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Title: EXPERIMENTAL COMPARISON ON TRIBOLOGICAL PAIRS UHMWPE/TIAL6V4 ALLOY, UHMWPE/AISI316L AUSTENITIC STAINLESS AND UHMWPE/AL2O3 CERAMIC, UNDER DRY AND LUBRICATED CONDITIONS

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Abstract: Friction and wear behaviour of ultra-high molecular weight polyethylene (UHMWPE) sliding against TiAl6V4 alloy, against AISI316L austenitic stainless steel and against Al2O3 ceramic under dry and lubricated conditions was investigated. Tests were conducted by using a reciprocating pin-on-flat tribometer with several applied normal loads. Lubricated sliding tests were carried out with a fluid containing a large amount of sodium hyaluronate. The worn surfaces of the UHMWPE were examined with a 3D confocal microscopy. The tribological performances of pairs UHMWPE/AISI316L, UHMWPE/TiAl6V4 and UHMWPE/Al2O3 were also investigated for the purpose of comparison. The results were interpreted on the basis of the evolution of the friction coefficient and worn surfaces in order to understand the acting wear mechanisms.



POLITÉCNICA

Madrid, November 16, 2015

Editor-in-Chief  
Tribology International, Elsevier

Dear Mr. Fillon:

Enclosed for your consideration is our original research paper:

*"EXPERIMENTAL COMPARISON ON TRIBOLOGICAL PAIRS UHMWPE/TIAL6V4 ALLOY, UHMWPE/AISI316L AUSTENITIC STAINLESS AND UHMWPE/AL2O3 CERAMIC, UNDER DRY AND LUBRICATED CONDITIONS"*

By Prof. Alessandro Ruggiero, Dr. Roberto D'Amato, Prof. Emilio Gómez, Massimiliano Merola.

We confirm that all authors were fully involved in the study and preparation of the manuscript.

The content of this manuscript have not been copyrighted or published previously, nor is now under consideration for publication elsewhere.

Linked with our former and ongoing research, in this paper we compare the tribological behaviour of the UHMWPE (GUR 1050) against AISI 316L austenitic stainless steel, against TiAl6V4 alloy and against Al<sub>2</sub>O<sub>3</sub>. The tests were carried out by using a reciprocating biotribometer in dry and lubricated conditions. The friction coefficient was measured with several loads to investigate on the tribological behaviour of the couplings.

The proposed methodology and calculation possibilities are foreseen as a potential contribution to studies of the biomechanical properties of the materials in relationship with lubrication failure in total joint replacements.

We thank you in advance for the attention paid to our paper which would hopefully be of interest to the readers of the Tribology International.

Yours sincerely,

Dr. Eng. Roberto D'Amato

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## Statement of Originality

Linked with our former though still ongoing research, in this paper we compare the tribological behaviour of the UHMWPE (GUR 1050) against AISI 316L austenitic stainless steel, against TiAl6V4 alloy and against Al<sub>2</sub>O<sub>3</sub>. The tests were carried out by using a reciprocating biotribometer in dry and lubricated conditions. The friction coefficient was measured with several loads and several frequencies to investigate on the tribological behaviour of the couplings. The worn surfaces of the UHMWPE were examined with a 3D confocal microscopy. The tribological performances of pairs UHMWPE/AISI316L, UHMWPE/TiAl6V4 and UHMWPE/Al<sub>2</sub>O<sub>3</sub> ceramic were also investigated for the purpose of comparison. The results were interpreted on the basis of the evolution of the friction coefficient and worn surfaces in order to understand the acting wear mechanisms. The novelty of the proposed methodology and calculation possibilities resides in a contribution to studies of the biomechanical properties of the materials in relationship with lubrication failure in total joint replacements by also testing a lubricant coming from a drug which has been already used in orthopedics

## Highlights

- Experimental analysis of tribological behaviour of UHMWPE against TIAL6V4 Alloy;
- Experimental analysis of tribological UHMWPE behaviour against AISI316L AUSTENITIC STAINLESS;
- Experimental analysis of tribological behaviour of UHMWPE against AL<sub>2</sub>O<sub>3</sub> CERAMIC;
- We used a reciprocating bio-tribometer in dry and lubricated conditions (Hyalgan®);
- The friction coefficient and the wear were measured;
- 3D Optical System Leica DCM 3D for analysis of UHMWPE worn surface specimens.

Reviewer #2: This paper deals with analysis of a sliding contact which aims to simulate the conditions in the human joint with the purposes to clarify the tribological properties, under dry and lubricated condition, of UHMWPE sliding faces against AISI316L austenitic stainless steel, against TiAl6V4 alloy and against Alumina (Al<sub>2</sub>O<sub>3</sub>) by using a pin-on-flat reciprocating tribometer. The manuscript is well written and structured and the experimental activity is significant and original especially for the use of the lubricating fluid; however, in order for this paper to be published in Tribology International the following points should be addressed:

- Highlights are not in accordance with the requirements of the Journal. Recommend changes.
- In the page 4/22, section 2.1, lines 29-32 "...cut into pieces of 12.200 mg... and 11,900 mg for the sample B." the quantities should have the same format. They should be "...12,200mg..." and "...11,900 mg..."
- In page 6/22, section 2, line 16 "From the table 1 ..." should be "From the Table 1...". Please check carefully the whole manuscript.
- When referring to the figures, in the manuscript, always use the same format to indicate them. Use Fig. x and Figs. x-y. Please check carefully the whole manuscript.
- Figure 8 should be the same colour as the figure 9 and 10.
- In the Figures 12a and 12b it is not possible to read the first values of the time axis.
- The final conclusion was too lengthy to summarize this paper. Recommend change the title of the section 4 in Discussion and Conclusion.

### **Answers**

Authors: The authors gratefully acknowledge the comments and suggestions of the reviewer. In response to these comments, we have made changes, improvements and clarifications that are outlined below:

- 1) We have changed the Highlights: the sentences have been written within the word count in accordance with the requirements of the Journal.
- 2) We checked and corrected the lines indicated by the Reviewer.
- 3) We checked and corrected the lines indicated by the Reviewer and the whole manuscript.
- 4) We checked and corrected the whole manuscript as requested by the Reviewer.
- 5) The choice of colours has turned out to be necessary for a better understanding of Figure 11. In fact, the latter shows the average values of the friction coefficient for each kind of materials under lubricated conditions for samples A and B.
- 6) We have bettered the Figures indicated by the Reviewer.
- 7) We changed the title of the section 4 as requested by the Reviewer.

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# EXPERIMENTAL COMPARISON ON TRIBOLOGICAL PAIRS UHMWPE/TIAL6V4 ALLOY, UHMWPE/AISI316L AUSTENITIC STAINLESS AND UHMWPE/AL<sub>2</sub>O<sub>3</sub> CERAMIC, UNDER DRY AND LUBRICATED CONDITIONS

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## Abstract

Friction and wear behaviour of ultra-high molecular weight polyethylene (UHMWPE) sliding against TiAl6V4 alloy, against AISI316L austenitic stainless steel and against Al<sub>2</sub>O<sub>3</sub> ceramic under dry and lubricated conditions was investigated. Tests were conducted by using a reciprocating pin-on-flat tribometer with several applied normal loads. Lubricated sliding tests were carried out with a fluid containing a large amount of sodium hyaluronate. The worn surfaces of the UHMWPE were examined with a 3D confocal microscopy. The tribological performances of pairs UHMWPE/AISI316L, UHMWPE/TiAl6V4 and UHMWPE/Al<sub>2</sub>O<sub>3</sub> were also investigated for the purpose of comparison. The results were interpreted on the basis of the evolution of the friction coefficient and worn surfaces in order to understand the acting wear mechanisms.

**Key Words:** Friction; Wear; dry; lubricated; reciprocating tribometer; artificial joints; UHMWPE; TiAl6V4; Al<sub>2</sub>O<sub>3</sub>, AISI316L

## 1. Introduction

Due to its several excellent properties, Ultrahigh Molecular Weight Polyethylene (UHMWPE) has been used as a bearing material for total joint replacement for over 60 yrs. Since 1962, when it was introduced to replace polytetrafluoroethylene (PTFE) for its biocompatibility, low friction and high wear resistance, it is the material of choice for total joint arthroplasty bearings [1], mostly implanted in the hip and the knee of a human body [2,3]. As the service life of artificial joints prolongs, the lubrication mechanisms in the normal human joints and the problems of friction and wear in the prosthesis have been addressed by many authors [4–9] due to its importance in the performance of these devices. Currently, the hip and the knee joints surgical implants undergo degradation after 10–15 years of use [10]. The mechanical resistance, friction

1 and wear are not the only properties to be considered as for chosen materials regarding  
2 the head and the cup of the prosthesis but also biocompatibility and corrosion  
3 resistance. Therefore, it is inevitable to improve the above mentioned properties by  
4 combining in the best way the UHMWPE for the cup Total Hip Replacements (THR)  
5 and for the tibial bearings Total Knee Replacements (TKR) and alumina, stainless steel  
6 or titanium alloy for the head in the hip implants and for femoral condylar components  
7 in TKR [11]. Another very important aspect to consider for improving the lubrication of  
8 the prosthesis is the choice of a proper lubricant fluid that simulates the behavior of the  
9 joints in vivo [12]. Several studies reveal that the effects on friction and wear of the  
10 various components of the synovial fluid (SF) depend on the presence of Hyaluronic  
11 Acid (HA) and Albumin. In fact, the HA is responsible for the high value of viscosity  
12 and albumin enhances the boundary lubrication of the joint [13-15]. Accordingly,  
13 purposes of this study are to clarify the tribological properties, under dry and lubricated  
14 condition, of UHMWPE sliding faces against AISI316L austenitic stainless steel,  
15 against TiAl6V4 alloy and against Alumina ( $Al_2O_3$ ) by using a pin-on-flat reciprocatory  
16 DUCOM tribometer [16-18]. In the case of lubricated conditions a biological model  
17 fluid has been used: sodium hyaluronate (Hyalgan®). In order to measure the friction  
18 coefficient and the wear several load conditions and several frequencies conditions have  
19 been simulated to investigate on the tribological behaviour of the above mentioned  
20 couplings. The worn surface of the UHMWPE specimens was analyzed by a 3D Optical  
21 Surface Metrology System Leica DCM 3D, which provided three-dimensional scans of  
22 the tribometer tracks on UHMWPE surfaces.

