Friction and wear characteristic of natural bone for water hydraulic: A computational analysis

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Abstract. Instead of mineral oil, water hydraulic uses seawater or tap water as the medium in its operation. Most of the materials tested have some reaction towards friction and water lubrication. While hydraulic system may be advantaged by natural materials, the related work remains unestablished. In present work, the tribology of bone in contact with stainless steel is computationally simulated. The materials combination used in this study were metals (316L stainless steel and Al2O3) and natural bone. Increase in contact pressure is found to be contributed by the extent of sliding distance. Wear depth is also subsequently increased in this manner. Higher normal load applied on the model exhibits higher contact pressure in between metal-bone pair model.

Keywords. Bone; Water hydraulics; Biomaterials; Wear; Friction.

1. Introduction
Water hydraulic is preferable in industries as it much more cost effective and safe to the environment [1]. Instead of mineral oil, water hydraulic uses seawater or tap water as the medium in its operation. However, water has low viscosity, promotes corrosion, and exhibits poor lubrication. These features limit the development and applications of water hydraulic system. Therefore, it is urgent to evaluate materials to be implemented as water hydraulic valves to ensure this green technology can be eventually adapted and fully utilized in industries.

Studies of tribological properties of hydraulic components in water have been focusing on plastic, ceramic, and metal pairs. It was found that the tribological properties of a material are influenced by sliding velocity [2]. The sliding velocity also contributes largely to the effect of friction on materials [3]. Most studies on this terms agreed that polymer-metal, polymer-ceramic, and ceramic-ceramic pairs work well in water medium. However, some limitations persist. Most of the materials tested have some reaction towards friction and water lubrication. While hydraulic system may be advantaged by natural materials, the related work remains unestablished.

Animal bone consists of both organic and inorganic constituents. The organic part toughens the bone with collagen and non-collagen proteins. The bone is hardened by hydroxyapatite crystals in its inorganic part. Specifically, cortical bone well resisted stress and tension due to the richness of these
two constituents. Cortical bone may be regarded as biological ceramic with properties closed to engineering plastics [4]. Bone naturally has tiny cavities and pores in its tissue. This is desirable in improving water lubrication by formation of puddles within these cavities. Furthermore, bone is highly resistant to corrosion.

Fretting behaviour of cortical bone against titanium alloy has been investigated by Yu et al. [5]. It was found that the wear characteristics of cortical bone are influenced by its microstructure. The higher the friction coefficient also found to lead to more wear depths on cortical bone. Further, Davim and Marques [6] found no dependency on experimental variables towards friction of bovine cancellous bone-metal pair in water, but the sliding distance.

In present work, the tribology of bone in contact with stainless steel is computationally simulated. To the best of the authors’ knowledge, there are very few of such analysis have ever been presented. Basic parameters using ring-on-ring test design are implemented in order to validate the results with experimental study, which representing the water hydraulic valve component. This study aims to evaluate the effect of load and sliding distance on the contact pressure and volume loss of bone.

2. Methodology

The materials combination used in this study were metals (316L stainless steel and Al2O3) and natural bone. A three dimensional model was developed to simulate the wear process at the most critical section of the metal-bone contact pair. The key steps in the development of this model are given in figure 1. The bottom specimen model has 38 mm outer diameter, with 16 mm inner diameter and 8mm height. This model was assigned as the metal, either 316L stainless steel or Al2O3. The upper model was assigned as natural bovine bone with 35 mm outer diameter, 22 mm inner diameter and 18 mm in height. Mechanical properties of the materials used in this simulation are tabulated in table 1.

![Figure 1. Example of a metal-bone tribo-pair model (bottom model represents either 316L stainless steel or Al2O3, while the upper model represents bovine cortical bone).](image)

| Mechanical properties | Materials |
|-----------------------|-----------|
|                       | Bone   | 316L | Al2O3 |
| Hardness (HV)         | 51.3   | 197  | 1680  |
| Modulus (GPa)         | 10     | 200  | 300   |
| Density (kgm⁻³)       | 2060   | 8030 | 3870  |
| Poison ratio          | 0.3    | 0.499| 0.499 |
A MATLAB (The MathWorks, Inc., USA) code was developed to model the fretting wear with the surface nodes can be controlled using COMSOL Multiphysics® (Comsol, Inc., USA) subroutine. The control was done within adaptive meshing constraint. Archard law as equation. (1) was used as the main formulation in present work.

\[ V = \frac{ksF}{H} \]  

Where \( V \) is lost volume, \( S \) is sliding distance, \( k \) is wear coefficient, \( F \) is normal load, and \( H \) is material hardness.

JF Archard [7] proposed this law with validations on various materials [8, 9]. The localize ability of this model can be implemented in finite element (FE) method as shown in figure 2.

3. Results and discussion

The present work simulates the tribological behavior of metal-bone pair as water hydraulic valve during sliding. It is expected that the progressive weakening of contact pairs due to wear can be demonstrated. Figure 3 shows relationship in between contact pressure and force applied. Increased in normal force had increased the contact pressure. On the other hand, longer sliding distance exhibited lower contact pressure, as the load is largely distributed across the area. At initial stage, only a few points on the counter interacted surfaces were in contact to withstand the applied force [10]. As the force grows, the surfaces move towards each other, limiting the distance in between surfaces and growing the contact. At the region where the two surfaces are in contact, deformation and reaction occur. Stress is developed in opposed to the applied load.
Figure 3. Contact pressure on metal-bone pair across normal applied force at different sliding distance.

Friction causes lost in energy and wear off the surfaces in contact. As sliding distance extent, wear volume is consistently increased (Figure 4), regardless of different rate of wear as in 316L stainless steel and Al₂O₃. The wear volume was also affected by the load applied.

Figure 4. Wear volume of the bovine cortical bone model at different sliding distance and force applied.

A fine mesh in FE analysis model is vital in order to guarantee the accuracy of results. Wear volume was found to increase as the ring travel through the contact pair, causing friction and wear on the bovine cortical bone surface. However, bone was found to be more resistant to deformation, friction and wear in comparison to polymer-based materials.
4. Conclusions

Based on the simulation work, the relationship between contact pressure and wear behavior of bovine cortical bone in sliding with metal counterparts is validated. This can be used as reference to computationally investigate the potential of spool valve material performance in water hydraulic system. The conclusion for the present work summarized as follows:

- Increase in contact pressure is contributed by the extent of sliding distance. Wear depth is also subsequently increased in this manner.
- Higher normal load applied on the model exhibits higher contact pressure in between metal-bone pair model.
- Diversity of physical and mechanical properties of materials in contact may affect the test results.

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