Wear Property of Machined Ultra High Molecular Weight Polyethylene (UHMWPE) Acetabular Liner Product with CNC Milling

W D Lestari1\*, A T Danaryanto2, A Nugroho3, R Ismail2, J Jamari2, A P Bayuseno2

*1Department of Mechanical Engineering, Faculty of Engineering, University of Pembangunan Nasional “Veteran” Jawa Timur,*

*Jl. Raya Rungkut Madya, Gunung Anyar, Surabaya, 60294, Indonesia*

2*Department of Mechanical Engineering, Faculty of Engineering, Diponegoro University,*

*Jl. Prof. Soedarto, Tembalang, Semarang, 50275, Indonesia*

*3PUTP (Pusat Unggulan Teknologi Plastik) Politeknik ATMI,*

*Jl. Mojo No.1, Karangasem, Laweyan, Surakarta, 57102, Indonesia*

*\*Corresponding author:wahyu.dwi.tm@upnjatim.ac.id*

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| ABSTRACT |
| UHMWPE has been used as a cushion in artificial hip joint for the last decades. The reliability of the components of a hip joint implant can be achieved by understanding their wear behavior. This study observed the tribological performance of the UHMWPE acetabular liner manufactured with a CNC milling machine on the femoral head made of SS 316L. Materials commonly used for tribo pairs in hip joint replacement. The wear tests were performed on a hip joint simulator in dry condition. The wear test is carried out by applying a constant load of 800N. Before and after the wear test, measurements of surface roughness and dimensional accuracy were carried out on the UHMWPE acetabular liner specimen. The correlation between the surface roughness of the machining process and the wear rate is seen from the value of the wear depth and the wear coefficient obtained. The results showed that the machining process affects the surface roughness of the acetabular liner, where the roughness also affects the wear rate of acetabular liner product. |
| ***Keywords:*** *Acetabular Liner, Milling, UHMWPE, Wear, Surface Roughness* |

**I. Introduction**

One of the vital parts of the human body is the hips [1]. The hip joint has an important role in the human body such as performing daily activities (walking, going down stairs, running, exercising, salat for muslim, etc.) because of its ability to transmit static and dynamic loads. Some of the problems that are often experienced by the hip joint include osteoarthritis, joint fractures, damage to the components of the femoral head and acetabular cup, and reduced synovial fluid in the joints. This makes the delivery painful and an artificial hip implant is needed. The process of removing the diseased hip joint with an artificial hip joint that is similar in shape and function to the natural hip joint which is made of biocompatible materials is known as Total Hip Replacement (THR). Many pairs of materials have been used for artificial hip joint. One of the most successful and widely used material pairs is UHMWPE against metal [2]. UHMWPE is the superior material used for today’s artificial hip joint components [3]. As for metal components commonly used for biomedical applications is stainless steel 316 L due to its strength, thermal stability, high specific moduli and most importantly good wear resistance [4].

Despite its excellent properties, UHMWPE as a cushioning material in artificial joints has significant tribological problems. These problems include the appearance of wear debris of small size which causes an adverse reaction in the surrounding tissue, resulting in aseptic loosening of the prosthesis components [5]. Because of this, UHMWPE materials have a limited lifespan of 15-20 years [6]. The wear behavior of hip implant materials depends on the condition of the surface which can be obtained through the manufacturing process. Several scientific papers report on the effect of the manufacturing process on the characteristics of the resulting surface which will certainly have an impact on the performance of the implant. Bruschi et al. [7] investigated the effect of the Ti6Al4V acetabular liner machining process for hip implants on their wear performance. The results show that the application of multiple passes and cryogenic cooling to achieve high surface quality can improve wear performance. Novovic et al. [8] studied the strength of surface texture variations on the fatigue resistance of titanium alloys where the results showed a correlation between surface integrity, surface topography, and material response. Furthermore, Affatato et al. [10] investigated the effect of surface roughness on the CoCrMo femoral head on the wear rate of UHMWPE through in vitro testing. Turger et al (2013) [11] also used a wear simulator for the wear behavior caused by the quality of the surface material due to the manufacturing process. Whittaker et al. [12] evaluated the effect of surface roughness on the wear rate of the MoM pairs material. The results show that only a few surface roughness parameters have a significant effect on wear control.