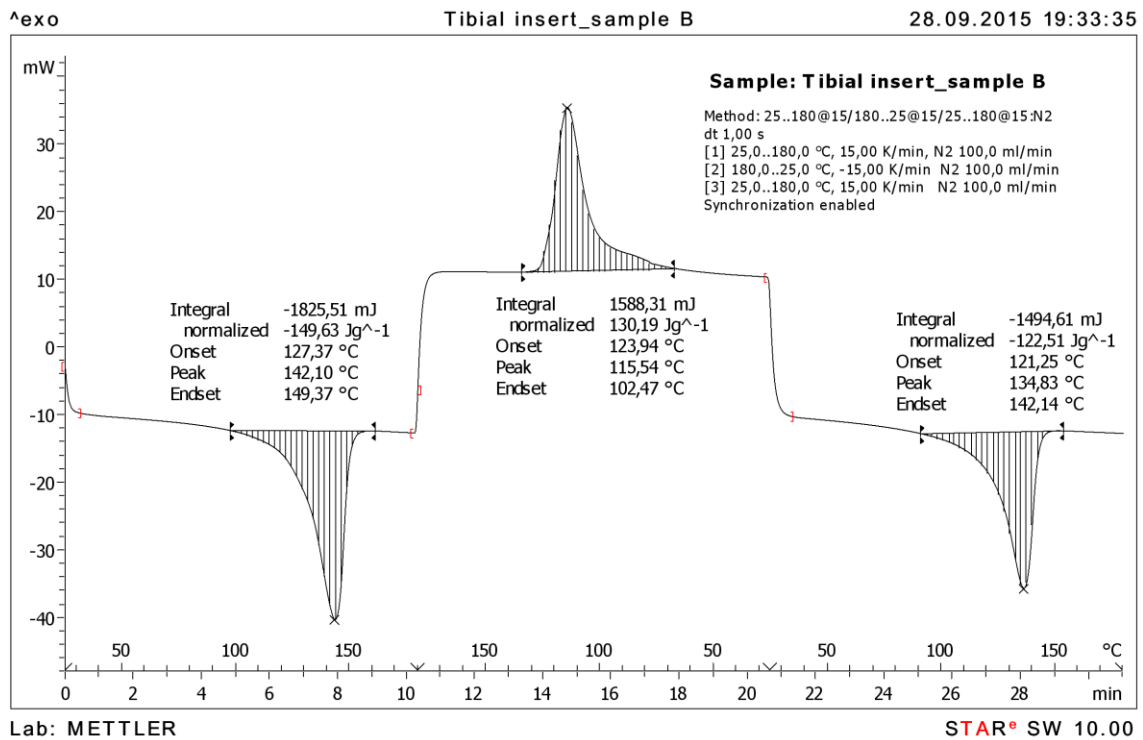
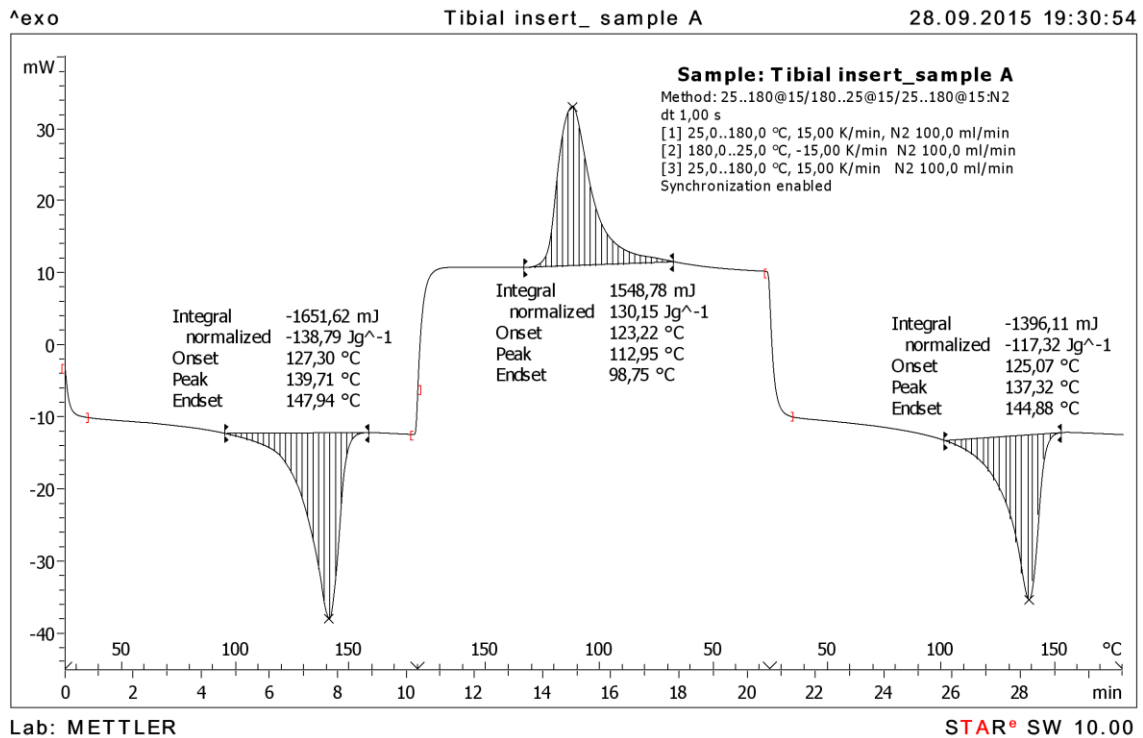
## 2. Material and methods

## 2.1. Materials

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2 TR\_Bio 282 pin-on-flat reciprocatory DUCOM tribometer was used to measure the  
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4 friction and wear properties of three following coupling materials: UHMWPE (GUR  
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6 1050) against AISI316L austenitic stainless steel, UHMWPE (GUR 1050) against  
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8 TiAl6V4 alloy and UHMWPE (GUR 1050) against Alumina ( $\text{Al}_2\text{O}_3$ -99.5%). The main  
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10 mechanical properties of the materials are shown in Tables 1 and 2.  
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14 Polyethylene has been cut and polished from two different tibial inserts in square-  
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16 shaped  $10 \times 10 \times 5 \text{ mm}^3$ . Calorimetric studies on both tibial inserts of two different  
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18 prostheses have been conducted to make sure we were in the presence of UHMWPE of  
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20 some characteristics. The differential scanning calorimetry (DSC) measurements were  
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22 carried out using a DSC-823<sup>e</sup> METTLER-Toledo of the Polymer Technology Lab at the  
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24 ETSIDI –Technical University of Madrid.  
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29 Both samples for the DSC analysis have been cut into pieces of 12,200 mg for the  
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31 specimen A and 11,900 mg for the sample B. All the dynamic scans were registered  
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33 between 25 and 180 °C (heating), 180-25°C (cooling) to eliminate thermal histories and  
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35 between 25-180°C (heating) for the analysis (Fig.1) [19, 20].  
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Figure 1: Differential scanning calorimetry DSC-823<sup>o</sup> METTLER-Toledo

The melting point ( $T_m$ ) was measured as the maximum temperature of the endotherm in a dynamic scan. The degree of crystallinity,  $X_c(\%)$ , of the UHMWPE was also calculated as the area under the endotherm ( $\Delta H$ ) divided by the enthalpy of fusion of a 100% crystalline ( $\Delta H_{100\%}$ ) UHMWPE, which was taken to be 293,6J/g [21]:

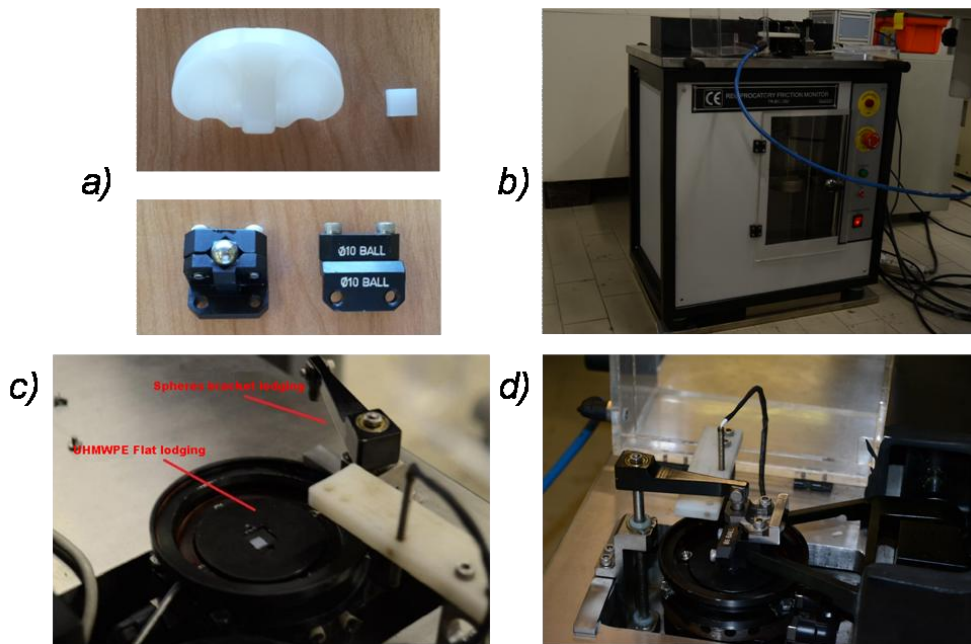
$$X_c(\%) = \frac{\Delta H}{\Delta H_{100}} * 100 \quad (1)$$

The melting point and the crystallinity of both samples are reported in Table 2.

**Tab. 1: The properties, melting point and crystallinity of both UHMWPE samples**

UHMWPE Sample	Young's Modulus [GPa]	Poisson's ratio	Hardness D scale	Melting point [°C]	Crystallinity (%)
A	0.69	0.46	48	137,32	39,96
B				134,83	41,72

From the Table 1 it is possible to note that the values of the obtained melting temperature in DSC test result to be just like those related to UHMWPE [22]. The austenitic stainless steel AISI 316L pin and Al<sub>2</sub>O<sub>3</sub> pin were sphere-shaped with a diameters of 3 mm, 6 mm and 10mm while for the TiAl6V4 alloy pin was sphere-shaped with a diameters of 3 mm and 6 mm. Fig. 2 shows: a) Polyethylene cuts from a tibial insert in square-shaped and an example of the assembly schema spheres of steel in its bracket, b) TR\_Bio 282 pin-on-flat reciprocatory DUCOM tribometer of the Applied Mechanics Lab of the Department of Industrial Engineering –University of Salerno- , c) and d) the assembly of the pin on flat in the tribometer.



**Figure 2: a) Polyethylene cuts from a tibial insert and an example of the assembly schema spheres of steel in its bracket, b) TR\_Bio 282 pin-on-flat reciprocatory DUCOM tribometer, c) and d) the assembly of the pin and flat in the tribometer.**

1 A pharmaceutical fluid, similar in consistency and in the properties to normal synovial  
2 fluid, called Hyalgan® was chosen for the test in lubricated conditions. This one  
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4 contains a large amount of sodium hyaluronate and it is used as intra articular injection  
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6 in arthritic joints induces a normalization of the viscoelasticity of the synovial fluid and  
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8 an activation of tissue repair processes at the level of the articular cartilage [3, 23].  
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## 10 11 12 13 *2.2 Tribological tests*

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15 Reciprocatory pin-on-flat friction tests have been carried out at controlled room  
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17 temperature and humidity (T=20°C and H=55±5%). The parameters of the test that must  
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19 be set are: frequency, time and load. In fact, the tribometer can apply a contact loads  
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21 from 1 N to 20 N and it can operate within a wide range of frequencies from 5 Hz to 60  
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23 Hz. In this study, the selected frequency is 10 Hz in order to avoid vibrations of the  
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25 plate and undesirable vertical motions, the chosen time is 120 minutes and the stroke  
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27 used is 2 mm. With regard to the choice of the load to apply to the tribometer, we must  
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29 keep in mind that the materials selected for testing come from knee prosthesis. Cerniglia  
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31 at al. [23] in their study calculate that the contact force between the tibia and femur,  
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33 during walking, is equal to three times the weight of the human body. By considering  
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35 the human body weight  $P = 70\text{kg}$ , the calculated normal load will be about 2000N. In  
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37 another experimental study, L. Zach et al. [25] calculate, through a FEM analysis and  
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39 the using of Pressure Sensitive Film, contact area between two given bone elements for  
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41 several loading forces. In our case, a load of 2000N corresponds to a value in the  
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43 contact area equal to  $75,8\text{ mm}^2$  [25]. Contact pressure to be used in order to calculate  
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45 normal loads for different pins' diameters to be employed in tribological test will be  
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$$p = \frac{2000[N]}{75.8[mm^2]} = 27MPa$$
. Therefore, by using the Hertz's contact theory [3] it is  
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58 possible to calculate the applied normal load for each kind of materials and for each  
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1 kind of sphere diameters. By using Hertz theory in general, the error for small  
2 curvatures (conforming contact) is notable because of the Hertz assumption that the  
3 contact area is small with respect to component dimensions. The error for  
4 nonconforming contact (our case) is due to the nonlinear behavior of the UHMWPE. In  
5 agreement with what has been so far stated, where it occurs, seems to be due to a  
6 coincidental combination of the two effects (conformity and nonlinear material  
7 behavior). Therefore, the Hertz theory is generally not applicable for the study of  
8 polyethylene stresses. In our case, the main purpose of the use of Hertz theory is the  
9 assessment (not the calculation of one exact value) of a typical value of the normal load  
10 to be applied to the investigated tribo-system by taking into account that in typical  
11 prosthetic contacts the contact pressure is largely variable: i.e a Total Knee Arthroplasty-  
12 FEM analysis showed that the contact pressure varies between values of few MPa to  
13 more than 30 Mpa [26] and the calculation of the contact stress during testing, based on  
14 Hertzian ball-on-flat contact mechanics, could be accurate in many cases [27]. As the  
15 tribometer provides an implementation system of the applied load with a minimum  
16 weight of 0.5 kg, the calculated values for the applied normal loads in the tests were  
17 approximated as shown in Table 2.

