Friction and Wear Testing of Lubricated Joint Implant Material using AMTI Ortho-POD

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Abstract
Friction and wear are caused by complex interactions between surfaces that are in mechanical contact and sliding against each other. The goal of this study was to determine the effect of different lubricants on the wear and friction of most commonly used implant material ultrahigh molecular weight polyethylene (UHMWPE), and to compare the results of UHMWPE with another materials polytetrafluoroethylene (PTFE). To accomplish this goal, pin-on-disk cyclic testing by AMTI Ortho-Pod pin on disk was used with lubricant. The lubricant used to mimic synovial fluid was bovine albumin, hyaluronic acid, and the artificial lubricant (silicone oil) were used. Gravimetric analysis was used to characterize wear after 700 thousand cycles at normal load 300 N, sliding velocity 87.92 mm/sec with different wear paths. Using these data, pin-on-disk wear tests were conducted to explore that circular path had a higher mean coefficient of frictions and specific wear rate than a line path. UHMWPE had a lower mean coefficient of frictions and specific wear rate than PTFE.

Keywords: Pin on disk, Wear rate, Friction coefficient, Lubricant, UHMWPE, and PTFE.

1. Introduction.
During the service life of the biomaterials face relative motion on micro- or macro-levels, this can bring a tribological damage. Besides, the surrounding biological environments can also contribute to that damage by having a corrosive effect. All of the combination and synergy of tribology as well as the corrosion and the biological environment are extremely complex and have a great importance [1]. Therefore, tribology has an important role in a number of medical devices and implants, like the artificial joints, artificial teeth, dental implants, orthodontic appliances, cardiovascular devices, contact lenses, artificial limbs, and not to forget the surgical instruments [2]. It can be defined as the study of
friction, wear and lubrication in the design of bearings, and it can be said that it is the science of interacting surfaces in relative motion [3]. However, friction is a common phenomenon in mechanical systems which may be increased or decreased basing on the sliding pairs and operating parameters [4].

Well, wear can be defined as ‘the progressive loss of substance from the surface of a body brought about by mechanical action’, besides, it is one of the most common causes of joint replacement failure which in turn causes aseptic loosening and then can result in chronic inflammation at the implant–bone interface, it is not surprising that all implants for total joint replacement is subjected to wear [5].

Mechanical wear assessment also includes the use of a pin and disk method in order to create wear in the material and see the result. One of the common screening tools is Pin-on-disk wear testing which is used to quantify the wear rate of polymer material that is used in orthopedics. Both friction coefficient and wear rate can differ significantly because of introducing an external lubricant to the polymer tribo- system. The external lubricant can define as a substance which can alter the nature of the surface interaction of the contacting solids. The main way a lubricant helps influences friction and wear of thermoplastics comes by reducing adhesion of the polymer to the counter face.

Today, polymers occupy a major position in the bearings field. Thus, the polymeric biomaterials main advantages compared to the metal or ceramic materials are seen ease of manufacturability to produce various shapes (latex, film, sheet, fibers, etc.), and ease of secondary process ability, however, a reasonable cost, besides the availability with desired mechanical and physical properties [6].

2. Materials and Methods:

2.1 Testing Machine

The Ortho-POD is a six-station pin-on-disk machine that can provide suitable test motions, environments, and loads to produce wear rates similar to the encountered in joints simulators. However, three independent servo-motors the engine has which control motions corresponding to the pin rotary motion, the plate with the disks rotary motion, and a constant normal load on the six pins. Each one of the six pin drive axes are centered on a planet gear which is driven by a single sun gear controlling all pins to move with the same rotary motion. Each of the pin load actuators provides an identical load, but any one of those pins can be turned off individually. Disk from AMTI lab, Watertown, USA. AMTI multi-component force sensors can measure the three force components (Fx, Fy, and Fz) at the pin-sample disk interface. The machine is attached with a PC so, the machine also contains a waveform board which has fixed microprocessor. The PC is for programming a desired waveform that is then be moved to the waveform board. However, circular wave that was used in the tests is programmed by 36 points and (7 mm) radius after being converted to the template file "wav". The controller reads are embedded by waveform generators, the template data and performs an interpolation algorithm in order to provide smooth real time wave generation. The interpolated digital signals are fed to a digital to analog converter that provides the desired time which varying analog
output voltages or the waveforms. These analog waveforms then being fed to the servo control loop circuitry that is, along with the proper feedback signals, are conditioned to provide the driving signals to both the force and the rotation actuators.

