Effects of Select Fluids on the Friction of Metal-on-Polyethylene Joint Replacement Surfaces

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ABSTRACT

Lubricants are important factors in the tribology of total joint arthroplasty (TJA) surfaces, which are primarily comprised of a polished metallic or ceramic component articulating on an Ultra-High Molecular Weight Polyethylene (PE) surface. Wear particles released from the PE surface are the primary cause of TJA failure. The human body responds to the foreign, micro-scale particles by activating a cascade of cytokine responses that ultimately leads to osteolysis and aseptic loosening. Although research in the materials selection and design of TJA components is continually advancing, one of the major intrinsic components that affect the tribological response in joints is overlooked. In particular, the properties and composition of joint fluid directly affect the fluid film and boundary lubrication of artificial prostheses. Since the characteristics of joint fluids are likely to differ from patient to patient as a result of varying disease indications, age, health, gender, and activity level, tribological behavior is also likely to vary significantly. The primary objective of this thesis is to examine the effects of variation in joint fluid composition on tribology.

Due to the relative high stresses applied to the knee, the tribological effects related specifically to total knee arthroplasty (TKA) are investigated in detail. Before any joint fluid samples are examined, however, an assay capable of determining appropriate tribological properties is adapted. A unidirectional pin-on-disk (POD) tribometer is therefore selected to measure friction between PE and cobalt-chromium-molybdenum alloy (Co-Cr). Its sufficient precision, short testing time-frame and low cost enables rapid evaluations. Preliminary friction data collected on fluids such as distilled water and bovine serum are used as standards and controls against lubricants in subsequent tests. From this data, the contributions to friction of boundary and fluid-film lubrication in PE on Co-Cr POD systems are discussed. Analysis of these friction properties in conjunction with previously published differences in wear between water and bovine serum leads to a rejection of a hypothesis directly correlating friction and wear. However, since ultimately wear is the important factor in the failure mechanism of TJA, an indirect relationship between friction and wear is investigated and proposed.

Friction is then recorded using joint fluids as the lubricant and compared to the standards. Analysis of the joint fluid data demonstrates significance in frictional behavior, indicating that compositional properties affect friction. Moreover, examination of the data reveals large variation in joint fluids. Comparisons of the data to standard lubricants exhibit the potential for large variations in wear among joint fluids.

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TABLE OF CONTENTS

ABSTRACT **2**

ACKNOWLEDGEMENTS **3**

TABLE OF CONTENTS **4**

ABBREVIATIONS **7**

LIST OF FIGURES **8**

SYMBOLS **9**

CHAPTER 1: INTRODUCTION AND BACKGROUND **10**

- **1.1. Purpose and Benefits of Research** **10**
- **1.2. Introduction to Knees** **10**
  - *1.2.1. Osteoarthritis* 11
  - *1.2.2. Background on Total Knee Arthroplasty* 11
  - *1.2.3. Synovium and Synovial Fluid Response to TKA* 12
- **1.3. Tribology of TKA** **13**
  - *1.3.1. Wear* 13
  - *1.3.2. Wear Mechanisms* 13
  - *1.3.3. Friction* 13
  - *1.3.4. Lubrication in Synovial Joints and in TKA* 14
- **1.4. Components of Synovial Fluid** **16**
  - *1.4.1. Proteins* 16
  - *1.4.2. Hyaluronic Acid* 16
  - *1.4.3. Phospholipids* 16
  - *1.4.4. Other Components* 17
- **1.5. Testing of Materials Used in TKA** **17**
  - *1.5.1. Lubricants* 17
  - *1.5.2. Joint Simulator* 18
  - *1.5.3. Pin-on-Flat* 18
  - *1.5.4. The Case for Pin-on-Disk vs. Simulator* 19
- **1.6. Previous Work** **20**
- **1.7. Aims and Hypotheses** **20**

CHAPTER 2: MATERIALS AND METHODS.. 21

2.1 Materials.. 21

2.1.1. Polyethylene Pins.. 21
2.1.2. Metal Disks.. 22
2.1.3. Lubricants.. 22

2.2. Experimental Setup.. 23

2.2.1. Pin-on-Disk Tribometer.. 23
2.2.2. Hertzian Contact Stress.. 24
2.2.3. Calibration... 25
2.2.4. Surface Roughness.. 26

2.3. Experimental Protocol.. 26

2.3.1. Testing Procedure... 26
2.3.2. Statistical Methods.. 28

CHAPTER 3: RESULTS AND ANALYSES.. 29

3.1 Response of Pins and Disks to Test.................................... 29

3.2 Lubricant Group Results.. 29

3.2.1 Distilled Water and Bovine Serum................................. 30
3.2.2. Bovine Serum Concentrations...................................... 33
3.2.3 Bovine Serum Additives.. 36
3.2.4 Protease Digestion of Bovine Serum............................... 37
3.2.5 Dry.. 39
3.2.6 Phosphate-Buffered Saline.. 40
3.2.7 Petroleum-based Oils... 42
3.2.8 Joint Fluid Samples.. 43
3.2.9 Compilation of Results... 48

