Methods for Wear Testing Hip Prosthetics

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ABSTRACT

The total population of persons receiving a hip transplant is growing and becoming younger. Therefore, the life span of hip replacements is becoming of the utmost concern. One of the most prevalent causes for a replacement (revision) of a hip is due to wear of the implant. There are several wear mechanisms that are prevalent in hip replacements, namely: adhesion, abrasion, third body, fatigue, and corrosion wear. Each mechanism is important to evaluate and therefore it is vital that the proper environment and kinematic loading are simulated. Original screening mechanisms consisted of a linear motion machines that were shown to underestimate the wear rate of materials by orders of magnitude and to rank materials in a different order than those tested utilizing a multi-axial joint simulator. Additionally, it is of the utmost importance to test the joint with a lubricant that simulates that found in the human body. If the protein concentration of the lubricant is too low or too high, compared to that of the human body, then the wear rates will be reported too low and unrealistic. Using data that has been collected on materials currently in use and comparing the wear patterns of the tested items to those used in vivo, wear testers can be developed that accurately represent the in vivo results during in vitro testing.
1. Introduction

A total hip replacement (also called total hip arthroplasty) is the complete replacement of the hip joint with prosthetic components [1]. The need for a total hip replacement can be due to several causes of degradation of the joint, including: age, disease (such as arthritis), and injury. In an ever growing, and aging, population the need for joint replacements, such as a total hip replacement, is becoming more and more appropriate. The Agency for Healthcare Research and Quality has stated that more than 285 thousand total hip replacements are performed in the United States each year alone [1].

Figure 1 illustrates the anatomy of a healthy human hip joint and Figure 2 illustrates the anatomy of an artificial, or prosthesis, hip. The human hip consists of the femoral head of the femur and the acetabulum that is located within the pelvis. The femoral head is rounded and rides within the acetabulum (or socket) and acts like a mechanical ball and socket joint. The prosthetic hip utilizes a metal femur usually made of some sort of metal (316L stainless steel, Cobalt Chrome, Titanium alloys, for example) that is inserted into the femur where it is attached with or without the use of cement. The femoral head (ball of the ball and socket joint) can be manufactured from metal or ceramic. A metal cup (Acetabular cup) that is connected within pelvis by cement or screws replaces the socket portion of the hip joint. Within the metal cup, a liner is attached that acts as the wear surface for the head of the femur to interact with. The liner is manufactured from many different materials ceramic, metal, and polymers like ultra-high molecular weight polyethylene (UHMWPE). The choice of the material for the liner and femoral head are important in determining the friction and wear within the joint.
It has been shown that the patients are beginning to receive hip replacements at younger ages and therefore expect more out of these prosthetic joints. Currently, a patient has an 80 percent chance for the hip replacement to last 20 years [2]. Therefore, with this life span of a replacement joint, it is likely that a younger patient may have to undergo a revision (complete replacement of the hip replacement joint) surgery. Revisions have a lower success rates than the first joint replacement by roughly 10 percent [3]. Because of the need to have longer lasting replacement joints many studies have been performed to better understand the wear conditions within the prosthetic joints to attempt to prolong the life of hip replacements.
2. Theory/Methodology for Wear in Prosthetic Implants

2.1 Wear Mechanisms

There are five major processes that cause wear and damage to replacement hip joints, referred to as wear mechanisms – adhesion, abrasion, third body, fatigue, and corrosion [4 and 5]. These wear mechanisms are important as they cause limitations to the life of the replacement hip joints. A short description of each of the wear mechanisms is provided herein along with a comment on the methods used to calculate the amount of wear, or ware rate, of a material.

2.1.1 Adhesion Wear

Adhesion wear is caused by the asperities of two materials “sticking together” due to the atomic forces occurring between the two materials [4]. As the surfaces continue to move the asperity from one of the surfaces (usually the weaker material) will break and stick to the other surface creating a wear particle. The wear particle will cause additional damage to the other surface as the surfaces continue to move relative to each other. See Figure 3 for an illustration of adhesion wear.