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41 **Tab. 2: The properties, the Diameter Spheres and Normal load for each kind of materials**

Pin Materials	Young's Modulus [GPa]	Poisson's ratio	Hardness [HCR] *[Kg/mm <sup>2</sup> ]	Diameter Spheres [mm]	Calculated Normal Load [N]	Applied Normal Load [N]
<b>TiAl6V4</b>	114	0.34	28-42	3	1.006	1
				6	4.019	4
<b>AISI316L</b>	193	0.27	25-39	3	1.021	1
				6	4.055	4
				10	11.231	11
<b>Al<sub>2</sub>O<sub>3</sub></b>	370	0.22	1440*	3	1.011	1
				6	4.037	4
				10	11.181	11

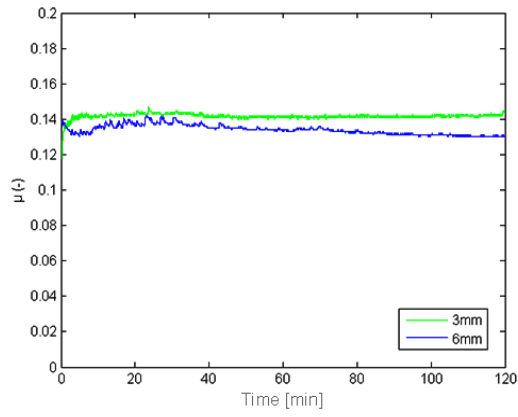
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As regards the evaluation of wear mass loss, it has not been possible to evaluate it with gravimetric methods because the available precision balance has an accuracy of 0.1mg whereas the results are approximately of  $10^{-5}$ g for the tests under dry conditions. Therefore, with the purpose of comparing the wear rates of the three tribological pairs under study, the worn surfaces of the UHMWPE specimens, after the tests, were analyzed by 3D Optical Surface Metrology System Leica DCM 3D (Fig.7) of the LIMIT Lab at the ETSIDI –Technical University of Madrid, only in the case in which the pins' diameter was of 6mm. By knowing the density of UHMWPE ( $0.93\text{g/cm}^3$ ) [22], it was possible to estimate the wear mass loss by measuring the groove volume left by the pin on the specimens during the tests. For the tests carried out under lubricated conditions it was no possible to evaluate the wear mass loss for, as it will be detailed in results section later on, most of tests have lead to the breaking of the lubricant fluid film on both the UHMWPE samples (A and B)

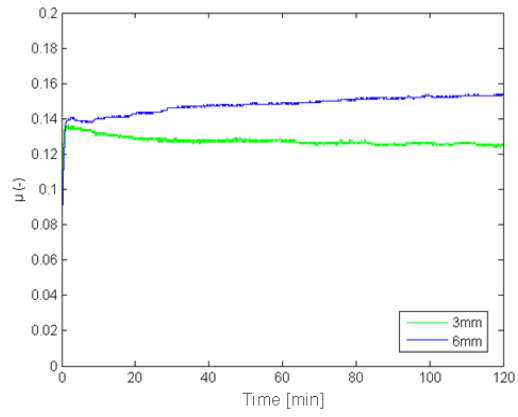
### 3. Results

#### 3.1. Tribological test under dry conditions

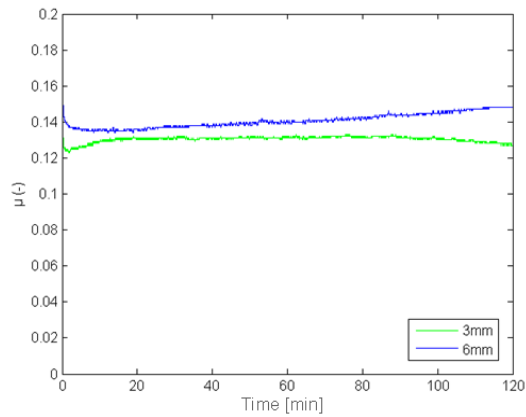
The Figs. 3, 4 and 5 show the evolution of the friction coefficients during the test under dry condition in the TiAl6V4-UHMWPE, AISI316L-UHMWPE and  $\text{Al}_2\text{O}_3$ - UHMWPE respectively.



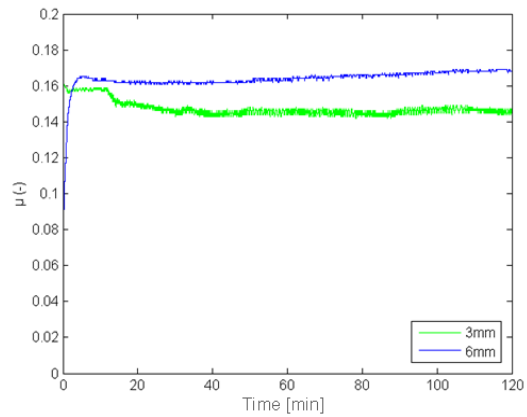
Diameter [mm]	$\mu$	STD	$\mu_r$	STDr
3	0.141	0.0037	0.142	0.0035
6	0.133	0.0039	0.134	0.0028



Diameter [mm]	$\mu$	STD	$\mu_r$	STDr
3	0.127	0.0042	0.127	0.00098
6	0.147	0.0065	0.149	0.0028



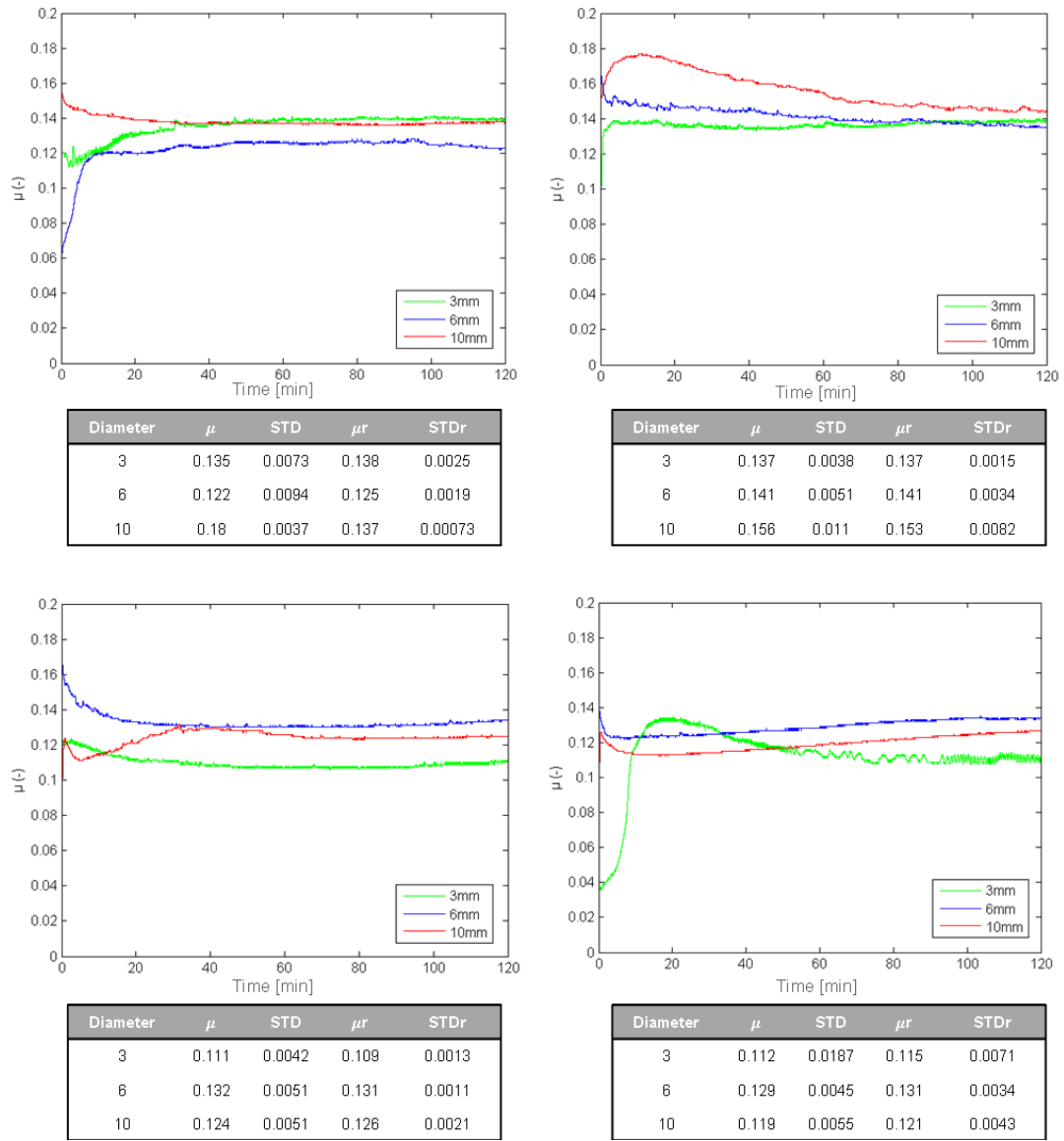
Diameter [mm]	$\mu$	STD	$\mu_r$	STDr
3	0.129	0.0028	0.131	0.0011
6	0.139	0.0047	0.142	0.0035



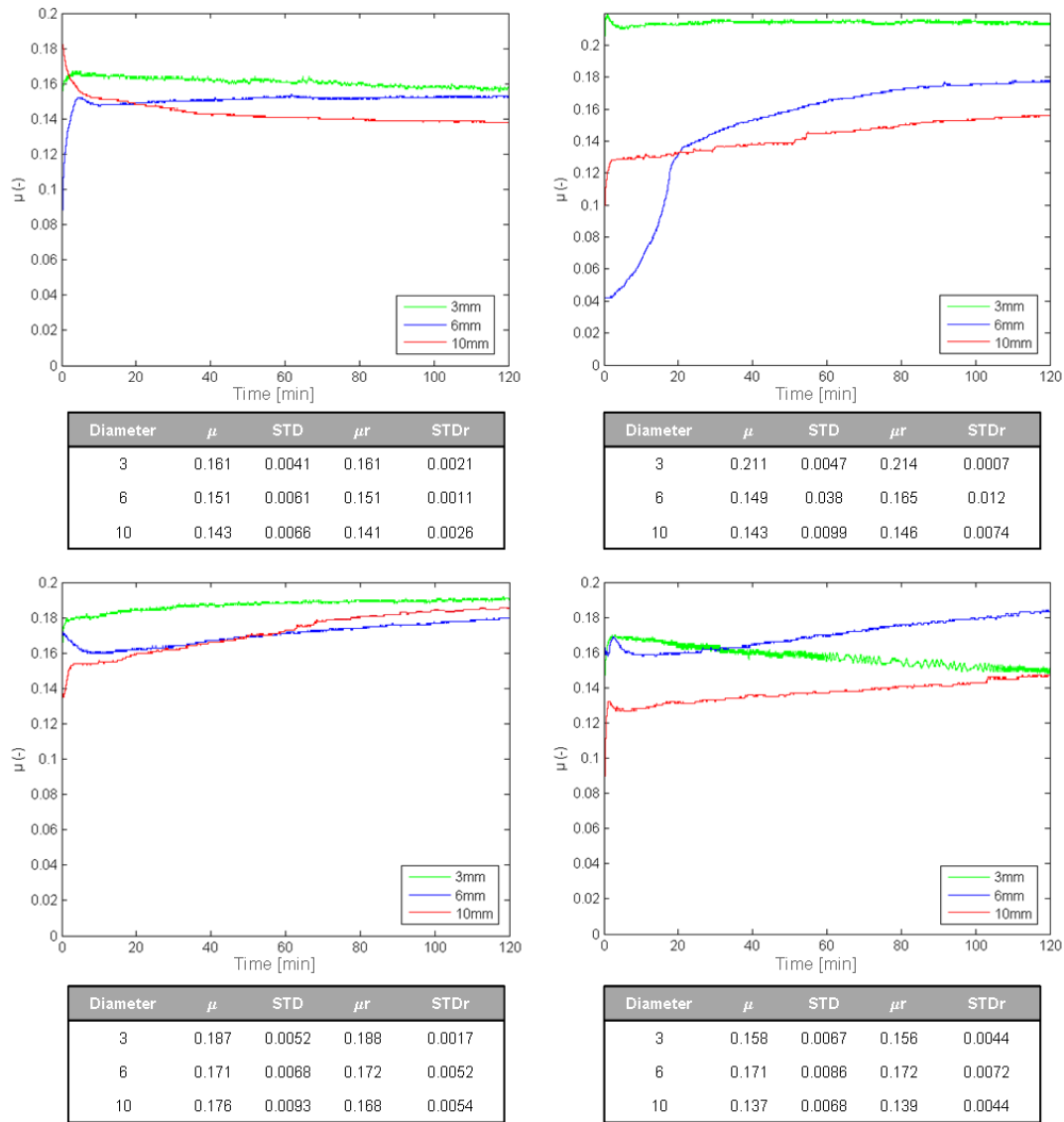
Diameter [mm]	$\mu$	STD	$\mu_r$	STDr
3	0.147	0.0048	0.146	0.0015
6	0.164	0.0067	0.165	0.0024

**Figure 3:** The evolution of the friction coefficient under dry conditions in: a) TiAl6V4-UHMWPE sample "A" contact, b) TiAl6V4-UHMWPE sample "B" contact

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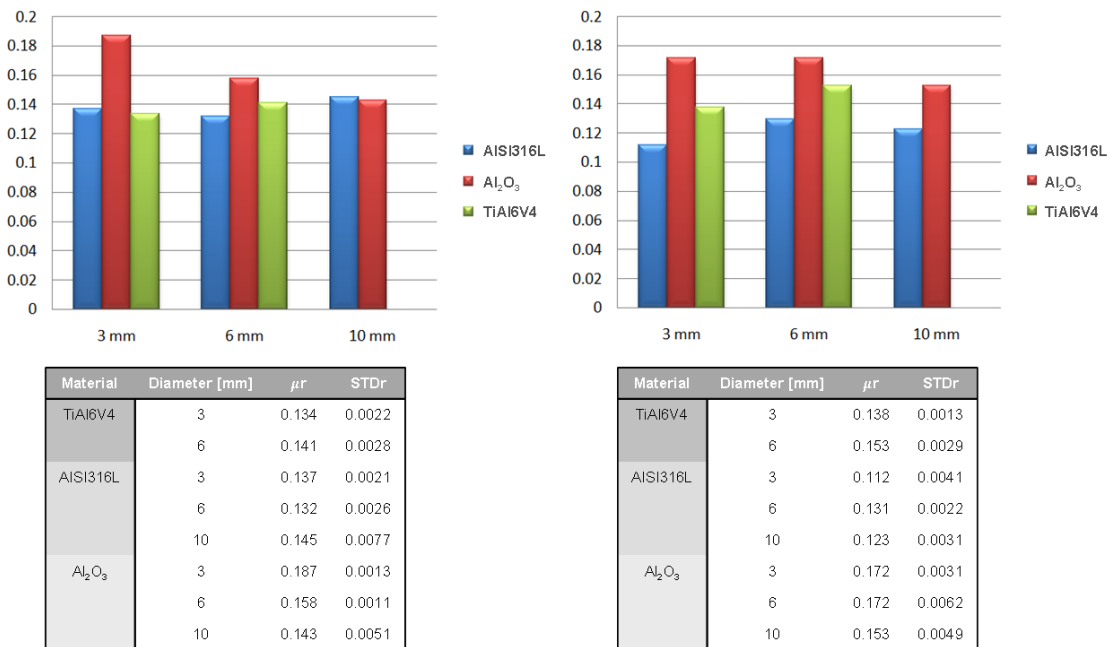
**Figure 4:** The evolution of the friction coefficient under dry conditions in: a) AISI316L -UHMWPE sample “A” contact, b) AISI316L -UHMWPE sample “B” contact