The wear if implant products is appreciated by the fact that the appearance of a large amount of wear has an adverse effect that can impact the life of the implant [13]. This wear rate can be reduced and its life can be significantly extended by improving the quality of the bearing material [14][15]. Based on these reasons, research analysis and testing is an important part in the design and development of the hip joint to improve function and quality before the implantation process. Wear tests on hip prosthetics are usually performed on a steady motion walking cycle obtained from the biomechanical literature [16][17]. The hip simulator is an experimentally proven tool for basic investigations and preclinical testing to minimize patient harm when receiving a new type of implant. Niemczewska-wójcik [18] used a hip joint simulator to study changes in surface topography at the research stage of ball and socket friction pair. Trommer et al. [19] used a hip simulator to observe the wear performance of a non crosslinked UHMWPE pair versus two metal counterfaces namely stainless steel (SS) and cobalt chromium (CoCr) alloys. De Fine et al (2020) [20] used a hip simulator to test the wear behavior of ceramic on ceramic pairs under walking and subluxation cycles. Viitala and Saikko (2020) [17] used a hip joint simulator to analyze wear on a variety of daily activities. In this study, Saikko (2020) used a hip joint simulator to analyze the wear rate of extensively cross linked ultra high molecular weight polyethylene (VEXLPE) liners.

However, from some of the available literature, no one has paid attention to the influence of the UHMWPE acetabular liner machining process using a milling machine on the wear rate. Therefore, the purpose of this study was to observe the effect of the acetabular liner machining process for UHMWPE hip joints on wear behavior. The machining process is carried out using a CNC milling machine in dry conditions. To evaluate the wear rate of the UHMWPE acetabular liner from the machining process, a hip joint simulator was used. Wear resistance tested for 30.000 cycles under walking cycle conditions. Wear quantity is calculated based on weight loss.

**II. Material and Methods**

1. *Specimens Preparation*

The hip joint consists of a ball and socket located between the acetabulum and the femur in the pelvis [21]. In this study, the acetabular liner component is derived from UHMWPE rod-shaped material which is manufactured using a CNC milling machine in dry conditions (Figure 1). The CNC milling machine used is YCM 1020 EV 20 with 3 axes. In this research, 9 samples of acetabular liner were produced with CNC milling machine cutting parameters such as feed rate, toolpath strategy, step over, and spindle speed [22]. The size of the UHMWPE acetabular liner formed is with an inner diameter of 28.2 mm. The result of this acetabular liner milling process must have a surface roughness below 2 μm and dimensional tolerance in the range of +0.3 and -0.0 according to ASTM F2033-12. Furthermore, optimization was carried out on 9 samples of acetabular liner from the results of the manufacturing process to get 3 samples with the best roughness value. The 3 samples (Figure 2) of the acetabular liner from the optimization results were then tested for wear. Based on the measurement results, the size range of the acetabular liner specimen is obtained, namely the outer radius of 18.5 mm and the inner radius of 14.1 mm, where the three samples are still within the dimensional tolerance. The femoral head component is made of SS 316 L material with a diameter of 28 mm.

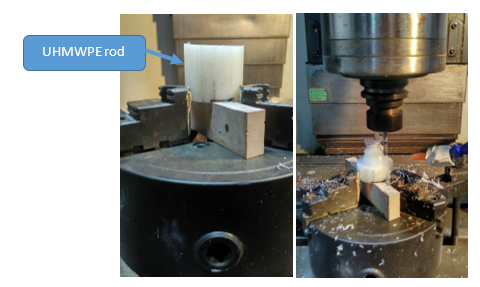


Fig. 1. Experimental set up for the milling of UHMWPE acetabular liner



Fig. 2. Acetabular liner

UHMWPE acetabular liner products resulting from the machining process are measured for surface roughness before wear testing is carried out. The process of measuring surface roughness was carried out using the Mark Surf PS1 surface roughness tester. The surface roughness measurement is carried out again after going through the wear test process, where the results can be seen in Table 1. The surface roughness values obtained from this study are in accordance with previous studies [23], which stated that the initial surface roughness of the polymer ranged from 0.4 μm - 2.2 µm, but generally has a surface roughness level of about 1 µm - 2 µm. In another study conducted by Trommer *et al.* [24], the maximum initial surface roughness level of UHMWPE was 2µm before the wear test was carried out.