CHAPTER 4: DISCUSSION.. 49

4.1 General Discussions... 49

4.1.1 Effect on Friction of Composition and Property Changes of Lubricant.......... 49

4.1.2 Boundary Lubrication and Fluid-Film Lubrication.. 49

4.1.3 Rejection of Correlation between Friction and Wear...................................... 51

4.1.4 Effects on Friction due to Variation in Joint Fluid... 53

4.1.5 POD Friction Test as Assay... 53

4.2 Potential Future Work... 54

4.4 Limitations of the Study... 55

4.5 Significance.. 55

CHAPTER 5: CONCLUSIONS.......... 56

REFERENCES.......... 57

APPENDIX A: PATIENT INFORMATION.......... 62

APPENDIX B: PATIENT DYNAMIC FRICTION DATA.......... 63

APPENDIX C: COMPONENTS OF JOINT FLUID.......... 64

APPENDIX D: CALIBRATION OF FRICTION APPARATUS.......... 65

APPENDIX E: POWER CALCULATION.......... 66

APPENDIX F: COMPILATION OF DYNAMIC FRICTION DATA.......... 67

APPENDIX G: "FRICTION MAP".......... 69

ABBREVIATIONS

Abbreviation	Term	First Reference
ANOVA	analysis of variance	2.4.2
ASTM	American Society for the Testing of Materials	1.5.1
Co-Cr	cobalt-chromium-molybdenum alloy	1.2.2
DPPC	L-α-dipalmatoyl phosphahtidylcholine	1.4.3
EDTA	ethylene-diaminetetraacetic acid	1.5.2
HA	hyaluronic acid	1.2.3
LSPD	least squares protected difference	2.4.2
OA	osteoarthritis	1.1
PBS	phosphate buffered saline	2.1.3
PE	ultra-high molecular weight polyethylene	1.1
POF	Pin-on-flat	1.5.1
POD	Pin-on-disk	1.5.4
THA	total hip arthroplasty	1.1
TJA	total joint arthroplasty	1.1
TKA	total knee arthroplasty	1.1

LIST OF FIGURES

No.	Description	Page
1.2.1.1	Anatomy of the knee	11
1.3.4.1	Example of Stribeck curve	15
2.1.3.1	Schematic of Pin-on-Disk Tribometer	23
2.2.3.1	Schematic of Calibration of Pin-on-Disk	25
2.3.1.1	Friction output versus time for a sample friction test	27
3.2.1.1	Distilled water vs. bovine serum	31
3.2.2.1	Bovine serum concentrations, Group 1	34
3.2.2.2	Bovine serum concentrations, Group 2	34
3.2.3.1	Bovine serum additives	36
3.2.4.1	Proteinase digestion of bovine serum	38
3.2.5.1	Dry	39
3.2.6.1	Phosphate-buffered saline	41
3.2.7.1	Petroleum-based oils	42
3.2.8.1	Joint fluid compilation	44
3.2.8.2	Mean of all joint fluid samples	44
3.2.8.3	Joint fluids in groups	45
3.2.8.4	Group mean of joint fluids in cleaning groups	46
3.2.8.5	Means of the two groups separated into Primary TKA and Revision cases	47
D.1	Calibration of friction apparatus	65
F.1	Compilation of lubricants	67
F.2	Compilation of joint fluid	68
G.1	Example of proposed “friction map”	69

SYMBOLS

Symbols	Description	Units
a	Hertzian contact radius	m
A	Area	m^2
A_a	Apparent area of contact	m^2
E	Young's modulus	Pa
E'	Reduced modulus	Pa
F	Force	N
R	Radius	m
V	Volume	ml
W	Normal load	N
α	Chance of false positive in evaluating null hypothesis	n/a
β	Chance of false negative in evaluating null hypothesis	n/a
μ	Coefficient of friction	n/a
μ_d	Average dynamic friction coefficient	n/a
μ_s	Maximum static friction coefficient	n/a
υ_{PE}	Poission's ratio for PE	n/a

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Purpose and Benefits of Research

The research described in this paper principally analyzes the effects of joint fluid on the tribology of total knee arthroplasty (TKA). Total joint arthroplasty includes both TKA and total hip arthroplasty (THA). For this research, TKA was selected as the primary subject due to the high stresses it is subjected to *in vivo*. Although the magnitudes of stress are higher than those in the hip, the basic concepts are applicable to total hip arthroplasty (THA) and to overall total joint arthroplasty (TJA). TKA is a common surgical treatment for patients with severely damaged knee joint cartilage due to such conditions as osteoarthritis (OA), rheumatoid arthritis and post-traumatic arthritis.

In 2001, the American Academy of Orthopaedic Surgeons approximated that surgeons performed close to 270,000 TKAs annually in the US.[1] Even though the surgery is generally considered a routine procedure, tribological failure primarily limits the success of prostheses. Ultra-high Molecular Weight Polyethylene (PE) wear, the result of tribological failure, leads to osteolysis and aseptic prosthetic loosening.[10] About 22,000 TKA revision surgeries a year are performed due to these failures.[64] Researchers have made a great effort to minimize the problem of wear by examining alternative materials and configurations to mimic the natural joint for low friction and low wear rates.[43,46] However, less emphasis has been placed on investigating the tribological effects of joint fluid on the articulating surfaces. The composition and properties of joint fluids varies for patient to patient, which will lead to variances in the tribological performance.

Thus, an in-depth study on effects of joint fluid composition on tribology will allow researchers to understand how lubricants will react to certain materials and tribological conditions. Better materials and designs can be developed that are tailored specifically to perform optimally with the components of joint fluid. Similarly, if surgeons have knowledge prior to surgery that a patient has a specific distribution of protein, phospholipids and HA concentrations, the surgeon may be able to determine an optimal material and design for the patient. Moreover, the best treatment for disease is prevention. So if future research is able to determine how the concentration levels of components within the fluid is related to certain diseases, early treatment methods involving pharmaceutical intervention or injections may be initiated to help reduce the symptoms of disease.

This thesis builds off the Ph.D. thesis of D. Mazzucco,[37] who investigated the effects of joint fluid on the tribology of TKA in a comprehensive study. As part of his work, an examination of the relationship between component concentrations in joint fluids and friction was initiated. Therefore, much of the background work as presented in this thesis is based on the doctoral thesis. Moreover, in order to assess repeatability of experiments, the testing procedures were followed as close as possible.