**Figure 5:** The evolution of the friction coefficient under dry conditions in: a) Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample "A" contact, b) Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample "B" contact

There are two pairs of graphs for each figure. The first one is for the rubbing contact against UHMWPE sample "A" for two tests under same working conditions (Fig.3a, 4a, 5a), and the second one for the rubbing contact against UHMWPE sample "B" for two tests under same working conditions (Fig 3b, 4b, 5b). Under each graphs a summary of the results for the mean values of the friction coefficient and their standard deviation in continuous ( $\mu$ ,  $STD$ ) and after the initial transient (first 20 minutes) is shown ( $\mu_r$ ,  $STD_r$ ). It can be seen that the friction coefficients of all rubbing pairs were low at the initial stage, but rapidly increased and stabilized with time sliding (Fig. 3, 4, 5). No immediate

1 correlation can be identified between the pins' diameters (loads) and the friction  
 2 coefficients. It is to be noted that the fluctuations observed in the dry test are  
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 4 accentuated during the first 20 minutes of the test. The earlier cited issue thus implies  
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 6 morphological changes in the contact between the matching materials. Accordingly, the  
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 8 energy of the friction forces and their work prove to be crucial under dry conditions.  
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 10 Consequently, all pins and the UHMWPE flat will be worn by the friction forces thus  
 11  
 12 causing overheating. Such a process along with local overstressing simultaneously  
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 14 generates geometric and chemical modifications on the three pins and on the UHMWPE  
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 16 flat during sliding. As for the above mentioned changes further study is needed. Figs.  
 17  
 18 6a and 6b show the histogram of the friction coefficients in all rubbing pairs for the  
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 20 UHMWPE sample "A" and for UHMWPE sample "B" respectively. It is possible to  
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 22 note that in each test, the maximum value of the friction coefficient corresponds to the  
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 24 couple  $\text{Al}_2\text{O}_3$ -UHMWPE.  
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**Fig. 6:** Average values of the friction coefficient for each kind of materials under dry conditions in contact with: a) UHMWPE sample "A", b) UHMWPE sample "B"

This effect is probably due to its high hardness and its wear resistance properties [28, 29]. Fig. 7 shows the qualitative analysis of the UHMWPE surfaces (samples A) after

the test under dry conditions for pins' diameter of 6mm in the case of materials of pins were: a) TiAl6V4; b) AISI316L; c) Al<sub>2</sub>O<sub>3</sub>. After a metrological characterization of the worn surfaces during the tribological tests, it was possible to calculate the groove volume left by the pin on the UHMWPE samples. The several deformation processes associated with different micro-structural characteristics and the different hardness of the pin material are partially grounds for the diverse values of the wear mass loss and for diverse shapes of worn surfaces. Evidences of abrasion wear can be found on the worn surfaces of the tested specimens. Table 3 shows the results for the wear mass loss for each kind of tribological couple. The penetration depth relies on the relative hardness of the flat specimen surface with respect to the hardness of the pin abrasive.

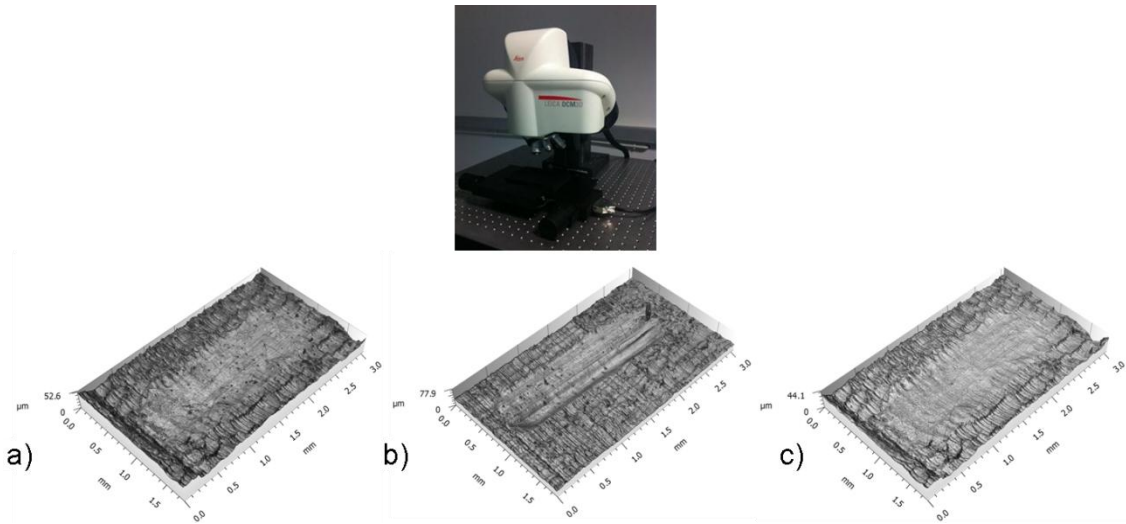


Fig. 7: 3D Optical Surface Metrology System Leica DCM 3D and qualitative analysis of the UHMWPE (samples A) surfaces after the test under dry conditions for pins' diameter of 6mm in the case of: a) TiAl6V4; b) AISI316L; c) Al<sub>2</sub>O<sub>3</sub>.

Tab. 3: The wear mass loss in the test under dry conditions for pins' diameter of 6mm in UHMWPE samples A

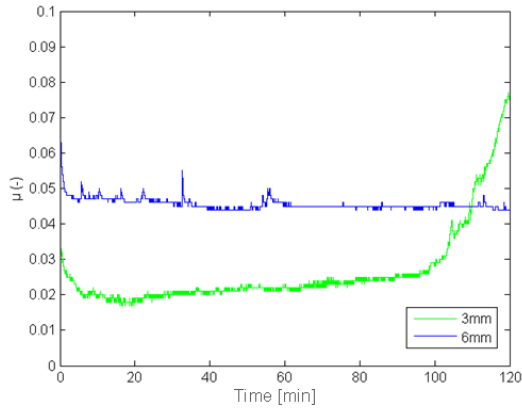
Tribological Pair	Groove Volume [mm <sup>3</sup> ]	Wear mass loss [g]
TiAl6V4-UHMWPE	0.79*10 <sup>-2</sup>	0.74*10 <sup>-5</sup>
AISI316-UHMWPE	0.61*10 <sup>-2</sup>	0.57*10 <sup>-5</sup>
Al <sub>2</sub> O <sub>3</sub> -UHMWPE	1.02*10 <sup>-2</sup>	0.95*10 <sup>-5</sup>

From the analysis of results, congruence between the value of the wear mass loss and the friction coefficient can be easily inferred. In fact, for the pins' diameter of 6 mm, a

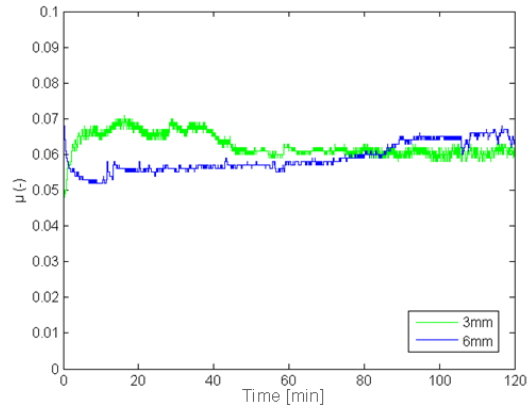
1 maximum value of the friction coefficient (Fig 6a) corresponds to a maximum value of  
2 the wear mass loss (Tab.3) followed by TiAl6V4 and ultimately by AISI316. Through  
3 the observing of the UHMWPE worn surfaces samples in all rubbing pairs, plastic  
4 deformations producing grooves aligned with sliding direction were found. These  
5 phenomena are due to adhesive wear mechanisms.  
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### 11 12 13 *3.4. Tribological test under lubricated conditions* 14 15

16 Figs. 8, 9 and 10 show the evolution of the friction coefficients during the test under  
17 lubricated conditions in the contacts AISI316L-UHMWPE, TiAl6V4-UHMWPE and  
18 Al<sub>2</sub>O<sub>3</sub>-UHMWPE respectively. The introduction of the lubricating fluid tends to  
19 decrease the values of the friction coefficient. In contrast to the dry tests, the graphs  
20 show that the phase of initial transient expires after 10 minutes after which it remains  
21 for a time that varies depending on the conditions of each test. Only in two tests, the  
22 friction coefficients remain stable after the initial transient for all pins' diameter:  
23 TiAl6V4-UHMWPE sample "B" (Fig. 8b) and Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample "B". In the  
24 contacts TiAl6V4-UHMWPE sample "A" (Fig. 8a), AISI316L -UHMWPE (Fig. 9a,  
25 9b) and in Al<sub>2</sub>O<sub>3</sub> -UHMWPE sample "A" (Fig.10a) the lubricant meatus breakage  
26 occurs by causing an increase of the value of the coefficient of friction for the pins'  
27 diameters: 3mm, 6mm and 10mm respectively. Notably, such a phenomenon occurs  
28 because of the viscosity of the lubricant which, if added to a combination of applied  
29 loads and set speeds, might cause distinct and several lubrication mechanisms such as  
30 boundary or transient lubrication. Consequently, such a critical inquiry needs future  
31 experimental developments.  
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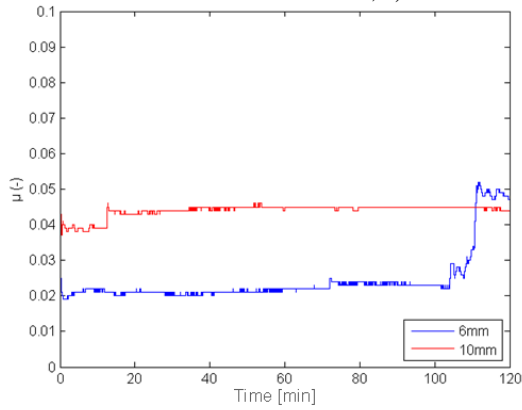


Diameter	$\mu$	STD	$\mu_r$	STD <sub>r</sub>
3	0.266	0.0117	0.0221	0.0023
6	0.485	0.0017	0.0454	0.0011

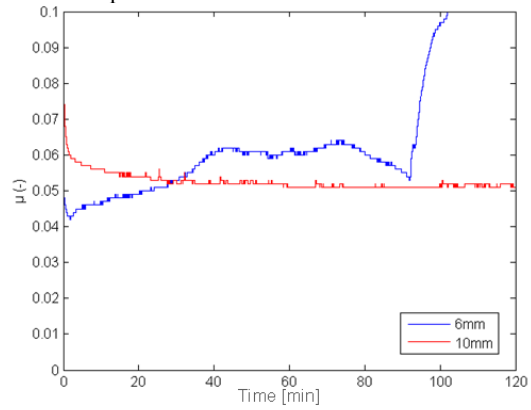


Diameter	$\mu$	STD	$\mu_r$	STD <sub>r</sub>
3	0.0625	0.0036	0.0626	0.0031
6	0.0589	0.0041	0.0593	0.0038

**Figure 8:** The evolution of the friction coefficient under lubricated conditions in: a) TiAl6V4-UHMWPE sample "A" contact, b) TiAl6V4-UHMWPE sample "B" contact

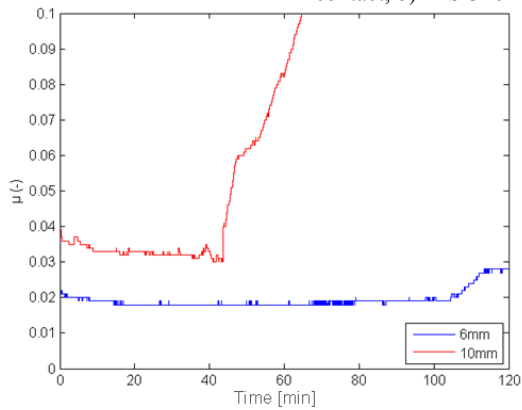


Diameter	$\mu$	STD	$\mu_r$	STD <sub>r</sub>
6	0.0241	0.0074	0.0218	0.0012
10	0.0441	0.0019	0.0441	0.0011