Table 1. The value of roughness of the inner acetabular liner before and after the test

|  |  |  |
| --- | --- | --- |
| Acetabular liner | Surface roughness | |
| Before | After |
| Specimen 1 | 0.926 | 0.7756 |
| Specimen 2 | 1.161 | 0.7182 |
| Specimen 3 | 0.848 | 0.6786 |

1. *Wear Test using Hip Joint Simulator*

The prototype joint generated from the manufacturing process is then carried out preclinical testing using a simulator that is able to imitate motion behavior, biomechanics, and environmental conditions in the human body [25]. Tribological measurements in this study was carried out using a specially modified tribometer in the chamber to test the wear of the acetabular liner. The working principle of this tribometer machine is similar to the human hip joint, where there is a femoral head which is a parable of a human femur and a cup as a human pelvis. The maximum load that this testing machine can accept is 3000N. According to Hua et al [26], the resultant force of the hip joint is 2500N which is equivalent to 3-4 times the human body weight of 70 kg. The test design applied in this study is to provide as much insight as possible about the physical loading and motion that occurs between the femoral head and the acetabular liner upon contact.

The testing parameters in this study are based on the ISO 14242 standard and previous research [27]. This study focuses on the effect of the UHMWPE acetabular liner machining process with CNC milling machine on the wear rate. The amount of force on the acetabular liner is determined by the weight of the human body. In this study, the amount of force applied is 800N which is based on the assumption of the patient's average weight [27]. The number of cycles applied in this test is 30000 cycles. The UHMWPE acetabular liner is attached to the SS 316L femoral head and encapsulated in the specimen chambers. The pair of specimens was sterilized first using 70% alcohol before being installed on the test machine. The wear testing process is carried out in dry conditions and at a temperature of 200C. Gravimetric wear obtained from the test results based on mass transformation. The entire experimental process in this study is shown in the flow chart in Figure 3.

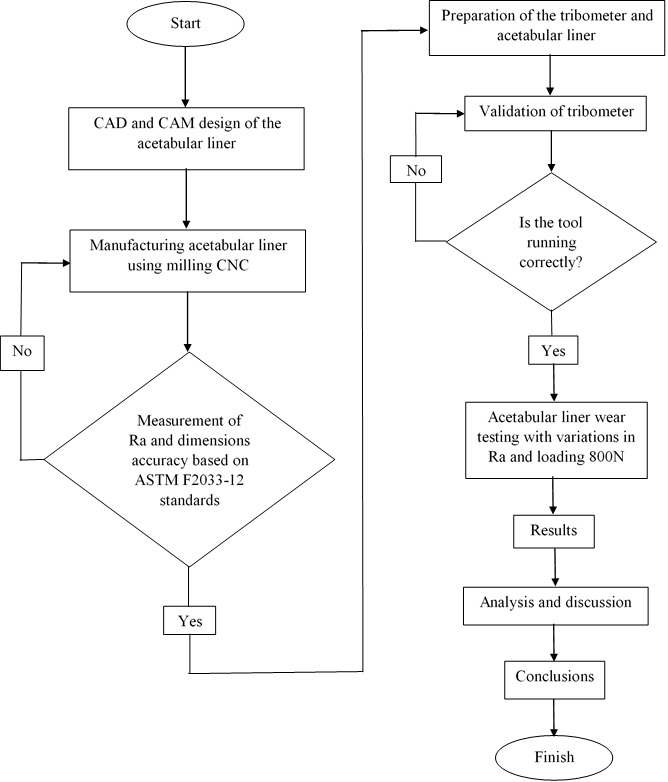


Fig. 3. Flowchart of the testing procedure of the UHMWPE acetabular liner using tribometer

1. *Dimensional Accuracy Measurement*

In addition to surface roughness, this study also measures the dimensional accuracy of the acetabular liner product. This measurement is carried out to ensure whether the resulting product conforms to the specified dimensional tolerance or not. Dimensional accuracy measurement using a coordinate measuring machine (CMM). Measurements are also carried out before and after the wear test process.

**III. Experimental Results**

1. *Measurement of Wear Mass*

The results of this study will be used as a reference to improve the hip implant prototype. The resulting data in the form of the number of cycles and the depth of wear will be made into a graph of the relationship between the cycles and the depth of wear of the three test specimens. Changes in the volume of the acetabular liner were obtained by weighing. Changes in the initial and final weight data of the acetabular liner are shown in Table 2. Changes in the weight of the three samples prove that there is wear caused by the testing process in the walking cycle. Based on the weight change data contained in the Table 2, it can be seen that the test sample 2 has the largest weight change among the three samples. Furthermore, the data changes in the three samples are compared into a single graph to determine the difference in the depth level of each specimen (Figure 4). The wear rate is determined by linear regression of the wear (mm) with the number of cycles. The wear depth (mm) of the UHMWPE acetabular liner is recorded as a function of the cycle length with a force of 800N.