1.2 Introduction to Knees

The human skeletal system is made up of just over two-hundred bones, which meet at junction points. The knee joint is a type of hinge joint that is able to handle large loads. Articular cartilage and synovial fluid in the joint enable movement at coefficient of friction values below 0.01.[1] The low friction in a healthy knee allows it to function for many decades without wearing out. However, disease and trauma can unbalance the biological equilibrium of healthy knee function. Even with the aid of pharmaceutical and physical treatments, the relatively low regenerative nature of articular cartilage may eventually lead to artificial replacement of the joint. There have been numerous studies on synovial fluids in natural joints over the past several decades due to the large volume of patients with knee complications. However, less has been studied on the impact of joint fluid on artificial joints. For distinction, fluids referring to the natural joint will be referenced as synovial fluid while those referring to the artificial joint will be called joint fluid for the remainder of this paper.

1.2.1 Osteoarthritis

Osteoarthritis (OA) is the most common form of arthritis, especially in the elderly. This disease is due to the gradual degeneration of cartilage that lines the surfaces of the bones. Once the protective layer of cartilage wears away and no longer cushions impact and facilitates sliding for joint movement, the exposed bone may rub, causing pain, swelling, and loss of movement. OA can be caused by bone misalignment, trauma, or misuse, and the symptoms typically take years to emerge. Moreover, OA affects more than just the joint. It will undoubtedly have an impact on the general lifestyle of the patient, due to limited mobility and exercise. Thus, patients may form additional physical complications such as heart disease, as well as changes to psychological behavior, thereby compounding the difficulties in treatment.

20 million Americans are afflicted with this disease, and the number is likely to grow with the general increase in life expectancy. As a safe estimate, more than half the people over 65 years of age will show symptoms of OA in at least one joint.[47]

Treatment options include exercise, weight control, rest and joint care, pain relief techniques, medicines, and/or surgery. Controlled exercise is the best option, and can be used as a preventive measure as well. Surgery is the most invasive procedure, but may be the only option left to prevent pain.

1.2.2 Background on Total Knee Arthroplasty

A surgeon and patient take into consideration such factors as the level of pain, disability, age, general health and lifestyle to determine the appropriateness of undergoing TKA surgery. It is a procedure that is used to treat OA and other joint disorders. Generally, these prostheses have 10-year survivorship rates of above 90%,[46] and patients experience increased mobility, less pain and less swelling. The general lifestyle of the patient will likely improve as well.

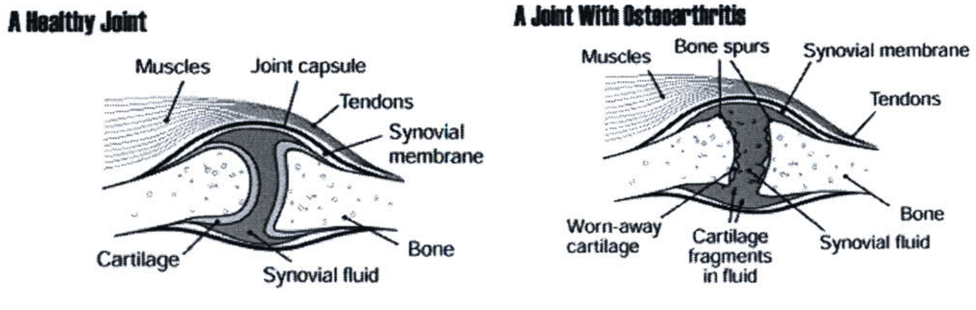


Figure 1.2.1.1 Anatomy of the knee A healthy knee joint (left), a knee joint with osteoarthritis (right). (source: www.niams.nih.gov)

In TKA surgery, the surgeon removes portions of the distal femur and replaces it with a metal component, typically of cobalt-chromium-molybdenum (Co-Cr) alloy. The proximal portion of the tibia is also removed and replaced with a PE-capped metal mount. A PE button is then placed on the platella. The menisci, collateral ligaments and anterior cruciate ligament, synovial sac and fluid, and articular cartilage are all removed as well. Numerous materials and surgical techniques are used, with the patient weight, sex, age, and activity level considered as factors in determine the appropriate design.

1.2.3 Synovium and Synovial Fluid Response to TKA

TKA surgery is an invasive and traumatic procedure. Much of the native knee tissue is sacrificed. The body naturally responds in a variety of ways, which will not be discussed in detail. The tissue of importance in this study is the synovial membrane, or synovium, which houses the joint fluid and is a thin membrane of connective tissue found in the innermost lining of the joint capsule. This membrane begins a regeneration process. Regeneration of the synovial membrane to the extent of arthrofibrosis has been studied.[8] Although the completeness of the regeneration and level of functionality of the synovium is unclear, the membrane seemingly has regenerative effects in TKA.

Synovial fluid is found within the synovium, which is comprised of two cell types, referred to as type A and type B synoviocytes. Type A cells are similar to macrophages, while type B cells resemble fibroblasts. The synovium acts as a control of nutrient supply to the avascular cartilaginous tissues in the intra-articular region. It is also responsible for molecular component synthesis of synovial fluid, including HA and Lubricin.

Since most of the synovial fluid is aspirated or lost during the surgical procedure, a new joint capsule forms following surgery around the prosthetic. In the natural joint, synovial fluid functions as a lubricant, facilitating both fluid-film and boundary lubrication.[13] In addition to water, the fluid consists of proteins derived from blood serum, hyaluronic acid (HA), glycoproteins, and phospholipids.[69] Other components in smaller concentrations, such as sugars, ions, and small proteins are found the fluid, which are filtered in through the synovial membrane. Fluid film lubrication in the natural joint is enabled by the elasticity of cartilage, which allows the surface to deform and provide a larger surface over which the fluid can be squeezed. This form of lubrication is called elastohydrodynamic lubrication.[21] The porosity of cartilage allows fluid to secrete out, causing squeeze-film lubrication[26] and weeping lubrication. Fluid film lubrication is thus not likely to happen in artificial joints, due to the physical properties of the materials.

