Types of Metal on Metal Hip Prostheses During Two Decades of Use", Clin. Ortho., Vol.329S, pp. 128-140.

Northfield, M. R., Schmalzriedf, T.P., Belcher, G. and Amstutz, H.C., 1994, "Quantitative Assessment of Activity in Joint Replacement Patientes", Trans. Orthop. Res. Soc., Vol.40, p. 680.

Patil, S., Bergula, A., Chen, P.C., Colwell Jr, C.W. and D'Lima, D.D., 2003, "Polyethylene Wear and Acetabular Component Orientation", J. Bone Joint Surg. [Am], Vol. 85-A, Suppl. 4, pp. 56-63.

Queiroz, R.D., 1999, "Análise do Desgaste do Polietileno do Componente Acetabular da Prótese Total do Quadril, Utilizando o Método de Elementos Finitos de Simulação Computadorizada", Tese de Mestrado Apresentada UNIFESP-EPM.

Saikko, V., 1998, "A Multidirectional Motion Pin-on-Disk Wear Test Method for Prosthetic Joint Materials", J. Biomed. Mater. Res., Vol.41, pp. 58-64.

Saikko, V. and Ahlroos, T., 2000, "Wear Simulation of UHMWPE for Total Hip Replacement with a Multidirectional Motion Pin-on-Disk Device: Effects of Counterface Material, Contact Area and Lubricant", J. Biomed. Mater. Res., Vol.49(2), pp. 47-154.

Saikko, V., Calonius, O. and Keränen, J., 2001, "Effects of Counterface Roughness on the Wear of Convetional and Crosslinked Ultra-High Molecular Weight Polyethylene Studied with a Multidirectional Motion Pin-on-Disk Device", J. Biomed. Mater. Res., Vol.57, pp.506-512.

Saikko, V and Keränen, J., 2002, "Wear Simulation of Alumina-Alumina Prosthetic Hip Joints Using a Multidirectional Motion Pin-on-Disk Device", J. Am. Ceram. Soc., Vol.85(11), pp.2785-2791.

Schmidt, M., Weber, H. and Schön, R., 1996, "Cobalt Chromium Molybdenum Metal Combination for Modular Hip Prostheses", Clin. Ortho., Vol.329S, pp.35-47.

Skinner, H.B., 1999, "Ceramic Bearing Surfaces", Clin. Ortho., Vol.369, pp. 83-91.

Urban, J.A., Garvin, K.L., Boese, C.K., Bryson, L., Pedersen, D.R., Callaghan, J.J. and Milek, R.K., 2001, "Ceramic-on-Polyethylene Bearing Surfaces in Total Hip Arthroplasty – Seventeen to Twenty-one-year Results", J. Bone Joint Surg. [Am], Vol.83-A, pp.1688-1694.

Wimmer, M.A., Loos, J., Nassutt, R., Heitkemper, M. and Fischer, A., 2001, "The Acting Wear Mechanisms on Metal-on-Metal Hip Joint Bearings: in Vitro Results", Wear, Vol.250, pp.129-139.

8. Responsibility notice

The authors are the only responsible for the printed material included in this paper.