Table 2. The initial and final weight of the acetabular liner

|  |  |  |  |
| --- | --- | --- | --- |
| Specimens | Initial weight (g) | Final weight (g) | Weight change (g) |
| Specimen 1 | 6.8274 | 6.8260 | 0.0014 |
| Specimen 2 | 6.3646 | 6.3350 | 0.0296 |
| Specimen 3 | 6.1734 | 6.1720 | 0.0014 |

Fig. 4. Comparison of test results of 1,2,3 specimens with 800 N force

Based on Figure 5, it can be seen that the test results of the three specimens showed almost the same trend. The lowest wear depth is owned by specimen 3, where the largest wear depth is owned by specimen 1. There is a difference in the wear depth on the test results of specimen 1 from cycle 0 to cycle 3000 compared to specimen 2 and specimen 3. Furthermore, the trend of the three objects shows the same trend after cycle 3000 to cycle 30000. The test results in this study indicate that there are different wear values of each acetabular liner specimen, where this is influenced by the presence of different roughness as well. Based on the graph, the value of the depth of wear for each specimen is obtained through 30000 cycles of wear testing. Each specimen has a wear depth of 0.52 mm, 0.471 mm, and 0.454 mm respectively from specimen 1, specimen 2, and specimen 3.

1. *Dimensional Accuracy Measurement of Acetabular Liner*

An understanding of wear behavior is an urgent part of obtaining preclinical data on the prosthesis prior to implantation. In this regard, in this study, we conducted a wear test on a laboratory scale to determine the wear behavior of the acetabular liner from machining process as a bearing on an artificial hip joint. Wear measurement is especially needed to measure new designs and materials because of the continuous need to manufacture new joints. One of solution to get the right component prosthesis design is to take geometry measurements before, during, and after wear testing. For this purpose, this study uses a coordinate measuring machine (CMM) to measure the dimensional accuracy of the acetabular liner specimen before and after the wear test. The results of dimensional accuracy measurements on the three acetabular liner specimens are presented in Table 3.

Table 3. The value of dimency accuracy of the inner acetabular liner before and after testing

|  |  |  |
| --- | --- | --- |
| Acetabular liner | Accuracy Dimensions | |
| Before | After |
| Specimen 1 | 14.439 | 14.331 |
| Specimen 2 | 14.470 | 14.134 |
| Specimen 3 | 14.354 | 14.228 |

Uddin et al.[28], in their research, measured the wear of polyethylene acetabular liner with CMM where the average linear and volumetric wear rates were 0.12 mm/year and 37.18 mm3/year, respectively. Previous studies [29] also reported acetabular linear and volumetric wear rates with XLPE materials of 0.024 mm/year and 4.5 mm3/year, respectively. In this study, the specimen 2 had the biggest difference between before and after the test, which was 0.336 mm during the testing of 30000 cycles. Furthermore specimens 1 and specimens 3 had differences in accuracy dimensions of 0.108 mm and 0.126 mm, respectively. This result is bigger when compared to previous studies.

**IV. Discussion**

1. *Validation*

Validation is needed before carrying out the wear testing process using a tribometer machine to find out whether the tool used is valid enough to take data. The validation method is to calculate the wear coefficient value generated from the test using the Archad equation with the femoral head radius of 14 mm and the acetabular liner radius of 14.1 mm. The load used is equal to 800 N with 30000 cycles. The value of the wear coefficient produced in this test is equal to 1.945 x 10-4 mm3 / Nm. This value is then compared with the results of research conducted by Dowson [30], by entering the research parameters in the formula. Dowson et al. [30] conducted a wear test and obtained two wear coefficient values, namely 1.35x10-7 mm3 / Nm and 4.49x10-7 mm3 / Nm. The results of the validation can be seen in the Figure 5 as for the wear depth formula from Dowson et al (1993), namely:

(1)

Where P is penetration or wear depth (mm), k is wear coefficient (mm3 N-1 m-1), B is Body weight (N), N is number of cycles (cycles), R1 is femoral head radius (mm), and R2 is acetabular liner radius (mm).

Fig. 5. Validation of test with Dowson model

The results show that there are differences in the test results where the wear value obtained is higher than that produced by Dowson when the cycle runs more than 4,500 cycles, but the trend is almost the same. Thus it can be concluded that the tools used are valid enough to be used in conducting research.