![Adhesion wear](image)

Figure 3: Adhesion wear [6]

2.1.2 Abrasive Wear

Abrasive wear is due to a relative difference of relative hardness between two surfaces [4]. When two surfaces, of different hardness, move relative to each other they contact at their asperities. The surface that is made of harder material
plows through the softer surface wearing the softer surface. See Figure 4 for an illustration of adhesion wear.

![Figure 4: Abrasive wear](image)

### 2.1.3 Third Body Wear

Third body wear is due to separate body, which becomes lodged in between two adjacent surfaces that are in motion relative to each other [4]. The third body can then cause abrasive wear on the two surfaces. In the case of a hip replacement the third body could be bone or metallic or cement pieces from the implant. See Figure 5 for an illustration of third body wear.

![Figure 5: Third body wear](image)

### 2.1.4 Fatigue Wear

When the cyclic loading between two surfaces exceeds the fatigue limit of one of the surfaces, subsurface cracks form, causing pitting in the material [4]. This is referred to as fatigue wear, and could occur in hip replacements from normal use, such as walking. Therefore, it is important that the fatigue properties of the materials in a hip replacement are well understood to limit the fatigue wear in implants. Figure 6 provides an illustration of fatigue wear.
2.1.5 Corrosion Wear

Corrosion wear is a form of third body wear caused by a chemical reaction between a surface and an unfavorable environment. As the surface breaks down, debris is formed which would result in third body wear of the mechanism. In a hip implant, this could be caused by environment of the human body and therefore it is important to understand the chemical reaction of the components of the hip implant with the fluids in the human body. This is why choosing the correct lubricant for testing is important. Figure 7 provides an illustration of corrosion wear.

Figure 7: Chemical wear

2.2 Wear Rate

Along with understanding the mechanisms that cause wear and damage to the components, it is important to be able to characterize the ability of a material to withstand wear. This is referred to as the wear rate of a material. Wear rate (w) is defined as the amount of material removed ($V_{removed}$) per unit distance (L). Therefore, in a formulaic form, wear rate is described as the following:
Additionally, it is possible to define a wear coefficient (K) for each mechanism of wear based on the force applied ($F_n$), the hardness ($H$) of the material, and the wear rate ($w$). Namely:

$$w = K \frac{F_n}{H} \quad \text{or} \quad K = w \frac{H}{F_n} \{\text{unitless}\}$$

Eq. 2 [8]

As each mechanism has its own wear coefficient, defined in a similar manner, and the wear rate of a material is defined in the same manner, it is difficult to understand what wear mechanism it causing the wear using these numbers alone. Investigation and testing is necessary to determine the factor, or wear mechanism, that is responsible for the wear or damage. However, using these general numbers can help determine the appropriate materials to use within a prosthetic joint.
3. Measurement of Wear in Prosthetic Implants

As discussed herein, it is important to understand not only the wear rate of a material but it is important to understand the mechanisms that cause this wear. Therefore, it is important to accurately model the articulation of a joint during in vitro testing to represent the wear that occurs within a joint during in vivo use. Numerous studies have been performed and papers have been written on the subject of proper wear testing of potential material for hip replacements. It has been determined that there are two important factors to be evaluated while testing a new material. First, it is important to determine the type of lubrication that should be utilized to simulate the environment of the human body. Second, it is important to properly simulate the wear from the joint.

3.1 Lubrication for in Vitro Testing of Prosthetic Joints

Many studies have been performed and documented indicating that one of the most significant factors in developing a good wear model is the lubrication that it utilized during testing. A study performed by Wang and colleagues [9] investigated the necessity to carefully select the lubrication choice during joint testing by evaluating the effect of protein concentration on the wear rate of the material. The lubricants ranged from pure water to a 100% bovine solution enriched with proteins [9]. The study showed that an increase in protein concentration increased the wear rate of the material until a critical protein concentration was reached, at which time the increase in protein concentration actually decreased the wear rate of the material [9]. It was noted that the “critical protein concentration” is actually within the range for normal protein levels within the human body, see Figure 8. This is interesting as it indicates that the human body is not a favorable environment for prosthetic joints.
At the conclusion of his paper, Wang indicated [9] that lubrication is one of the least understood mechanisms of joint tribology. Because of the lack of knowledge and data in this area, Wang stated [9] that it deserves much more attention and study than it has thus far.