2.2 Sample Preparation

The size of all pins is Ø9.525mm x 30mm (.375 in x .787 in) to fit existing Ortho-POD pin holders, for each of the tests a group of six samples with same materials being used. Pins will be reused during the different tests. Every pin and pin holder are identified with the same distinct number in all tests. The cleaning and weighting of the samples should be done after every 100000.

2.3 Fluid Test Medium

The counter face surfaces of the components will be kept immersed in a lubricating solution at 33°C ± 3 degrees during the test. Validation of the lubrication solution temperature can be controlled by the temperature of the external base plate and external circulating temperature control unit. Each pin on disk specimen should have its own environmental chamber for every separate station of that machine, which will contain both the specimen and lubricating solution. Any fluid lost by evaporation during the test is to be compensated by adding extra amount of fluid. The fluid test medium is to be replaced fully at each stopping point for gravimetric weighing.

2.4 Test Fluids

Synovial fluid is considered as the best lubricant for a natural hip or knee joint. The Synovial fluid has unique lubricant properties that protect cartilage and bone surfaces from extremely high contact pressures during the patient’s life span. There are four major biological components can be found, which make synovial fluid an efficient lubricant, hyaluronic acid (HA), albumin, mucinous glycoproteins (mainly lubricin), and globulin [7].

Different test lubricants were used for wear tests in which synovial fluid components and an artificial oil was used.

2.4.1 Bovine Albumin.

Diluted filter-sterilized bovine serum 20 ±2 g/L protein concentration similar to the protein content found in a healthy human body with 1% Sodium Azide to retard bacterial growth. The bovine serum is stored in the fridge until ready for use.

2.4.2 Hyaluronic Acid.

Diluted hyaluronic acid with deionized water 3 g/900ml which within the normal range of hyaluronic acid concentration in the synovial fluid [8], the fluid is stored in the fridge until ready for use.
2.4.3 Artificial Lubricant Silicone Oil.

Silicones are polymers consists mainly macromolecular compounds of organic silicone polysiloxanes. That silicone oils kinematic viscosity being proportional to the degree of polymerization (i.e. proportional to polymers molar mass) [9]. Silicone fluids are mainly clear, colorless, bland, and tasteless, and they are produced in a wide range of viscosities. They are so much inert and are remarkably stable, bringing a little, change in physical properties over a wide temperature range [10].

2.5 Experimental polymer materials

2.5.1 Ultra-High Molecular Weight Polyethylene (UHMWPE).

Ultra-high molecular weight polyethylene (UHMWPE) is considered to be a unique polymer with both stellar physical and mechanical properties. Most amazing is its chemical inertness, lubricity, impact resistance, and also abrasion resistance. However, polyethylene consists only of carbon and hydrogen. In the first place, the UHMWPE should be polymerized from ethylene gas. Then, the polymerized UHMWPE, as a powder, has to be consolidated and machined into the required shape. UHMWPE was utilized in orthopedics as a bearing material in artificial joints for the past 45 years. The UHMWPE that was used in orthopedic implant is a type of polymer generally classified as a linear homopolymer [11].

2.5.2 Polytetrafluoroethylene PTFE.

Polytetrafluoroethylene (PTFE), known as Teflon®, is a fluorocarbon solid, and is a high-molecular-weight compound consisting wholly of carbon and fluorine.