1. *Wear Behavior*

The level of wear on biomedical components such as acetabular liners with variations in specifications and materials can be predicted through in vitro tests. The hip simulator test is the most commonly used tool by researchers to test the wear level of the acetabular liner with various parameter tests. In this study, the tribological behavior of the UHMWPE acetabular liner from the results of the CNC milling process with the femoral head pair was observed using a hip simulator based on the walking cycle. The difference in the wear rate of each specimen is caused by the difference in the surface roughness values obtained from the machining process [31]. This study took three samples of UHMWPE acetabular liner with the best roughness value based on the optimization results of nine samples made. The calculation results of the wear coefficient with the difference in the surface roughness values are shown in Figure 6, where the values of the wear volume and the level of penetration are presented in Table 4.

Table 4. Summary of UHMWPE wear behaviour in simulator test condition.

|  |  |  |  |
| --- | --- | --- | --- |
| Sample | Wear volume (mm3) | Penetration rate (mm/year) | Wear coefficient  ( mm3N-1m-1) |
| Specimen 1 | 102.98 | 0.33 | 2.78 x 10-4 mm³/ Nm |
| Specimen 2 | 79.54 | 0.289 | 2,2 x 10-4 mm3/Nm |
| Specimen 3 | 75.46 | 0.279 | 1.95 x 10-4 mm3/Nm |

Fig. 6. Graph of wear coefficient calculations

Based on the graph in Figure 6, it can be seen that the highest wear coefficient value is found in specimen 1 of 2.78 x 10-4 mm³/ Nm. Then followed by specimens 2 and 3 with values of 2.2 x 10-4 mm3/Nm and 1.95 x 10-4 mm3/Nm, respectively. If observed, these results are related to the value of surface roughness. In accordance with previous studies [32], where the wear coefficient value produced is different in the contact test between UHMWPE which has an initial roughness value range of 1-2 µm with high density alumina ceramic in dry conditions and lubricated with distilled water. After the wear test process, the surface roughness of the UHMWPE acetabular liner became smoother and the value decreased from the initial surface roughness value (Table 2). This is as a result of the contact surface. This is also supported by previous research conducted by Trommer et al. [24] where the surface roughness value of UHMWPE was reduced from the initial value after going through a wear test process with a hip joint simulator for 5 million cycles. Furthermore, Roussignol et al. [33] in his research also found that the average surface roughness of UHMWPE acetabular liner decreased ranging from 0.053 0.053 µm and 0.25 µm from the initial average surface roughness of 0.95 µm.

The observations results on the surface of the acetabular liner sample after testing 30,000 cycles indicate the presence of wear areas such as polish due to continuous loading. The surface of the acetabular liner may be scratched due to the appearance of a third body particle trapped between the polymer and metal surfaces. The scratch occurs because the counterface metallic is forced to move against the surface of the acetabular liner polymer. Research conducted by Trommer et al. [24] also showed a third body abrasion characterized by random directional scratches on the acetabular liner.

In this study the wear mechanism that occurs is the third body abrasion with the test results in the form of wear depth and wear coefficient koefisien. The amount of wear in vivo generally ranges from 50-100 mg per year [34]. In various simulators it is found that the wear value of polyethylene is in the range of 20-35 mg per 1 million cycles [35]. In his research, Affatato et al. [36] found the total wear of the UHMWPE acetabular liner was 6378 mg for the acetabular liner with gamma irradiation and 7672 mg for the acetabular liner with EtO sterilization after going through five million cycles of testing. With a linear wear rate of 0.16 mm/year, Trommer et al. [24] achieves UHMWPE wear of around 48 mg/106 cycles. Furthermore Shibo et al. [37] resulted UHMWPE wear of 31.73 mg/million cycles and 15.20 mg/million cycles at 784 N and 392 N loadings, respectively. Bragdon et al. [38], obtainedan annual wear rate similar to the annual wear rate obtained from the observed popular MoP hip reconstruction which was 25 mg per million cycles.

In this study, the lowest weight obtained after going through the wear testing process was 0.0014 g (1.4 mg/30000 cycles). The data obtained from this study cannot be compared directly with the results of wear experiments from the literature using a hip endoprosthesis simulator, because the mechanism used is still simple on a laboratory scale [37]. The focus of this research is to examine the effect of the UHMWPE acetabular liner manufacturing process with CNC milling on surface roughness, where this roughness will affect the wear level of product for artificial hip joints. However, if plotted on a graph and calculated based on a linear equation of 1 million cycles, the wear rate of UHMWPE manufactured using a CNC milling machine is still in accordance with the in vivo wear rate provisions in the literature [39]. The wear tests performed in this study are in accordance with the literature which describes the material wear of a commonly applied hip implant component under appropriate loading. Based on the test data and observations on the sample, it can be obtained that the surface roughness of the acetabular liner resulting from the milling process affects the depth and coefficient of wear.