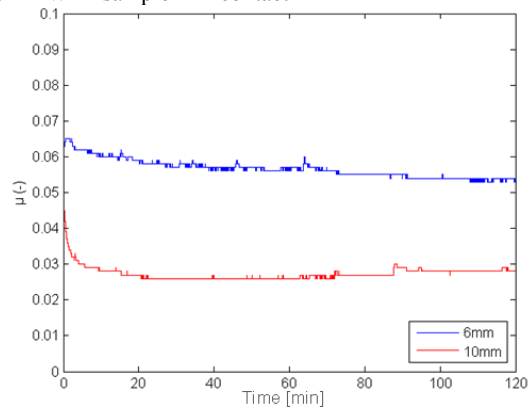


Diameter	$\mu$	STD	$\mu_r$	STD <sub>r</sub>
6	0.0586	0.029	0.0574	0.0051
10	0.0527	0.0024	0.0521	0.0011

**Figure 9:** The evolution of the friction coefficient under lubricated conditions in: a) AISI316L-UHMWPE sample "A" contact, b) AISI316L-UHMWPE sample "B" contact



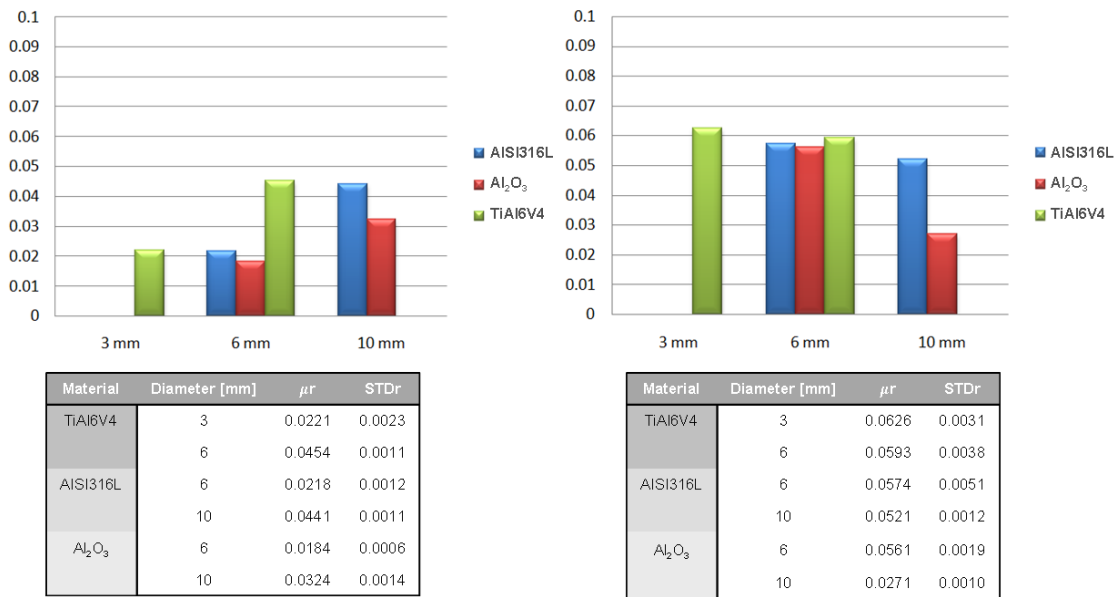
Diameter	$\mu$	STD	$\mu_r$	STD <sub>r</sub>
6	0.0193	0.0026	0.0184	0.0006
10	0.0326	0.039	0.0324	0.0014



Diameter	$\mu$	STD	$\mu_r$	STD <sub>r</sub>
6	0.0586	0.0027	0.0561	0.0019
10	0.0273	0.0019	0.0271	0.0010

**Figure 10:** The evolution of the friction coefficient under lubricated conditions in: a) Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample "A" contact, b) Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample "B" contact

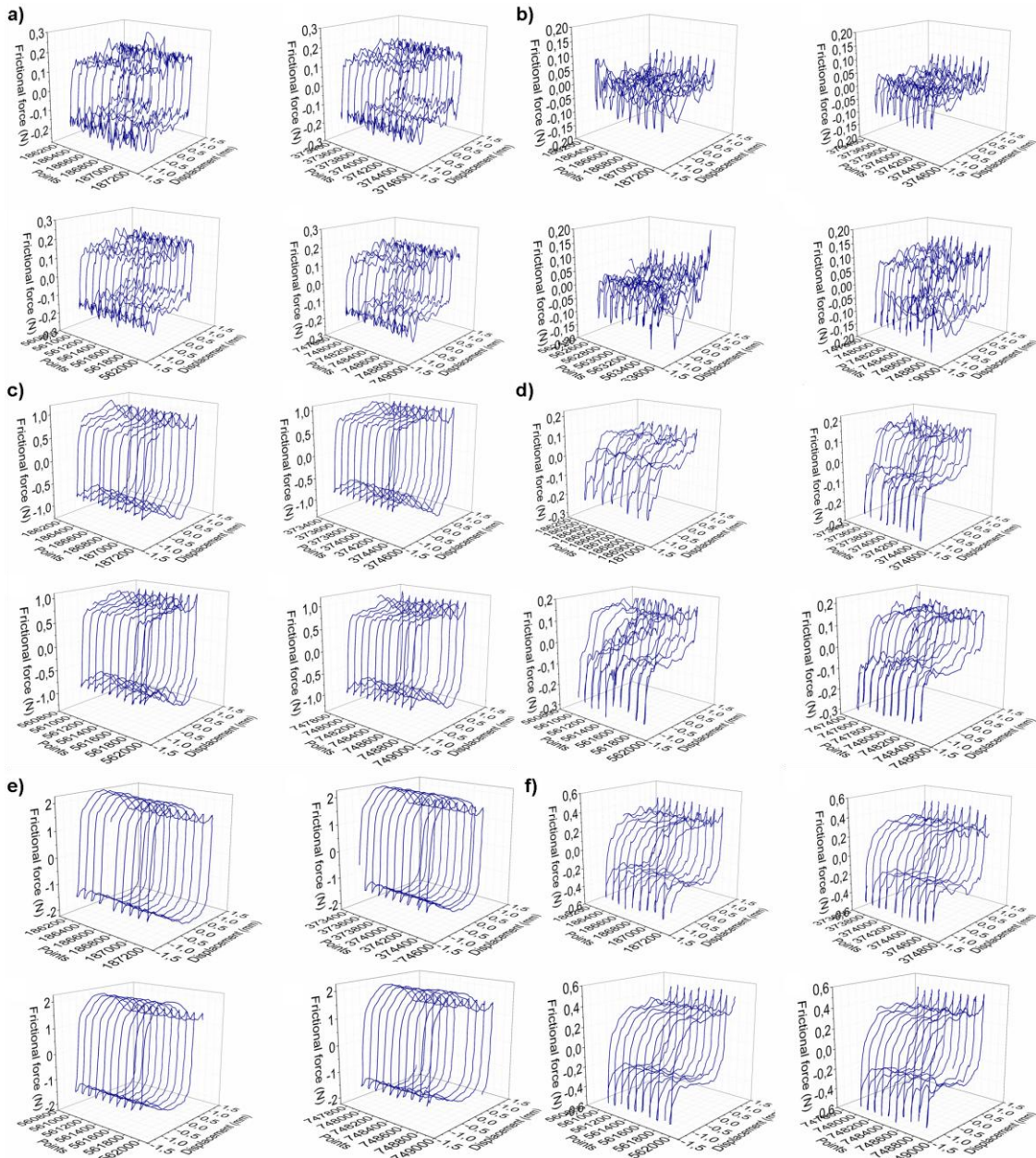
For this reason, the average values of the friction coefficient and its standard deviation in steady operation, shown in the histograms of Fig. 11, were calculated between 10 and 110 minutes in the contact TiAl6V4-UHMWPE sample “A” with a pin diameter of 3mm (Fig 8a). In the contact AISI316L-UHMWPE sample “A” with a pin diameter of 6mm (Fig 9a) the friction coefficient and its standard deviation in steady operation were calculated between 10 and 105 minutes, whereas they were evaluated between 10 and 90 minutes in the contact AISI316L-UHMWPE sample “B” with a pin diameter of 6mm (Fig 9b). Ultimately, the friction coefficient and its standard deviation in steady operation were estimated between 10 and 40 minutes in the contact Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample “A” with a pin diameter of 10mm (Fig 10a) and between 10 and 110 minutes in the contact Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample “A” with a pin diameter of 6mm (Fig 10b).



**Fig. 11:** Average values of the friction coefficient for each kind of materials under lubricated conditions in contact with: a) UHMWPE sample “A”, b) UHMWPE sample “B”

Figures 12, 13 and 14 show the evolution of the friction forces in the rubbing pairs under study with respect to the test cycles (about 1000) and the displacements for 4 time intervals of the test: initial, intermediate x2 and final. These images provide information on the gait of the force and on the transition between the static and the kinetic phases. During the inversion of the harmonic motion the ball is temporary still, which leads to

force peaks corresponding to the static friction phase. The force rapidly decreases and becomes almost constant during the sliding period, leading to the kinetic friction. Figures 12(a, c and e) are related to the tests under dry conditions for TiAl6V4-UHMWPE, AISI316L-UHMWPE and Al<sub>2</sub>O<sub>3</sub>-UHMWPE pairs respectively, while Figs. 12 (b, d and f) are related to the tests under lubricated conditions for TiAl6V4-UHMWPE, AISI316L-UHMWPE and Al<sub>2</sub>O<sub>3</sub>-UHMWPE pairs accordingly.



**Fig. 12:** Plot of friction force vs. time (points) vs. displacement in the contact: (a) TiAl6V4-UHMWPE with a pin diameter of 3mm, applied load 1N in dry and lubricated (b) conditions; (c) AISI316L-UHMWPE with a pin diameter of 6mm, applied load 4N in dry and lubricated (d) conditions; (e) Al<sub>2</sub>O<sub>3</sub>-UHMWPE with a pin diameter of 10mm, applied load 11N in dry and lubricated (f) conditions.

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Apart from the already mentioned differences in the force intensity for the dry and lubricated cases, the main distinction between these two conditions is the shape of cycles. In cases of dry conditions, evolution of friction forces during sliding is more regular and milder; in lubricated tests, the friction forces come across high oscillations and the static friction peaks are sharper. This condition is an indication of an unstable boundary lubrication regime, which requires further studies to gain deeper comprehension of the lubrication phenomena under reciprocating motion.

#### 4. Discussion and Conclusion

In this work a tribological experimental study was performed in order to obtain the friction coefficients of UHMWPE against TiAl6v4 alloy, against AISI316L steel and against Al<sub>2</sub>O<sub>3</sub>. The tests were performed under dry and lubricated conditions. As lubricants, we used a commercial drug containing the sodium hyaluronate fluid: “Hyalgan®”. Tests were conducted by using a reciprocating pin on flat tribometer with several load conditions and for 120 minutes. The pins in all tests have been chosen taking in account the applied load and the Hertz’s theory for the three materials under study. The flats in the tribological tests have been cut, cleaned and prepared by two different knee prostheses. The differential scanning calorimetry (DSC) has been employed to compare the two UHMWPE samples.