2.6 Load Profile, Wear Path Procedure, and Wear Measurement

A waveform was programmed to apply constant loading for all pins with a peak load of 300 N (maximum contact pressure of 4.205 MPa) which is well within the physiological range [12], and a 14mm diameter of circular wear path was conducted at a frequency of 2 Hz, sliding periodically on its own 316 stainless steel disk.

The setup of these wear tests was unique to this study, where each test was further divided into three subtests. Every subtest utilized a certain wear testing lubricant composition for the set number of the intervals. Using this setup, the effect of different lubricant compositions on UHMWPE and PTFE wear could be successively shown. Each polymer submitted to 0.7 million cycles with each lubricant of the three lubricants, when the lubricant type changed at the end of 0.7 million cycles other parameters (circular wear path, load & chambers temperature) are kept constant.

Pins are changed when the previous material is tested with three lubricants. At regular intervals (every 0.1 million cycles) during the wear tests, the pins were detached from the experimental apparatus, wiped clean and weighed using a high-precision balance which reads 0.0000g. The weight
loss of each pin due to wear was determined by calculating the difference in the weight of the sample between two measurement points. The volumetric wear ($\Delta\nu$) in $(mm)^3$ was estimated by taking the change in mass of the specimen and dividing it by the density of the specimen material as shown in equation (1)

$$\Delta\nu = \frac{w_1-w_2}{\rho}$$

(1)

$w_1$ The weight loss in gram of the specimen before test.
$w_2$ The weight in gram of the specimen after test.
$\rho$ The experimental density of the specimen, which is for UHMWPE and PTFE 0.00093, 0.00214 ($g/\text{mm}^3$) respectively.

The specific wear rate ($W_s$) of the specimen is calculated as in equation (2).

$$W_s = \frac{\Delta\nu}{F_n S_s}$$

(2)

Where $S_s$ is Sliding distance (m), $F_n$ is Normal load (N) [13].

The data acquisition system of the AMTI Ortho-POD collects multi-component force data and friction coefficients. Force sensors in those three vertical legs of that machine measures three of the force components. The nine outputs are summed to deliver a single value for each of the forces $F_x$, $F_y$, and $F_z$ where $x$ and $y$ are the transverse direction and the perpendicular direction is $z$. Each test runs for 0.7 million cycles, friction was collected every 50,000 cycles. The sample rate was 200 data sets/second and its duration were ten seconds. Data were measured and collected for the last ten cycles. The friction coefficient was determined by the ratio of the transverse force to the vertical load, equation (3).

$$c_f = \sqrt{\frac{(f_x)^2+(f_y)^2}{(f_z)}}$$

(3)

$fx$, $fy$ and $fz$ computed by AMTI Ortho-Pod machine.

3. Results and Discussion

Figures 1 shows the average weight loss results obtained from the test for the six pins PTF components with bovine albumin over 0.7 million cycles. The average volumetric wear rate of all pins at the end of each 100000 cycles is illustrated in figure 2. This configuration of figures is repeated for all tests.
Because, all pins of PTFE, and UHMWPE were not presoaked for all tests, that caused increasing in weight due to lubricant absorption specially when HA was the lubricant medium, because the HA more aqueous than others lubricants (see figures 3, 4, 5, 6, 7, 8, 9 & 10) show that UHMWPE more Absorbent than PTFE. When the test was conducted, they absorbed the lubricant causing their weight to be increased. Silicone oil is more viscous than HA, however, it showed greater wear rates than those for HA, that is due to the amount used of SO in the test which was less than that used for HA (see table 1) which results in less absorption of lubricant, another cause to that is changing the HA and BA each 50000 cycles, whereas SO was changed after 300000 cycles for both PTFE and UHMWPE that resulted in more wear debris accumulation within SO solution which acted as third particles causing abrasive wear. Wear results of PTFE with HA was more than those of UHMWPE, this is due to high coefficient of friction of PTFE which caused increasing liquid temperature leading to weakening of the interactions among the polymer chains which form HA leading to a decrease in its viscosity.
Figure 5. The average weight loss with number of cycles of PTFE with silicone oil.