**V. Conclusions**

This study explores the influence of the UHMWPE acetabular liner manufacturing process with a CNC milling machine on the level of wear. Based on the results of the study, the conclusions obtained that the results of the wear coefficient calculation of the UHMWPE acetabular liner specimen indicate that the greater the surface roughness value of the acetabular liner, the greater the wear coefficient value, where the highest wear coefficient value is owned by specimen 1 of 2,57 x 10-4 mm3/Nm.The rate of wear depth and the wear coefficient of the UHMWPE acetabular liner produced in this study is influenced by the surface roughness value of the machining process with CNC milling.

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**References**

[1] O. Hussain, S. S. Saleem, and B. Ahmad, “Friction and wear performance evaluation of UHMWPE using Taguchi based grey approach: A study on the influence of load and bio-serum lubrication,” *Mater. Chem. Phys.*, vol. 239, no. April 2019, p. 121918, 2020, doi: 10.1016/j.matchemphys.2019.121918.

[2] V. Saikko, V. Vuorinen, and H. Revitzer, “Analysis of UHMWPE wear particles produced in the simulation of hip and knee wear mechanisms with the RandomPOD system,” *Biotribology*, vol. 1–2, pp. 30–34, 2015, doi: 10.1016/j.biotri.2015.03.002.

[3] L. Hongtao, G. Shirong, C. Shoufan, and W. Shibo, “Comparison of wear debris generated from ultra high molecular weight polyethylene in vivo and in artificial joint simulator,” *Wear*, vol. 271, no. 5–6, pp. 647–652, 2011, doi: 10.1016/j.wear.2010.11.012.

[4] W. Qin, J. Kang, J. Li, W. Yue, Y. Liu, D. She, Q. Mao, and Y. Li, “Tribological behavior of the 316L stainless steel with heterogeneous lamella structure,” *Materials (Basel).*, vol. 11, no. 10, pp. 1–12, 2018, doi: 10.3390/ma11101839.

[5] S. M. Kurtz, D. W. Macdonald, S. Kocagöz, M. Tohfafarosh, and D. Baykal, “Can Pin-on-Disk Testing Be Used to Assess the Wear Performance of Retrieved UHMWPE Components for Total Joint Arthroplasty ?,” *Biomed Res. Int.*, vol. 581812, pp. 1–6, 2014.

[6] A. Laska, V. M. Archodoulaki, and B. Duscher, “Failure analysis of retrieved PE-UHMW acetabular liners,” *J. Mech. Behav. Biomed. Mater.*, vol. 61, pp. 70–78, 2016, doi: 10.1016/j.jmbbm.2016.01.007.

[7] S. Bruschi, R. Bertolini, A. Bordin, F. Medea, and A. Ghiotti, “Influence of the machining parameters and cooling strategies on the wear behavior of wrought and additive manufactured Ti6Al4V for biomedical applications,” *Tribiology Int.*, vol. 102, pp. 133–142, 2016, doi: 10.1016/j.triboint.2016.05.036.

[8] D. Novovic, D. K. Aspinwall, R. C. Dewes, P. Bowen, and B. Griffiths, “The effect of surface and subsurface condition on the fatigue life of Ti – 25V – 15Cr – 2Al – 0 . 2C % wt alloy,” *CIRP Ann. - Manuf. Technol.*, vol. 65, no. 1, pp. 523–528, 2016, doi: 10.1016/j.cirp.2016.04.074.

[9] S. Affatato, G. Bersaglia, Y. Junqiang, F. Traina, A. Toni, M. Viceconti, “The predictive power of surface profile parameters on the amount of wear measured in vitro on metal-on-polyethylene artificial hip joints,” *Proc. IMechE Vol. 220 Part H J. Eng. Med.*, vol. 220, pp. 457–464, 2015, doi: 10.1243/09544119JEIM95.

[10] S. Affatato, N. Freccero, and P. Taddei, “The biomaterials challenge : A comparison of polyethylene wear using a hip joint simulator,” *J. Mech. Behav. Biomed. Mater.*, vol. 53, pp. 40–48, 2016, doi: 10.1016/j.jmbbm.2015.08.001.