Boundary lubrication is also likely to be different in the artificial joint than in the natural. The interaction between the surface and lubricant is important to boundary lubrication and its effect on tribology. The components within the fluids interact well with cartilage found in natural joints, but may not be compatible to the materials used in artificial joints in promoting boundary lubrication. The concentration of components that make up joint fluid is also likely to vary from case to case due to the uncertain response of the synovial membrane.

Furthermore, synovial fluid is partly composed of plasma filtrate and products of Type B synoviocytes and superficial chondrocytes.[38] Accordingly, the lack of filtration of joint fluid in artificial joints may upset the balance found in healthy synovial fluids. The damaged membrane may not be able to produce the same synoviocytes as before membrane injury. Thus, the synovium is responsible for the production of molecular components of synovial fluid and filtration, thereby making it essential in maintaining concentration levels in synovial fluid. The concentration of components between pre-surgery and post-surgery fluids is likely to be different due to the damage of the membrane, since molecular production may be hampered and the filtration integrity breached, allowing uncontrolled fluctuations in concentrations, until the membrane is regenerated.

1.3 Tribology of TKA

1.3.1 Wear

The overriding concern in TJA in general is wear. Overall, UHMWPE wears at an annual rate of 0.1 mm/year or 82 mm^3/year against a 32 mm diameter femoral head in THA.[49] These particles are typically smaller in hips (generally <1 μm, with few above 10 μm) as compared to the knee (2-20 μm).[60] Some other studies give knee particle sizes of around 0.8 μm.[41] Particles, especially those below 50 μm, cause complications in the body as macrophages gather and attempt to digest them. These synovial macrophages release regulators, including interleukin-1, interleukin-6, and tumor necrosis factor-α,[72] that eventually lead to osteolysis, which causes the breakdown of bone around the prosthesis, leading to loosening of the prosthesis. The main emphasis behind tribological research is to reduce wear generation particles, which leads to osteolysis, and ultimately causes aseptic loosening.[25] Also, depending on the type of PE that is used, macrophage response that causes osteolysis may be different as well.[63] Wear particles of less than 1 micron size have been found in the liver, spleen and abdominal lymph nodes of patients with TJA.[71] These particles are likely to cause problems in addition to localized osteolysis. Alleviating the wear process will greatly improve the prostheses performance and patient life.

1.3.2 Wear Mechanisms

There are three primary wear mechanisms in TKA: abrasive wear, adhesive wear, and fatigue/delamination wear.[65] Abrasive wear is the removal of material from one surface by another. Since no surface is absolutely smooth, local asperities on the harder surface will plow through the softer material and gouge out wear particles. Adhesive wear occurs when localized chemical bonding occurs between the two surfaces due to high pressure. The adhesive strength is higher than the yield strength of the material, and a small piece of the material is removed. This leads to transfer films of polymer on the metal surfaces, as the PE adheres to the metal surface. This type of wear is more common in hip replacements than in knee. Fatigue, or delamination wear, causes subsurface cracks to form and propagate due to cyclic loading. The crack tips experience high stresses, which propagate the cracks until one crack joins with another. This creates large wear particles, as the surface flakes off. In the knee joint, wear appears to be caused primarily by fatigue from evidence of larger wear particles than those in hips. Finite element models have shown that the contact stresses reach 40 MPa and 15 MPa in knees and hips, respectively. The yield strength of PE is generally around 20 MPa.

1.3.3 Friction

Although friction and wear are often mentioned and grouped together, friction values are not usually recorded for TJA. Due to the complexities involved in joint simulation, the testing simulators are not easily equipped to measure a meaningful friction measurement. Wear is much easier to record, since it generally considers the loss in mass at select times. Friction traditionally requires the ability to record force real-time. Furthermore, it is not easy to establish a direct and practical relationship of a friction reading taken on a unidirectional pin-on-flat apparatus to a multi-directional complexly oriented simulator.

The measurement of friction is nonetheless important, since it serves as one of the key components of tribology. Wear in TJA, as indicated in the previous section, is caused by abrasion, adhesion, and fatigue. Friction is similarly influenced by abrasive and adhesive wear.

In the case of metal-on-PE articulations, friction is proportional to the real area of contact, A_r. In elastic deformation conditions, the real area of contact is proportional to the 2/3 power (Hertzian contact stress), thereby decreasing the coefficient of friction with load.[51] The coefficient of friction is also independent of velocity.[70] In boundary lubrication conditions, velocity should not affect the friction.

1.3.4 Lubrication in Synovial Joints and in TKA

Lubricants are generally used to lower friction and reduce wear. Their roles include: 1) prevention of particle agglomeration at the interface, 2) removal of particles from the interface, 3) prevention of adhesion between the surfaces, 4) reduction of heat due to plastic deformation, and 5) creation of gap between surfaces to prevent plowing and plastic deformation. In the human body, lubricants are used for similar purposes. There are varying types of lubrication that need to be considered. The properties of the lubricant and the tribological conditions determine the type of lubrication. Overall, the lubrication in the knee joint is a combination of fluid-film and boundary lubrication.

Fluid-film Lubrication

Fluid-film lubrication relies on motion to generate relative fluid movement and support load. Movement causes the surfaces to separate, optimally eliminating friction and wear. It is dependent on the viscosity of the fluid, surface topography of the surfaces, and velocity. These variables bear the load of the work that is required to move the lubricant out of the way of the moving surface. If sufficient viscosity, speed and topography conditions are met, the two surfaces will separate. Successful fluid-film lubrication will cause the gap to exceed the asperity heights of the surface, eliminating certain contributors to friction and wear. The factors contributing to the friction and wear (adhesion, abrasion, and fatigue) decrease. In the natural joint, elastohydrodynamic lubrication (an extension of hydrodynamic lubrication where the elastic qualities and movement of cartilage allow support of high loads), squeeze film (where viscosity of the lubricant causes an exerted force as the surfaces approach each other), and weeping lubrication (where porosity of cartilage allows fluid to squeeze out and form a cushion barrier between the surfaces) are all variations of fluid-film lubrication. A recent theory of lubrication describing the sponge-like behavior of cartilage has been reported as well.[50] This theory compares cartilage movement to an object sliding over a sponge, where in the leading edge of the movement, liquid is squeezed out to form a thicker layer of lubrication. The reverse is true in the trailing edge. All in all, even though it is not certain which exact variation is responsible for fluid-film lubrication, the joint operates with characteristic of fluid-film lubrication.