The results of the tribological performances show that the AISI 316L austenitic stainless steel and TiAl6v4 alloy have marked in dry conditions better values in the friction coefficient and in the friction force. Findings are aligned with those involved in the analysis of the worn surfaces at the microscope and with the subsequent evaluation of the wear mass loss (Tab. 3) for the tests under dry condition and with a pins’ diameter of 6mm. When the friction coefficient is monitorized along larger time under dry

1 conditions it increases quickly independently of the pair and of the loading conditions.  
2 The increasing rate is not reproducible as well as the final value of the friction  
3 coefficient, which normally stays in the range 0.11–0.18 after a sliding time larger than  
4 20 min (Figs. 3a, 4a, 5a,). The presence of UHMWPE notably decreases the friction  
5 phenomena. In fact, the UHMWPE transfers to the counter face thus molding a  
6 lubricating film of UHMWPE in the contact surface due to self-lubrication phenomena  
7 [30]. Due to the hydrodynamic lubrication phenomena, in all tests under lubricated  
8 conditions the friction coefficient showed much lower values than in dry-sliding  
9 conditions. These phenomena require accurate and further tribological investigation.  
10 The final value of the friction coefficients for the tests carried out under lubricated  
11 conditions stays in the range 0.018–0.06 after a sliding time larger than 10 mins  
12 independently of the pair and of the loading conditions (Figs. 8b, 9b, 10b). Large  
13 fluctuations occurred by examining closely the evolution in the friction coefficient,  
14 probably as a result of formation and localized fracture of the UHMWPE flat.  
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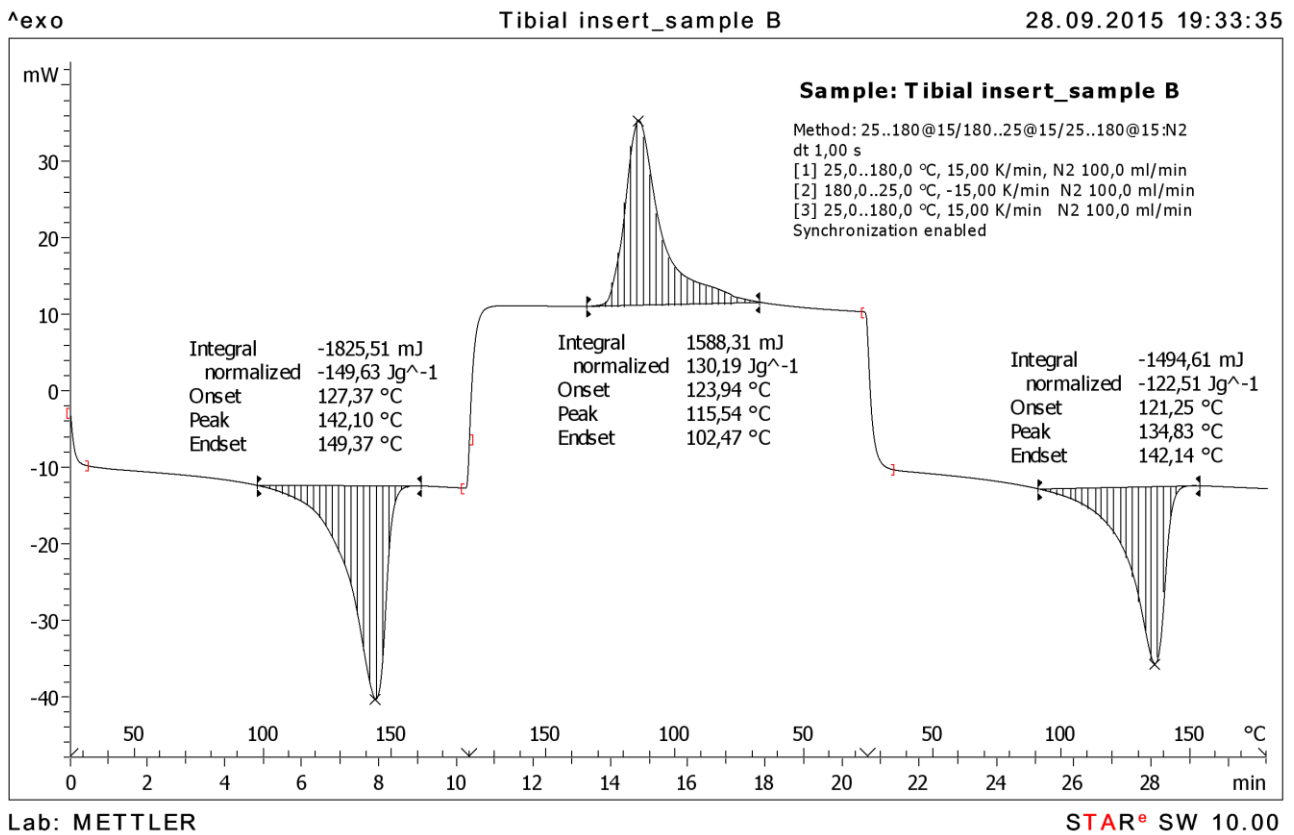
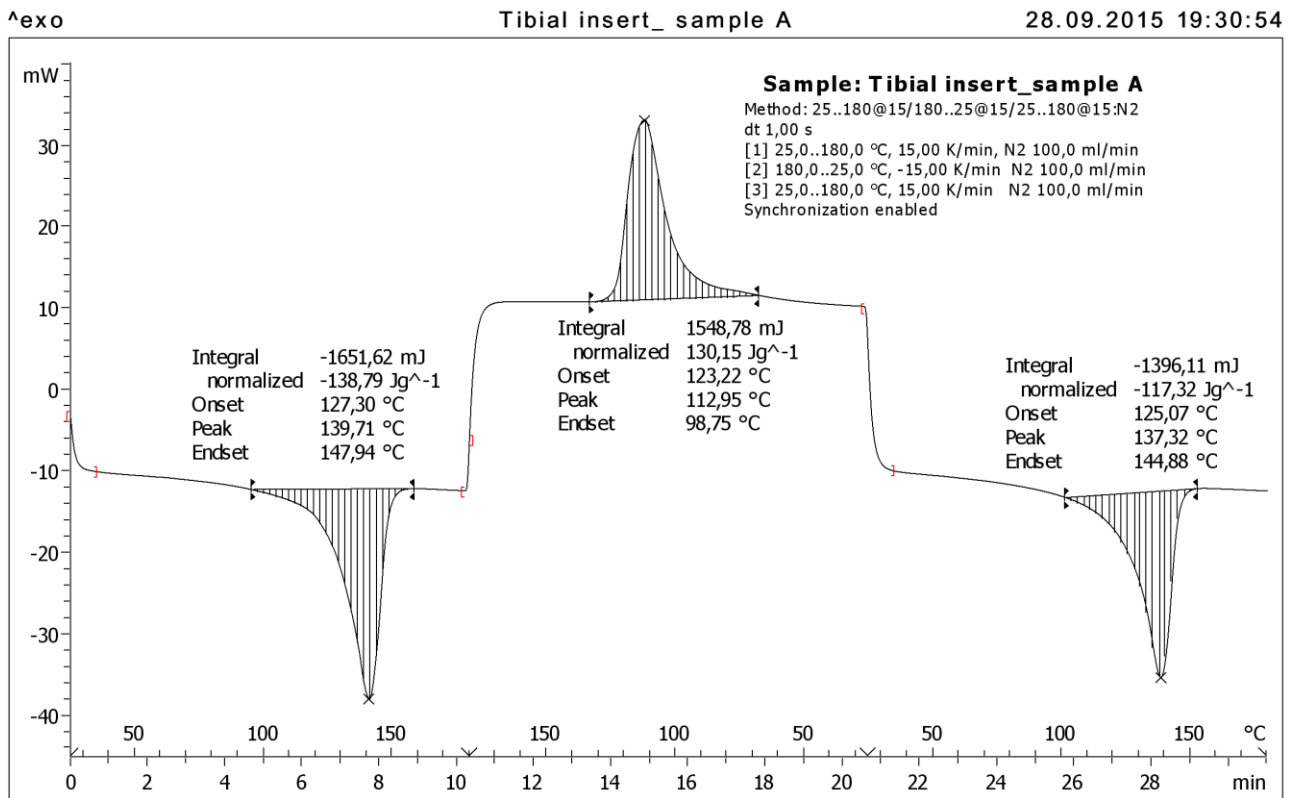
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## FIGURES

Figure 1: Differential scanning calorimetry DSC-823<sup>®</sup> METTLER-Toledo

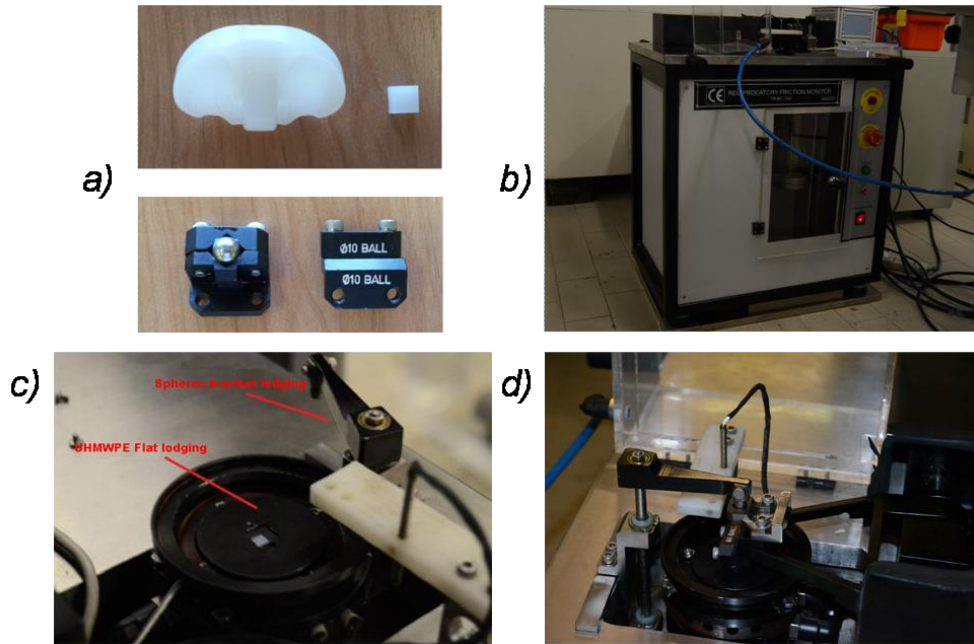


Figure 2: a) Polyethylene cuts from a tibial insert and an example of the assembly schema spheres of steel in its bracket, b) TR\_Bio 282 pin-on-flat reciprocatory DUCOM tribometer, c) and d) the assembly of the pin and flat in the tribometer.

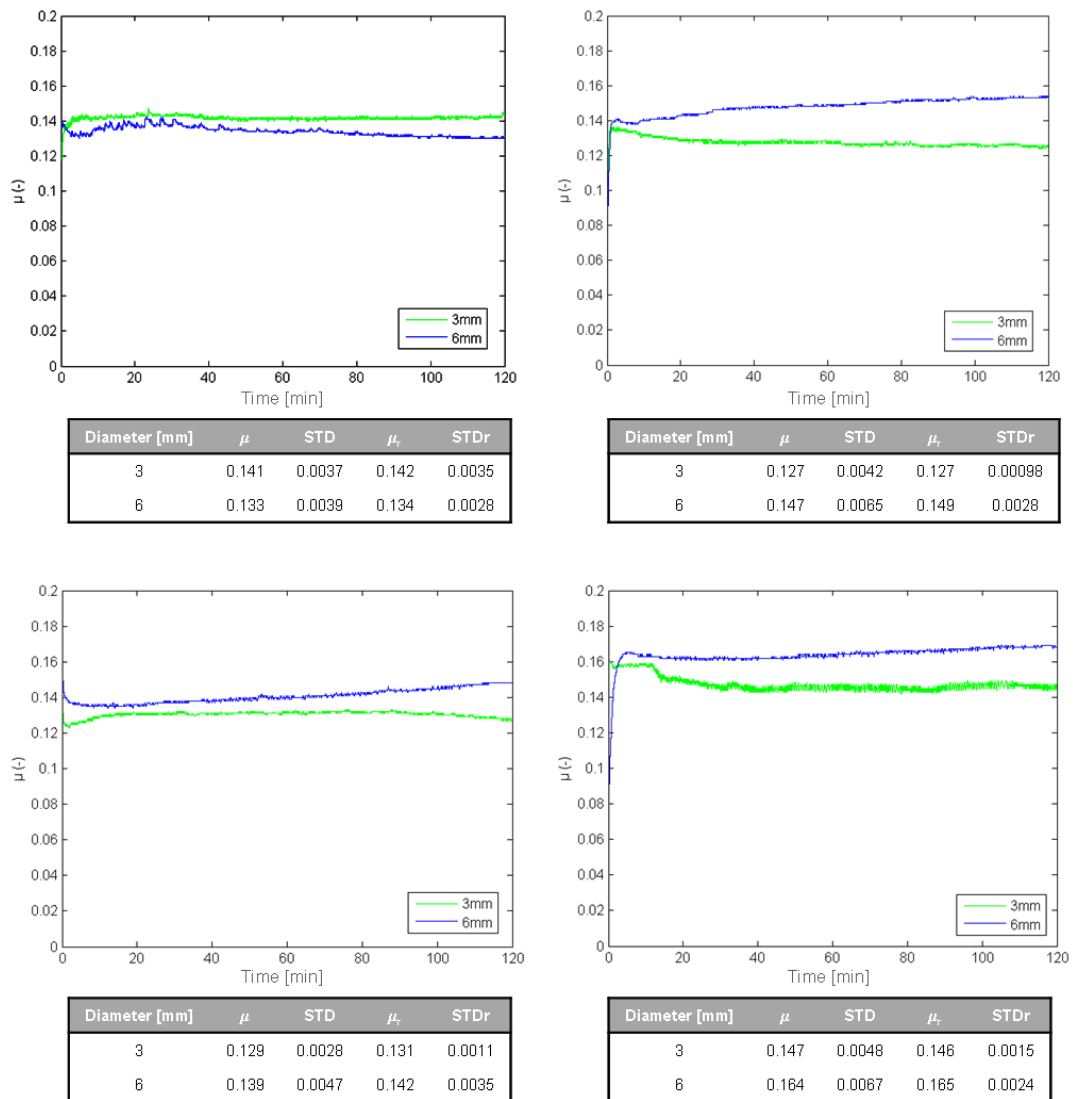


Figure 3: The evolution of the friction coefficient under dry conditions in: a) TiAl6V4-UHMWPE sample "A" contact, b) TiAl6V4-UHMWPE sample "B" contact