### 3.2 Simulating the Kinematic Loading of an in Vivo Joints for in Vitro Testing

The original testing for potential hip replacement joint material consistent of an articulating slider mechanism or pin and disk method, see Figure 9 for additional details. Both of these methods utilize the same sort of simulated linear motion to wear the material. As discussed in a previous section, the component is weighed before and after the experiment to determine the amount of material that is lost due to the interaction between the surfaces per distance traveled or rotation of the joint, also known as the amount of wear. Recent developments in joint testing have developed multi-axial joint simulators. Figure 9 provides an example of a multi-axial joint simulator.
Wang discussed in his paper [9] that during a 1995 ASTM Workshop, he and his colleagues presented information indicating the limitations of these screening wear testers utilized to evaluate materials for prosthetic joints. Their findings concluded that the linear motion of common screening wear machines were determining wear rates as much as three orders of magnitude lower than the multi-axial joint simulators [9]. Of greater importance was the discovery that not only were the wear rates different, they were not consistently different for all materials and therefore the resulting ranking of materials would be different using the multi-axial machines, compared to the linear motion screeners [9]. This was linked to the cross-shear motion produced by the multi-axial machines that was not present in the linear motion screeners.

### 3.3 Development of Test Methods for Evaluating New Material for Prosthetic Joints

A thorough study was performed by Schwartz and Bahadur [10] to develop a novel joint wear simulator. In this study the investigators utilized similar methods discussed by Wang [9] for evaluating a new wear-testing machine. These included evaluating the wear rates of well known and documented materials, and be able to replicate similar wear patterns to actual prosthetic joints that have been removed and examined, see Figure 10. Additionally, all of the testing should be conducted with a lubricant that is able to sufficiently simulate the conditions that are experienced within the human body.
[9]. For Schwartz’s study [10] the lubricant chosen was a bovine solution containing a protein level similar to that found within the human body. Figure 11 provides an illustration of the simulator utilized throughout the testing. The results of the testing documented by Schwartz indicated that this simplified joint simulator was able to produce credible results, making it a technically acceptable screening device to be utilized in determining materials suitable for use in prosthetic joints.

![Figure 10: Implant removed from the body][6]

![Figure 11: Illustration of the novel joint simulator][10]
4. Conclusion

Hip replacements may be necessary for a number of reasons, including joint damage or disease. Studies show that more people are getting hip replacements and that they are getting them at a younger age. The current life span of hip joints is approximately 20 years [2], which may require some patients to receive a revision. It is noted that revisions have a lower success rate and due to the increased age of the patient will have a longer recovery time. All of these factors have made it necessary to investigate the wear of prosthetic joints to attempt to find different materials to lengthen the life of the joint.

There are several wear mechanisms that are prevalent in hip replacements, namely: adhesion, abrasion, third body, fatigue, and corrosion wear. Each mechanism is important to evaluate and therefore it is vital that the proper environment and kinematic loading are simulated. Original screening mechanisms consisted of a linear motion machines that were shown to underestimate the wear rate of materials by orders of magnitude and to rank materials in a different order than those tested utilizing a multi-axial joint simulator, which better represents the hip joint. Additionally, it is of the utmost importance to test the joint with a lubricant that simulates fluid found in the human body. If the protein concentration of the lubricant is too low or too high then the wear rates will be reported too low and unrealistic. Using data that has been collected on materials currently in use and comparing the wear patterns of the tested items to those used in vivo, wear testers can be developed that accurately represent the in vivo results.
References