Boundary Lubrication

In contrast, boundary lubrication does not rely on motion, but rather on components of the lubricant adhering to the surface and creating a layer that repels load. Adhesive wear is reduced, as well as abrasive and fatigue wear. Successful boundary lubrication is effective in reducing damage to the surface, and thereby the production of wear particles since work is shared by the molecules covering the surface as well as the asperities. Boundary lubrication nevertheless makes contact with the asperities, causing its friction to be typically higher than fluid-film lubrication. Additionally, boundary lubrication functions better with long, unbranched chains compared to short, branched chains. A material that is hydrophilic at one end and hydrophobic also is a preferred boundary lubricant, as the hydrophilic end adheres to the metal. Therefore, long, unbranched fatty acids and alcohols are good boundary lubricants used in conventional applications, such as in grease and viscous oils.

Stribeck Curve

The load, relative velocity of the surfaces and lubricant determine the type of lubrication. Boundary lubrication supports higher loads than fluid film lubrication. Thus, at low velocity, boundary lubrication is the dominant form of lubrication, since it carries most of the load. No pressure is built up between the surfaces, and so loading is carried by the adsorbed molecules that line the asperities in the contact area. As the velocity increases, hydrodynamic pressure builds up between the articulating surfaces. Load is carried by both the hydrodynamic pressure and the contact pressure on the asperities. This is considered the mixed lubrication regime. As velocity increases even more, the hydrodynamic pressure is sufficient to support the applied load. There is no contact of asperities between the two surfaces. Lubrication enters the hydrodynamic regime. A Stribeck curve typically illustrates the three lubrication regimes.

In the boundary lubrication regime, however, friction is not dependent on load, viscosity, or velocity, but rather on the component adhering to the surface. In fluid film lubrication, friction rises with increased viscosity and velocity, but lowers with increased load. If altering any of these variables causes a change in friction coefficient, lubrication is most likely in the fluid-film regime.

As previously indicated, the natural synovial knee joint predominantly operates in fluid-film lubrication (elastohydrodynamic) and boundary lubrication. Since a natural joint has dynamic friction values of less that 0.01, fluid film lubrication is a likely mechanism. However, boundary lubrication contributes as well since the knee has low friction rates at no movement. For artificial joints, there is still uncertainty as to what lubrication regimes are important. In order to achieve fluid-film lubrication, it is estimated that the fluid-film thickness needs to be three times the surface roughness (R_a) in order to prevent asperity contact.[11]

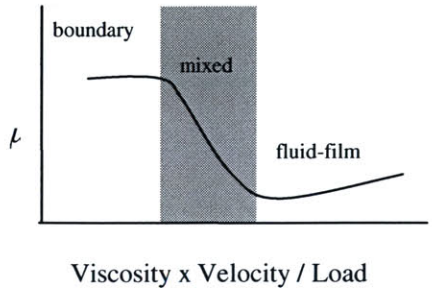


Fig. 1.3.4.1. Example of Stribeck curve The three lubrication regimes are shown.

1.4 Components of Synovial Fluid

1.4.1 Proteins

Proteins make up the largest portion in synovial fluid, other than water. In healthy joints, the synovial membrane filters out large proteins. Thus, synovial fluid has lower protein concentrations than serum.[37]

Protein concentrations, again as tabulated by Mazzucco[37], vary depending on patient indication. Healthy patients have concentrations close to 20 mg/ml. Concentrations in patients with OA double to about 35 mg/ml. RA patients have even higher concentrations at 45 mg/ml.

The large increases in concentrations in diseased patients seem to support the idea that the filtration process of the membrane is very influential. The question that rises from this result is what effect protein has on friction, and on tribology overall. This question is just starting to be examined by researchers.

1.4.2 Hyaluronic Acid

Hyaluronic Acid (HA) is a glycosaminoglycan that is found in connective tissue that is produced in fibroblast-like cells called Type B synoviocytes.[37] It is the largest molecule in synovial fluid (molecular weight of 10^6 and 10^7 Da), and is thought to influence the flow properties of the fluid (such as viscosity). Therefore, HA may be very influential in fluid-film lubrication. Additionally, HA chains may intertwine into high molecular weight and concentration,[68] which may affect tribology as well. The viscosity increases as the HA chains interlock when compared to a dilute solution.[18]

HA concentrations, again as tabulated by Mazzucco,[37] appear to have a relationship to disease. Healthy knees have concentrations from 1 to 4 mg/ml. OA cases have mean concentrations close to 1 mg/ml, while RA cases seem to be below 1 mg/ml. Joint fluid from THA were examined, and found to have HA concentrations less that OA.

Since concentration is influenced by the amount of HA molecules as well as the amount of fluid, two factors will fluctuate the concentration. In TKA patients, HA production may be affected by the presence and activity of the Type B (fibroblast-like) synoviocytes in the synovial membrane. Since the synovial membrane is damaged during surgery, production levels may not be the same as before surgery. Likewise, the body response to TKA may (likely) increase inflammation and permeability of the joint sac, thereby decreasing HA concentrations.