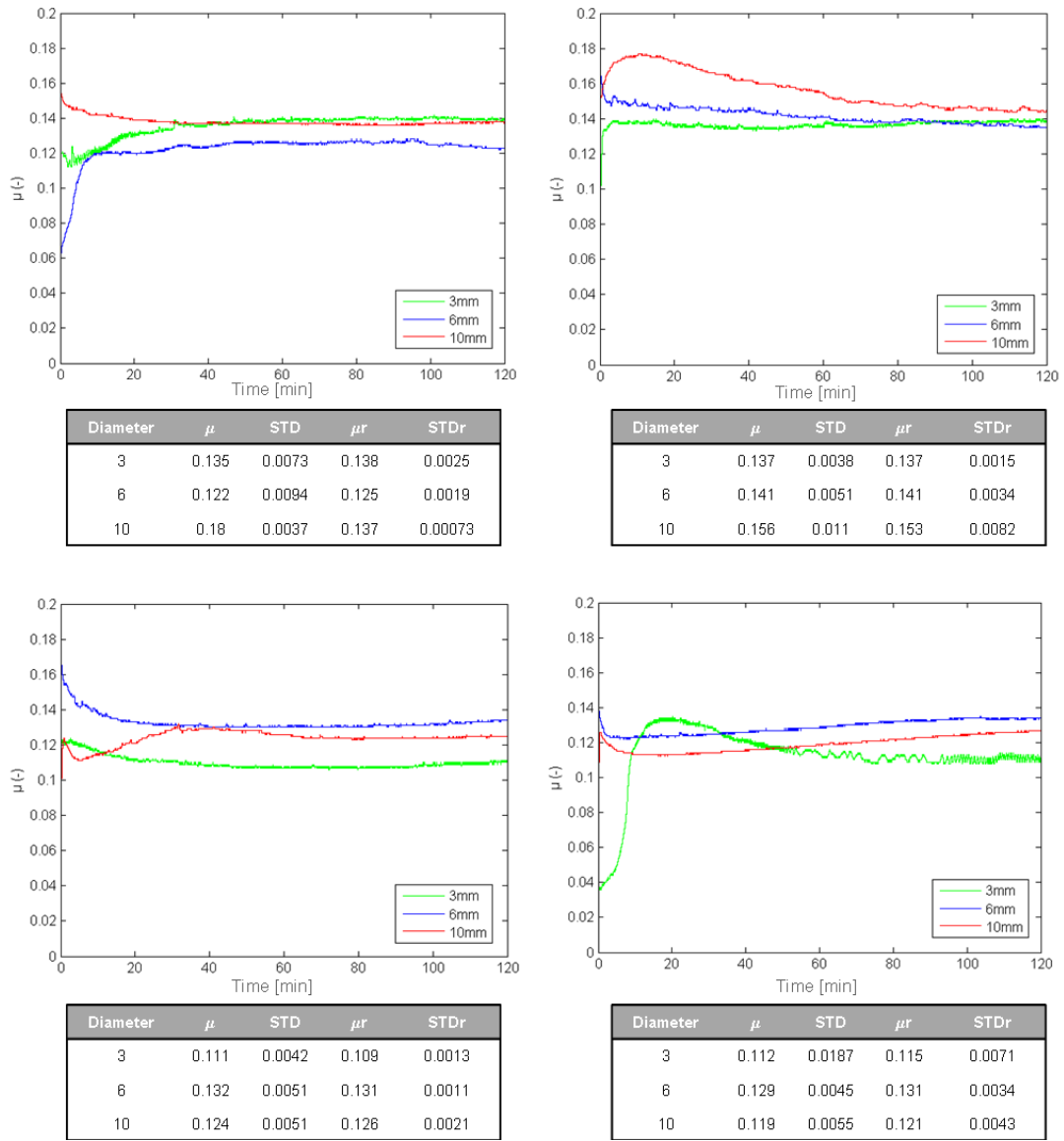
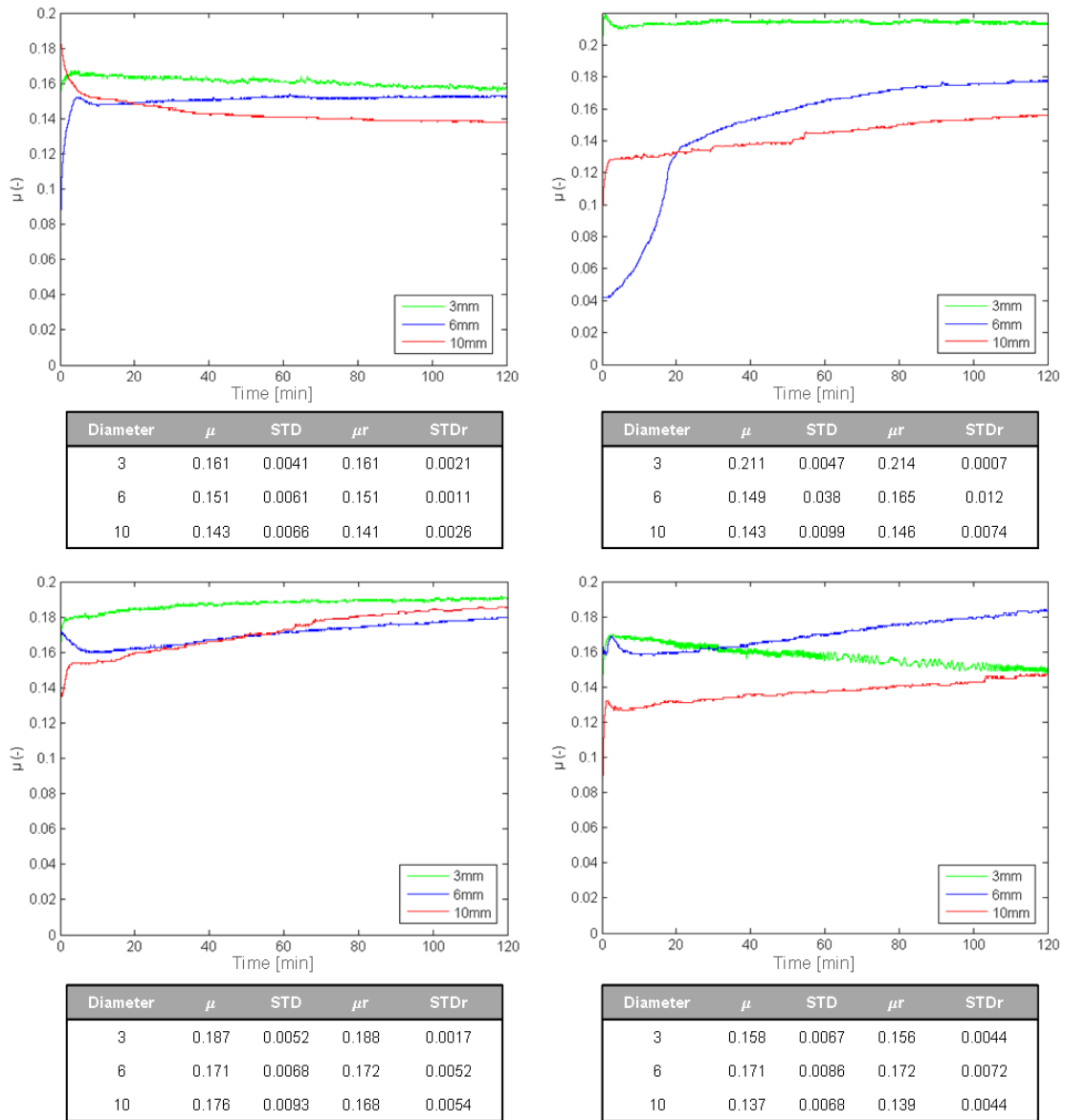
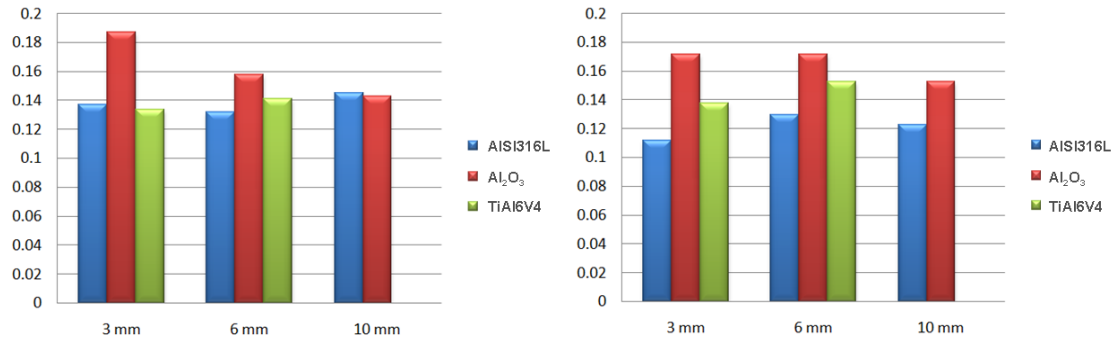


Figure 4: The evolution of the friction coefficient under dry conditions in: a) AISI316L - UHMWPE sample "A" contact, b) AISI316L - UHMWPE sample "B" contact



**Figure 5:** The evolution of the friction coefficient under dry conditions in: a)  $\text{Al}_2\text{O}_3$ -UHMWPE sample "A" contact, b)  $\text{Al}_2\text{O}_3$ -UHMWPE sample "B" contact



Material	Diameter [mm]	$\mu_f$	STDr
TiAl6V4	3	0.134	0.0022
	6	0.141	0.0028
AISI316L	3	0.137	0.0021
	6	0.132	0.0026
	10	0.145	0.0077
Al <sub>2</sub> O <sub>3</sub>	3	0.187	0.0013
	6	0.158	0.0011
	10	0.143	0.0051

Material	Diameter [mm]	$\mu_f$	STDr
TiAl6V4	3	0.138	0.0013
	6	0.153	0.0029
AISI316L	3	0.112	0.0041
	6	0.131	0.0022
	10	0.123	0.0031
Al <sub>2</sub> O <sub>3</sub>	3	0.172	0.0031
	6	0.172	0.0062
	10	0.153	0.0049

Fig. 6: Average values of the friction coefficient for each kind of materials under dry conditions in contact with: a) UHMWPE sample "A", b) UHMWPE sample "B"

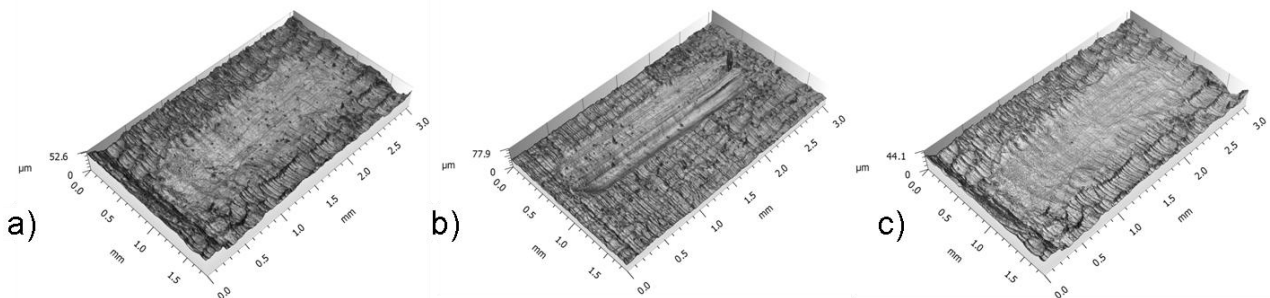


Fig. 7: 3D Optical Surface Metrology System Leica DCM 3D and qualitative analysis of the UHMWPE (samples A) surfaces after the test under dry conditions for pins' diameter of 6mm in the case of: a) TiAl6V4; b) AISI316L; c) Al<sub>2</sub>O<sub>3</sub>.