[11] A. Turger, J. Köhler, B. Denkena, T. A. Correa, C. Becher, and C. Hurschler, “Manufacturing conditioned roughness and wear of biomedical oxide ceramics for all-ceramic knee implants,” *Biomed. Eng. Online*, vol. 12, pp. 1–17, 2013.

[12] R. K. Whittaker, H. S. Hothi, A. Eskelinen, G. W. Blunn, J. A. Skinner, and A. J. Hart, “Variation in Taper Surface Roughness for a Single Design Effects the Wear Rate in Total Hip Arthroplasty,” *J. Orthop. Res.*, no. August, pp. 1784–1792, 2017, doi: 10.1002/jor.23456.

[13] D. J. Langton, T. J. Joyce, S. S. Jameson, J. Lord, M. V. Orsouw, J. P. Holland, A. V. F. Nargol, K. A. De Smet, “Adverse reaction to metal debris following hip resurfacing: The influence of component type, orientation and volumetric wear,” *J. Bone Jt. Surg. - Ser. B*, vol. 93 B, no. 2, pp. 164–171, 2011, doi: 10.1302/0301-620X.93B2.25099.

[14] C. Scemama, P. Anract, V. Dumaine, A. Babinet, J. P. Courpied, and M. Hamadouche, “Does vitamin E-blended polyethylene reduce wear in primary total hip arthroplasty: a blinded randomised clinical trial,” *Int. Orthop.*, vol. 41, no. 6, pp. 1113–1118, 2017, doi: 10.1007/s00264-016-3320-2.

[15] R. De Steiger, M. Lorimer, and S. E. Graves, “Cross-linked polyethylene for total hip arthroplasty markedly reduces revision surgery at 16 years,” *J. Bone Jt. Surg. - Am. Vol.*, vol. 100, no. 15, pp. 1281–1288, 2018, doi: 10.2106/JBJS.17.01221.

[16] G. Valente, L. Pitto, R. Stagni, and F. Taddei, “Effect of lower-limb joint models on subject-specific musculoskeletal models and simulations of daily motor activities,” *J. Biomech.*, vol. 48, no. 16, pp. 4198–4205, 2015, doi: 10.1016/j.jbiomech.2015.09.042.

[17] R. Viitala and V. Saikko, “Effect of random variation of input and various daily activities on wear in a hip joint simulator,” *J. Biomech.*, vol. 106, p. 109831, 2020, doi: 10.1016/j.jbiomech.2020.109831.

[18] M. Niemczewska-wójcik, “Wear mechanisms and surface topography of artificial hip joint components at the subsequent stages of tribological tests,” *Measurement*, vol. 107, pp. 89–98, 2017, doi: 10.1016/j.measurement.2017.04.045.

[19] R. M. Trommer and M. M. Maru, “Importance of preclinical evaluation of wear in hip implant designs using simulator machines ଝ,” *Rev. Bras. Ortop.*, vol. 52, no. 3, pp. 251–259, 2016, doi: 10.1016/j.rboe.2016.07.004.

[20] M. De Fine, S. Terrando, M. Hintner, A. A. Porporati, and G. Pignatti, “Pushing Ceramic-on-Ceramic in the most extreme wear conditions: A hip simulator study,” *Orthop. Traumatol. Surg. Res.*, vol. 107, no. 1, 2021, doi: 10.1016/j.otsr.2020.05.003.

[21] V. Jangid, A. K. Singh, and A. Mishra, “Wear simulation of artificial hip joints: Effect of materials,” *Mater. Today Proc.*, vol. 18, pp. 3867–3875, 2019, doi: 10.1016/j.matpr.2019.07.326.

[22] W. D. Lestari, D. K. Nababan, R. Ismail, J. Jamari, and A. P. Bayuseno, “Dimensional Accuracy and Surface Roughness of Acetabular Liner with UHMWPE : Assessment Results between Compression Molding and CNC Milling,” *Int. Rev. Mech. Eng.*, vol. 12, no. June, pp. 516–521, 2018.

[23] D. Dowson and R. T. Harding, “The Wear Characteristics Of Ultrahigh Molecular Weight Polyethylene Against A High Density Alumina Ceramic Under Wet (Distilled Water) And Dry Conditions,” *Wear*, vol. 75, pp. 313–331, 1982.

[24] R. M. Trommer, M. M, Maru, W. L. O. Filho, V. P. S. Nykanen, C. P. Gouvea, B. S. Archanjo, E. H. M. Ferreira, R. F. Silva, C. A. Achete, “Multi-Scale Evaluation of Wear in UHMWPE-Metal Hip Implants Tested in a hip Joint Simulator,” *Biotribology*, vol. 4, pp. 1–11, 2015, doi: 10.1016/j.biotri.2015.08.001.