In general, the addition of HA improves lubricating condition in the fluid-film regime. Adding 0.3 wt. % HA in saline can reduce the friction coefficient, as well as the wear factor.[59]

1.4.3 Phospholipids

The third major component of synovial fluid are phospholipids. Their role in boundary lubrication has been noted in natural joints. L-α-dipalmitoyl phosphatidylcholine (DPPC), which makes up 45% of the phospholipids in healthy fluids[23,53] and 15% of the total lipids in normal fluid may provide boundary lubrication in artificial joints. Papers indicate that the DPPC, of surface-active phospholipids (SAPL), act as boundary lubricants in THA.[52] Also, an increase in phospholipids concentration significantly reduced wear.[6]

From tables tabulated by Mazzucco,[37] healthy patients had phospholipids concentrations at 0.13 to 0.15 mg/ml. OA patients had 0.3 ± 0.1 mg/ml, and RA patients had 0.6 to 0.8 mg/ml.

1.4.4 Other Components

The components of synovial fluid are important to note independently. However, their interactions within the fluid likely have an impact on their effectiveness. For example, HA and proteins may bind together.[22] Thus, using these data for analysis of results is a preliminary step.

Most of the data presented pertain to synovial fluid. Concentration data for joint fluid is scarce compared to synovial fluid. See Appendix C for a chart compiled by Mazzucco relating component concentrations to disease.

Finally, Lubricin is a protein of interest in boundary lubrication. Radin and Swann[54] discovered during a cartilage-on-cartilage test that a protein was responsible for lubrication. Swann continued his research and isolated a 228 kDa glycoprotein which he named Lubricin. Jay *et al.* discovered that lubricin is made by synovial fibroblasts through the expression of megakaryocyte stimulating factor gene.[27] These researchers claim Lubricin effectively lowers friction and wear. However, Schwarz *et al.*[62] refutes this claim and contends Lubricin is simply a carrier for the insoluble surface-active phospholipids, which they assert is molecule actually responsible for friction reduction.

1.5 Testing of Materials Used in TKA

1.5.1 Lubricants

Historically, PE was chosen as one of the articulating surfaces due to its low coefficient of friction under dry conditions. As the role of lubricants became more known, experiments were considered using dry and wet conditions, with distilled water as the lubricant.[20] Dry conditions were found to generate ten times more wear. McKellop *et al.*, eventually began a movement some time later to replace water with bovine serum as the lubricant of choice since PE articulation on a pin-on-flat device with bovine serum resulted in lower wear rates and morphology more like those found at clinical retrieval.[40] The use of bovine serum apparently reduced adhesion. Also, one of the components in the serum appeared to have performed as a boundary lubricant. Although the exact mechanisms of wear and components of bovine serum and synovial fluid may be different, the basis to use bovine serum as the lubricant of choice was based on the overall similarity of wear rate results. Since that time, numerous groups have reported the advantages of using bovine serum rather than distilled water in reducing wear, with examples of water performing fourteen times worse than serum in terms of wear.[7,19,22,75]

Although the acceptance of bovine serum as the standard lubricant has been gradual, it is now considered the standard. The appropriate dilution of bovine serum is under debate, with ASTM standards set at dilution up to 75% by volume of bovine serum in water.[3]

Nevertheless, bovine serum has molecular and physiological properties distinct from joint fluid. The components of bovine serum that are responsible for lubrication is yet unknown, and the stability of bovine serum is questionable. Bell *et al.* showed that lipid levels in serum changes with time, with microbial contamination affecting its stability.[5] DesJardins *et al.* similarly found that protein content changed as well.[17] Thus, the results of a joint simulator test using bovine serum as the lubricant only serve as approximations of synovial fluid performance.

Some other lubricants of note are DPPC and saline with HA. In the former, Ahlroos and Saikko found that DPPC used as a lubricant reduced wear to near zero using a bi-directional pin-on-flat (POF) device in which they noticed a transfer film.[56] Numerous groups are still researching different lubricants to obtain wear rates and morphology similar to those found clinically in patients.

1.5.2 Joint Simulator

The standard for testing tribological features of joints is the joint simulator, which mimics the orientation and magnitude of the loads. Ideal simulators are those that produce similar type and amount of wear and particles of a comparable morphology as found in clinical cases. Typically, the simulator is sealed and temperature-controlled. After these simulators are run for millions of cycles, which take a considerable amount of time, the materials are generally just simply weighed and inspected for wear. Simulators do not generally provide quantitative data. Also, these simulators obviously only account for physical tribological factors, and do not take into consideration biological factors that would affect the tribology in a body. Moreover, joint simulators are expensive and difficult to manage.

The choice of lubricant in joint simulation is also an important factor to consider. Typically, human joint fluid is not available due to the limited supply. Joint simulators require a relatively large quantity of fluid. Healthy knees also do not contain much fluid, and only through inflammation do knees generally have enough synovial fluid for suitable extraction. Researchers are thus relegated to use synthetic lubricants, and ASTM[25] simply recommends that these lubricants be volume, concentration, and temperature controlled. There is no standard as to the lubricant type. Lubricants can also be replenished by the researcher. ASTM does recommend a bovine serum lubricant supplemented with 0.2 to 0.3% sodium azide and 20 mM ethylene diaminetetraacetic acid (EDTA). The sodium azide limits bacterial growth in the fluid through the lengthy process while the EDTA discourages calcium phosphate precipitation. Sodium azide also may have a role in inhibiting protein adsorption to the surfaces.[59]

Overall, joint simulators provide a reasonably good idea of wear performance for artificial joints. The cost, time, and variability of lubrication are some drawbacks to the efficiency in using a joint simulator system.

1.5.3 Pin-on-Flat

A pin-on-flat (POF) system is a device that allows a pin to articulate on a flat surface. While the bottom stage is stationary on a y-axis stage, the top stage holds a pin that is slid across the bottom stage in the x-axis direction. The top stage reverses direction, and slides back across in the negative x-axis direction. Normal load is applied, and the frictional force in the transverse direction is measured. This device provides both wear and frictional data, as strain gauges output quantitative frictional force and the pin can be weighed for loss of mass over a set period of revolutions (or distance slid).