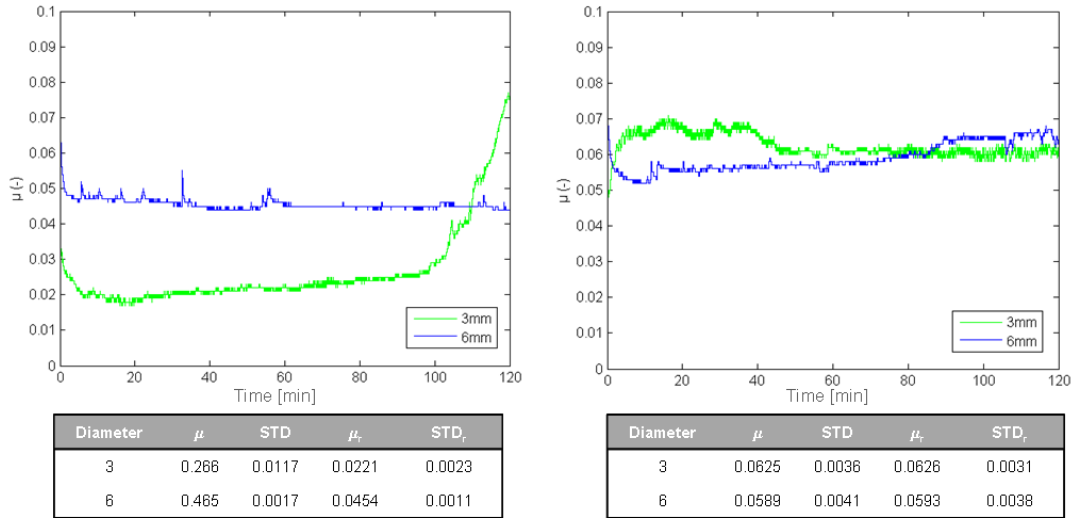


Figure 8: The evolution of the friction coefficient under lubricated conditions in: a) TiAl6V4-UHMWPE sample "A" contact, b) TiAl6V4-UHMWPE sample "B" contact

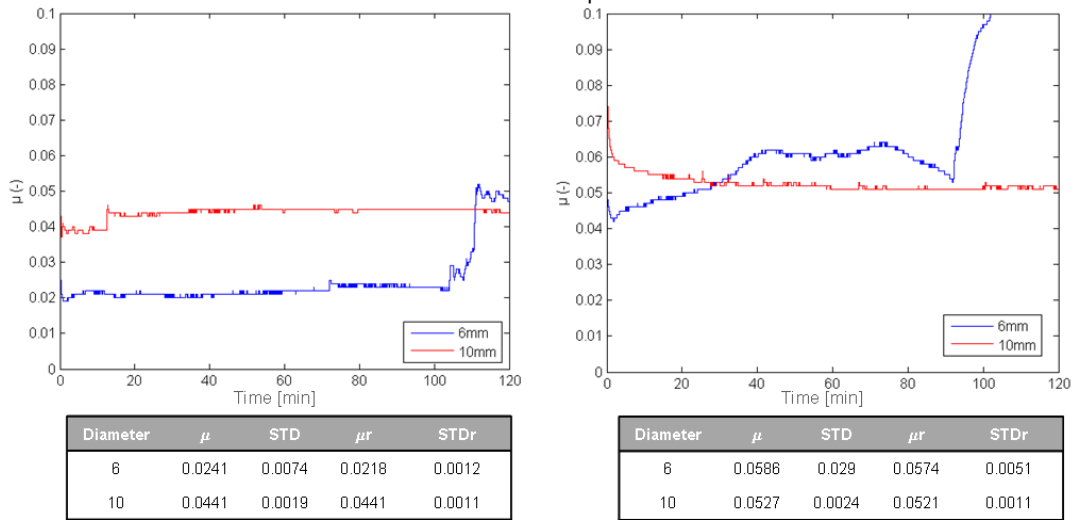


Figure 9: The evolution of the friction coefficient under lubricated conditions in: a) AISI316L-UHMWPE sample "A" contact, b) AISI316L-UHMWPE sample "B" contact

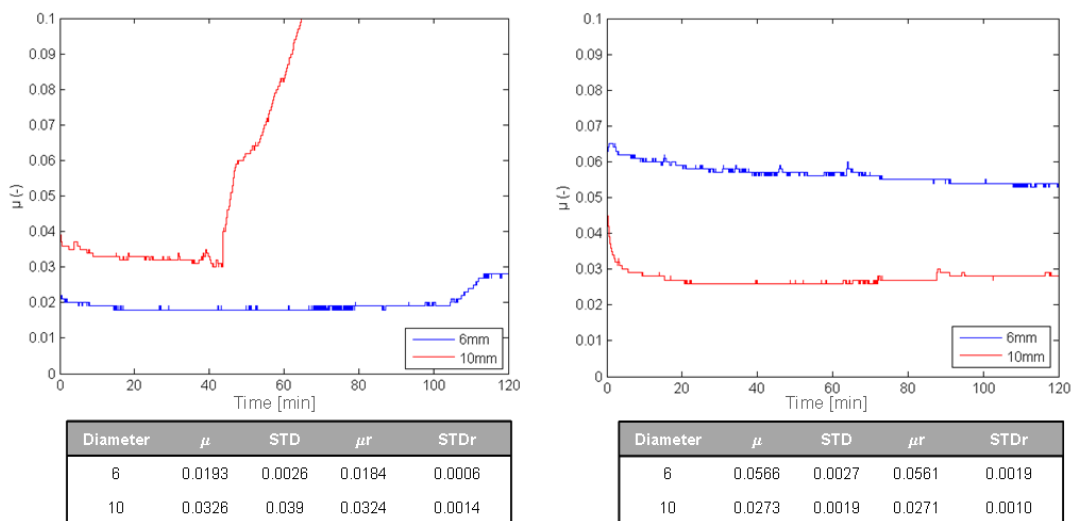
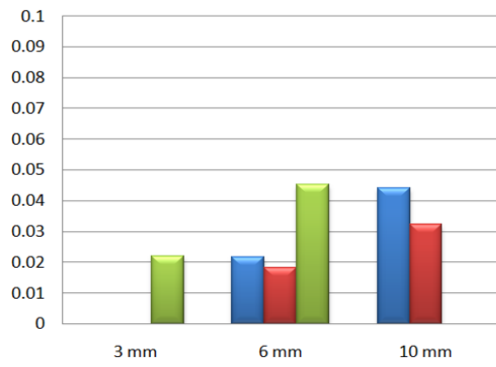
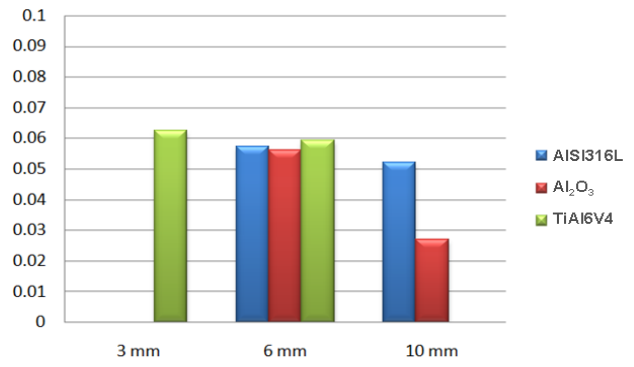


Figure 10: The evolution of the friction coefficient under lubricated conditions in: a) Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample "A" contact, b) Al<sub>2</sub>O<sub>3</sub>-UHMWPE sample "B" contact

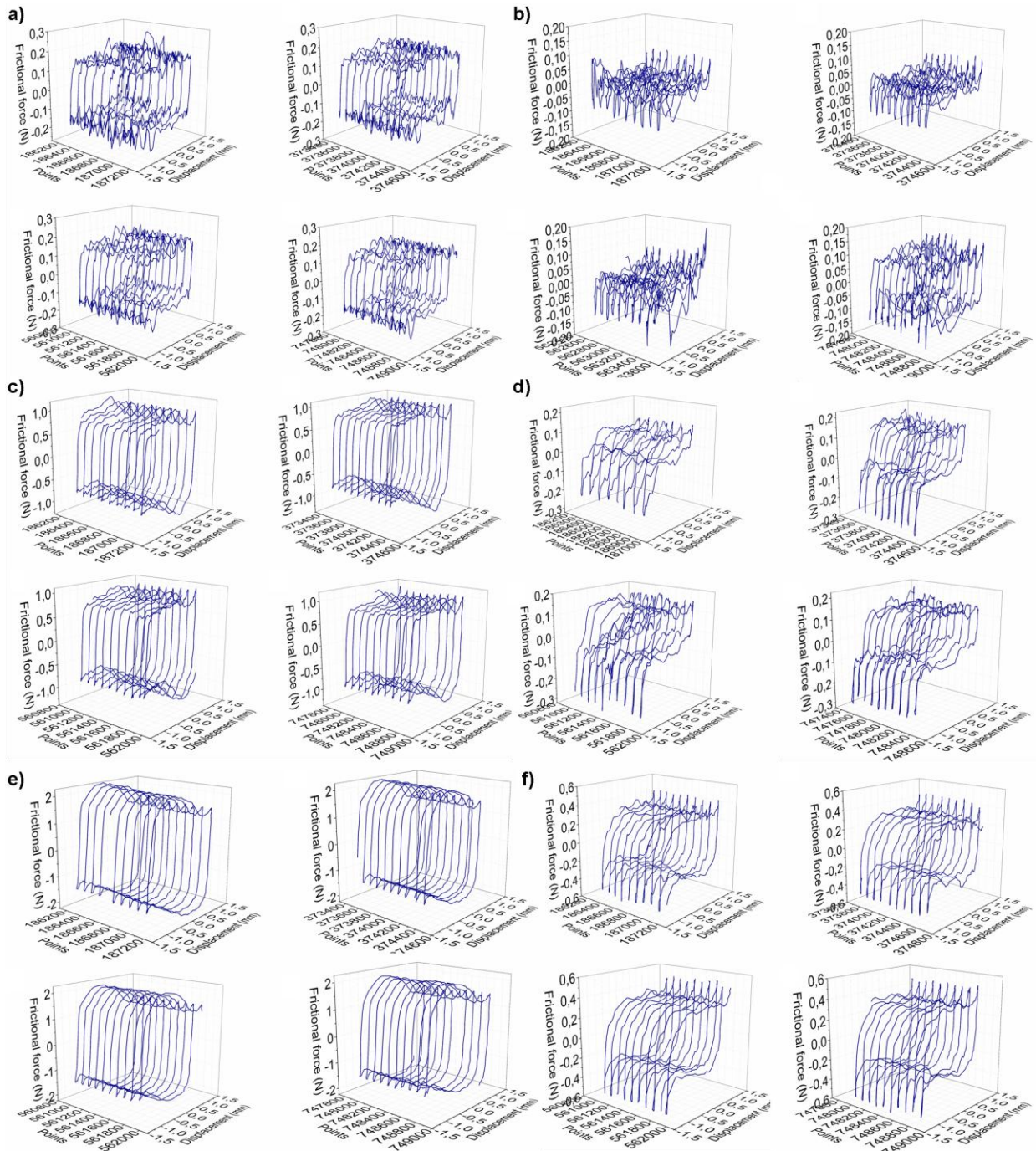


Material	Diameter [mm]	$\mu_r$	STDr
TiAl6V4	3	0.0221	0.0023
	6	0.0454	0.0011
AISI316L	6	0.0218	0.0012
	10	0.0441	0.0011
Al <sub>2</sub> O <sub>3</sub>	6	0.0184	0.0006
	10	0.0324	0.0014



Material	Diameter [mm]	$\mu_r$	STDr
TiAl6V4	3	0.0626	0.0031
AISI316L	6	0.0593	0.0038
	10	0.0521	0.0012
Al <sub>2</sub> O <sub>3</sub>	6	0.0561	0.0019
	10	0.0271	0.0010

**Fig. 11:** Average values of the friction coefficient for each kind of materials under lubricated conditions in contact with: a) UHMWPE sample "A", b) UHMWPE sample "B"



**Fig. 12:** Plot of friction force vs. time (points) vs. displacement in the contact: (a) TiAl6V4-UHMWPE with a pin diameter of 3mm, applied load 1N in dry and lubricated (b) conditions; (c) AISI316L-UHMWPE with a pin diameter of 6mm, applied load 4N in dry and lubricated (d) conditions; (e) Al<sub>2</sub>O<sub>3</sub>-UHMWPE with a pin diameter of 10mm, applied load 11N in dry and lubricated (f) conditions.

## TABLES

Tab. 1: The properties, melting point and crystallinity of both UHMWPE samples

UHMWPE Sample	Young's Modulus [GPa]	Poisson's ratio	Hardness D scale	Melting point [°C]	Crystallinity (%)
A	0.69	0.46	48	137,32	39,96
B				134,83	41,72

Tab. 2: The properties, the Diameter Spheres and Normal load for each kind of materials

Pin Materials	Young's Modulus [GPa]	Poisson's ratio	Hardness [HCR] *[Kg/mm <sup>2</sup> ]	Diameter Spheres [mm]	Calculated Normal Load [N]	Applied Normal Load [N]
TiAl6V4	114	0.34	28-42	3	1.006	1
				6	4.019	4
AISI316L	193	0.27	25-39	3	1.021	1
				6	4.055	4
				10	11.231	11
Al <sub>2</sub> O <sub>3</sub>	370	0.22	1440*	3	1.011	1
				6	4.037	4
				10	11.181	11

Tab. 3: The wear mass loss in the test under dry conditions for pins' diameter of 6mm in UHMWPE samples A

Tribological Pair	Groove Volume [mm <sup>3</sup> ]	Wear mass loss [g]
TiAl6V4-UHMWPE	$0.79 \cdot 10^{-2}$	$0.74 \cdot 10^{-5}$
AISI316-UHMWPE	$0.61 \cdot 10^{-2}$	$0.57 \cdot 10^{-5}$
Al <sub>2</sub> O <sub>3</sub> -UHMWPE	$1.02 \cdot 10^{-2}$	$0.95 \cdot 10^{-5}$