[25] L. Blunt, P. Bills, X. Jiang, C. Hardaker, and G. Chakrabarty, “The role of tribology and metrology in the latest development of bio-materials,” *Wear*, vol. 266, no. 3–4, pp. 424–431, 2009, doi: 10.1016/j.wear.2008.04.015.

[26] X. Hua, B. M. Wroblewski, Z. Jin, and L. Wang, “The effect of cup inclination and wear on the contact mechanics and cement fixation for ultra high molecular weight polyethylene total hip replacements,” *Med. Eng. Phys.*, vol. 34, no. 3, pp. 318–325, 2012, doi: 10.1016/j.medengphy.2011.07.026.

[27] A. L. L. Oliveira, R. G. Lima, E. G. Cueva, and R. D. Queiroz, “Comparative analysis of surface wear from total hip prostheses tested on a mechanical simulator according to standards ISO 14242-1 and ISO 14242-3,” *Wear*, vol. 271, no. 9–10, pp. 2340–2345, 2011, doi: 10.1016/j.wear.2011.01.062.

[28] M. S. Uddin, C. Y. E. Mak, and S. A. Callary, “Evaluating hip implant wear measurements by CMM technique,” *Wear*, vol. 364–365, pp. 193–200, 2016, doi: 10.1016/j.wear.2016.07.017.

[29] M. S. Uddin, “Wear Measurement and Assessment of Explanted Cross- Linked PE Acetabular Cups Using a CMM Wear Measurement and Assessment of Explanted Cross-Linked PE Acetabular Cups Using a CMM,” *Tribol. Trans.*, vol. 57 (5), no. July, pp. 37–41, 2014, doi: 10.1080/10402004.2014.911398.

[30] D. Dowson and B. Jobbins, “An evaluation of the penetration polyethylene acetabular cups,” *Wear*, vol. 164, pp. 162–164, 1993.

[31] A. Essner, G. Schmidig, and A. Wang, “The clinical relevance of hip joint simulator testing : In vitro and in vivo comparisons,” *Wear*, vol. 259, pp. 882–886, 2005, doi: 10.1016/j.wear.2005.02.105.

[32] C. Liu, S. M. Green, N. D. Watkins, P. J. Gregg, and A. W. Mccaskie, “A preliminary hip joint simulator study of the migration of a cemented femoral stem,” *Proch Inst Mech Eng H*, vol. 217, pp. 127–135, 2015.

[33] X. Roussignol, C. Siedlecki, F. Duparc, F. Dujardin, and M. Ould-slimane, “Do temperature variations at the bearing surface during gait affect polyethylene wear in Charnley low-friction arthroplasty of the hip ? Simulator study comparing UHMWPE and highly cross-linked polyethylene,” *Orthop. Traumatol. Surg. Res.*, vol. 102, no. 6, pp. 711–715, 2016, doi: 10.1016/j.otsr.2016.04.012.

[34] V. Saikko, “Adverse condition testing with hip simulators,” *Biotribology*, vol. 1–2, pp. 2–10, 2015, doi: 10.1016/j.biotri.2015.02.001.

[35] M. P. Gispert, A. P. Serro, R. Colac, and B. Saramago, “Friction and wear mechanisms in hip prosthesis : Comparison of joint materials behaviour in several lubricants,” *Wear*, vol. 260, pp. 149–158, 2006, doi: 10.1016/j.wear.2004.12.040.

[36] S. Affatato, B. Bordini, C. Fagnano, P. Taddei, A. Tinti, and A. Toni, “Effects of the sterilisation method on the wear of UHMWPE acetabular cups tested in a hip joint simulator,” vol. 23, pp. 1439–1446, 2002.

[37] 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,” *J. Biomimetics, Biomater. Tissue Eng.*, vol. 7, pp. 7–25, 2010, doi: 10.4028/www.scientific.net/JBBTE.7.7.

[38] C. R. Bragdon, D. O. Connor, J. D. Lowenstein, M. Jasty, and W. D. Syniuta, “The importance of multidirectional motion on the wear of polyethylene,” *Proc Instn Mech Engrs*, vol. 210, 1996.

[39] J. M. Kabo, J. S. Gebhard, G. Loren, H. C. Amstutz, “In vivo wear of polyethylene acetabular components,” *J. Bone. Jt. Surg.*, vol. 75-B (2), pp. 254–258, 1993.