Although there are questions raised about the relevance of the simple test compared to the complex tribological system of TJA, POF tests have shown similar wear factor results to clinical findings in THA when the motion of articulation was altered.[9,55]

A maximum sliding velocity of 30 mm/s for THA is set as a guideline.[28] ASTM also recommends that the temperature be controlled at 37 °C, the lubricant be bovine serum or equivalent, 0.2-0.3% sodium azide and 20 mM EDTA be added to the lubricant, the frequency be 1 Hz (equivalent to one human step), and sliding speed controlled at between 20-40 mm/s. Additionally, flat-tip cylindrical pins are usually recommended in order to easily calculate a nominal contact stress and conduct tests at stresses similar to those *in vivo*,[58] although other configurations are considered. These pins are made of the softer material, which is usually PE, in order to limit immediate scraping and gouging in the alternative arrangement of a hard pin on a softer material. ASTM finally recommends that the surface roughness of the metal be characterized.

The POF test has shortcomings as well, in that the complex stresses and geometry of a TJA system cannot be imitated. However, the apparatus has few parts and outputs quantitative information. Additionally, test time can be reduced to minutes rather than weeks. This apparatus will by no means provide precise measurement of friction and wear, but can be a reasonable source of data to begin preliminary analysis and assess relatively quick and simple tribological behavior of materials and lubricants.

1.5.4 The Case for Pin-on-Disk Test vs. Simulator

An alternative friction testing device is the Pin-on-Disk device (POD). This is a apparatus that allows a pin to articulate on a flat disk. The disk spins in a circular manner beneath the pin, inducing relative sliding motion between the pin and the disk. Normal load is applied, and the frictional force in the transverse direction and tangent to the circular track is obtained. This device provides both wear and frictional data, as strain gauges output quantitative frictional force and the pin can be weight for loss of mass over a set period of revolutions (or distance slid). Since ASTM does not set standards for POD, relevant conditions from the POF standards are applied. This device is preferable due to a limited testing area, allowing containment of the lubricant fluid. The disk is usually placed inside a well that spins on a spindle.

Wear tests in joint simulators require long test-time periods. It would undoubtedly be preferred to have a more rapid tribological assay that does not deal with the complications of the degradation of bovine serum as well as the cost considerations. Since friction can be evaluated rather quickly on a POD apparatus, it seems a good option to consider.

A frictional assay will alleviate the lubricant volume, time and cost concerns associated with wear studies. Even though wear is the main contributor to the clinical problem of TJA failure, evaluating friction may provide valuable information to overall tribological behavior, due to the related mechanisms contributing to both friction and wear (adhesion and abrasion). Frictional work is manifested in energy dissipation processes that damage the surface. Therefore, if the energy dissipated from frictional work is applied only to the surface, increased friction will increase wear.

The case for a relationship between friction and wear was claimed by Wang in a hip simulator.[74] However, his method of changing coefficient of friction was by changing the radial clearance of the heads. Since the geometry of the articulation changed, wear may have been affected by more than just friction change.

Some recent work shows attempts at obtaining coefficient of friction values. Weightman *et al.* measured friction between 0.05 and 0.1 in metal-on-PE hip designs lubricated by bovine serum.[77] Wang also found converted torque measurements to friction for bovine serum in THA to be 0.05 to 0.11.[74] Since these measurements were taken on simulators, the geometries and loading patterns will cause friction values to differ from those in POF.

Friction tests for joint fluids have been conducted at smaller scales compared to bovine serum tests. Walker reported μ of 0.05 for synovial fluid in Co-C on PE.[73] It is not known what apparatus he used. Sawae *et al.* also reported μ for PE and both alumina and stainless steel lubricated by saline, bovine serum, and albumin solution.[59] Saline and water gave similar results of ~0.05 for metal-on-PE. They eventually increased to 0.1 and 0.2 for saline, which was probably due to the transfer film. When sliding against stainless steel, bovine initially had higher friction than saline at around 0.06, but then maintained its friction while the saline jumped well above that to over 0.1.

1.6 Previous Work

As mentioned in Section 1.1, this thesis is an extension of the doctoral thesis by Mazzucco.[37] Much of the background information, as well as the experimental protocols, are based on his work in order to ensure repeatability.

1.7 Aims and Hypotheses

The overall objective of this research is to evaluate the effect of lubricants on the friction of metal-on-PE in joint replacement systems. Continuing on the doctoral thesis of Mazzucco,[37] experimental procedures and protocols are revisited to verify repeatability of POD tests. Identical testing conditions and materials are employed whenever possible, with slight modifications only when deemed necessary.

Groups of lubricants are tested on a POD apparatus. Analysis of the friction results of the lubricant groups assist in determining mechanisms of friction in TJA systems. The evaluated lubricant groups are:

- distilled water
- bovine serum
- pre-diluted bovine serum in varying concentrations
- bovine serum with additives
- bovine serum with protein digestion
- dry
- phosphate buffered saline and HA
- petroleum-based lubricants
- joint fluid samples

Once these lubricants are tested, the data will be analyzed and compared to determine the lubrication characteristics of joint fluid.

The hypotheses that are tested in this study include the following:

- Friction of PE on Co-Cr is affected by changes to compositions and properties of lubricants.
- PE on Co-Cr surfaces in POD testing are capable of both boundary lubrication and fluid-film lubrication.
- Friction results can reasonably and directly predict wear behavior. An increase in friction will lead to an increase in wear.
- The friction of PE on Co-Cr using joint fluids varies widely, due to the variance in joint fluid composition and properties from patient to patient.
- The POD friction test can be used as a relevant and reliable assay to determine wear behavior using joint fluids.