Figure 6. The average wear rate with number of cycles of PTFE with silicone oil.

Figure 7. The average weight loss with number of cycles for UHMWPE with hyaluronic acid.

Figure 8. The average wear rate with number of cycles for UHMWPE with hyaluronic acid.

Figure 9. The average weight loss with number of cycles for UHMWPE with silicone oil.

Figure 10. The average wear rate with number of cycles for UHMWPE with silicone oil.
Figures 11 & 12 show the average weight loss and the average wear rate of UHMWPE with BA and it is noticed that the average wear rate started with high magnitude then it decreased with number of cycles, that can be explained by the fact that the specimens were not soaked before the test.

| Pin Material | Load (N) | Wear Path | Lubricant | Lubricant Temperature (°C) ±2 | Lubricant Volume (ml) ±1 | Average $cf$ |
|--------------|----------|-----------|-----------|-------------------------------|--------------------------|--------------|
| PTFE         | 300      | Circle    | Bovine albumin | 36                             | 4                        | 0.2237       |
| PTFE         | 300      | Circle    | Silicone Oil  | 33                             | 2                        | 0.2515       |
| PTFE         | 300      | Circle    | Hyaluronic Acid | 33                             | 5                        | 0.3681       |
| UHMWPE       | 300      | Circle    | Bovine albumin | 30                             | 4                        | 0.0969       |
| UHMWPE       | 300      | Circle    | Silicone Oil  | 31                             | 2                        | 0.1845       |
| UHMWPE       | 300      | Circle    | Hyaluronic Acid | 32                             | 5                        | 0.0956       |

Table 1. The coefficients of friction ($cf$) during different tests with sliding distance 30772 m for each test steady velocity 87.92 mm/sec.
Regarding the comparison shown in figure 13, the volumetric wear rate of Polytetrafluoroethylene (PTFE) with Bovine Albumin (BA) is higher than PTFE with Hyaluronic Acid (HA) or PTFE with Silicone Oil (SO) that is because the PTFE wear rate was increased due to the increase in temperature on the polymer counter surface, where the (BA) temperature reached 36°C (see table 1), increasing temperatures in polymer contact surface results in the softening of polymer surface which leads to severe wear. Both polymers, the disks and the hollow acrylic plastic cylinder surround the samples were not sterilized that led to bacterial contamination of the serum lubricant (BA), which causes protein cleavage due to inflammatory response of the protein as a result of increase the friction and wear. Cleavage of proteins entails scission of the peptide chain, leading to smaller peptide fragments with exposed hydrophobic and hydrophilic moieties. Albumin affinity for the hydrophilic metal surface exposes the hydrophobic groups that can bond with the hydrophobic polymer surface. This results in the attachment of the albumin molecule to both metal and polymer surfaces. This interaction results in reduced friction by separating the surfaces, but also to increased wear due to effective removal of polymer where polymer–protein–metal adhesion has occurred. This adhesive wear effect was more pronounced against the smoother metal disk. Although the HA had higher protein concentration than BA, HA solutions display progressively increased viscosity and viscoelasticity.

4. Conclusions
The choice of lubricant can significantly affect the results and validity of in-vitro testing. The results from different laboratories are hardly ever comparable as, for example, the protein concentration and the protein composition of the liquids vary, and the differences in the roughness of counter surfaces, and the chambers temperature. The viscosity, the test environment and the chemical reactions of these test does not match the more viscous synovial fluid, biological environment and chemical reactions, which surrounds the polymer, so the in-vitro results still differ from in-vivo results.

The wear rate was higher for BA at all loads. When the hyaluronic acid and silicone oil were lubricants, PTFE and UHMWPE were at their lowest wear-magnitudes, due to the high viscosity of HA and silicone oil. The effect of lubricant makes the difference in friction coefficient and wear rate values...
based on their lubricating ability. The results show that BA and silicone oil exhibited stable wear rate with the passage of time.

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