CHAPTER 2: MATERIALS AND METHODS

2.1 Materials

The friction apparatus primarily consisted of a pivoting arm and turntable. This custom pin-on-disk apparatus (Komvopoulos *et al.*[31]) was provided by the Laboratory for Manufacturing and Productivity in the Mechanical Engineering Department at MIT.

A test disk was mounted inside a disk carrier well that was attached to a rotating turntable (spindle) by a central bolt. The turntable was driven by a variable-speed controlled DC motor. The track radius for this project was set and unaltered throughout the duration of the tests. Thus, only one test was performed on one disk specimen. The rotating well also provided ample room to contain about 5 ml of optional lubricants in addition to the disk. The lubricants used in the study were dispensed onto the disk along the circumferential path of the pin prior to contact of the articulating surfaces, thereby ensuring exposure of the lubricant to the metal surface.

A UHMWPE pin, the opposing articulating material, was fixed to one end of an arm pivoting about a vertical axis. The arm was, however, fixed along the horizontal axis. Dead weights were placed directly on top of the PE pin, applying normal force directly above the contact point. At the start of a test, the PE pin was placed on top of the metal disk, establishing the articulating point of contact. A counter-weight to balance the apparatus with zero dead weight and normal force was applied at the opposing end of the pivoting arm. This guaranteed that the placed dead force was the normal force applied to the metal disk.

Strain gauges were used to measure transverse displacement of the vertically pivoting but horizontally fixed arm. When a load was applied to the pin and the disk was rotated beneath it, a frictional force was manifested in a transverse force applied to the pin and the arm. The strain gauges emitted a voltage reading that was recorded onto a computer using an input board (68-pin E Series, 16 AI Channels; National Instruments, Austin, TX), Data Acquisition hardware (DAQCard 6062E; National Instruments, Austin, TX) and Measurement and Automation software (LabVIEW v.7.0; National Instruments, Austin, TX). The voltage reading was converted to frictional force through a daily calibration procedure.

2.1.1 Polyethylene Pins

The cylindrical PE pins were provided by Smith & Nephew (Memphis, TN), which were machined from accepted rod stock of PE (GUR 1150; Westlake Plastics, Lenni, PA). The pins had a length of 20 mm and diameter of 3 mm. One end of the pin, the articulating tip, was spherical, with 3 mm radii. The hemispheroidal pin permitted simplified contact stress and contact area calculations, which are not true contract stress and area calculations, but an estimate.

The pins were visually examined both before and after testing using an optical microscope (SZ-PT optical microscope, Olympus, Japan). Prior to testing, the tips of unused pins exhibited tiny steps that formed the curvature of hemispheroidal tip likely due to the machining process. Thus, the curvature was not entirely smooth. However, the steps were very small and were only visible through a microscope, thereby allaying concerns of a rough PE surface. The PE tip was in essence smooth for the purposes of testing.

Additionally, the PE pins were not sterilized in general before testing. Ultrasonic cleaning, detergent cleansing, and alcohol rinsing techniques were attempted but were deemed not necessary or influential to testing results.

2.1.2 Metal Disks

The metal disks were formed from accepted bar stock cobalt-chromium provided by Smith & Nephew (Memphis, TN). The 50 mm in diameter and at least 6 mm in thickness disks were polished to implant grade specifications. Each disk was manually polished to a mirror finish and cleaned prior to every test. First, the disks were first rinsed in tap water and swabbed clean of surface contaminants left over from previous tests. The disks were then manually polished for several minutes using 0.3 μm Alpha Alumina Micropolish solution (Buehler, Lake Bluff, IL) on an 8-inch diameter micro-cloth (catalog number 40-7218, Buehler, Lake Bluff, IL) fixed to a Vari-Pol VP-50 (Leco Corporation, St. Joseph, MI) operating at 150 rotations per minute. The disks were rinsed and swabbed using tap water.

A second polishing step was performed using a Mastermet Colloidal Silica Polishing Suspension (catalog number 40-6370-064, Buehler, Lake Bluff, IL). This minute-long process was again carried out manually on another 8-inch diameter micro-cloth (catalog number 40-7218, Buehler, lake Bluff, IL) fixed to a Vari-Pol VP-50 (Leco Corporation, St. Joseph, MI) operating at 150 rotations per minute. The polished disk was quickly rinsed in distilled water.

Two varying final cleaning steps were performed through the course of the study. The first version took the colloidal silica-polished disk and soaked it in a 100 ml beaker filled with distilled water. The beaker was then placed in a Branson 3510 ultrasonic cleaner for 10 minutes. The disk was removed from the beaker and dried by warm air convection using a hand dryer.

The second version took the colloidal silica-polished disk and placed it in a 100 ml beaker. Powdered detergent (Pex Laboratory Cleaner; Peck's Products Company, St. Louis, MO) was mixed with distilled water and then placed in the Branson 3510 ultrasonic cleaner for 5 minutes. The beaker was subsequently rinsed out with fresh distilled water and then placed again in the ultrasonic cleaner for an additional 5 minutes. Finally, the cleaned disk was removed from the beaker and dried by forced warm air convection using a hand dryer. Throughout the whole process, no contact with the top (articulating) surface was made.

Additional cleaning steps, such as rinsing with methanol and swabbing with cotton, was attempted through the course of the study. However, these steps were not permanently implemented to the cleaning process because they seemed to have little effect to the testing results. The second cleaning version utilizing the powdered detergent was added to the process due to slight colloidal silica residue remaining after the completion of the first cleaning version.

If a scratch or contamination appeared at any point during the polishing and cleaning processes, the most recent polishing step was repeated. Also, since the friction testing process did not usually form scratches on the Co-Cr surface, the polishing process more often than not commenced with the colloidal silica stage. Following the final polishing step, all cleaning methods were employed to ensure contaminant-free articulating metal surfaces.

2.1.3 Lubricants

Due to the large number of lubricants and sorted lubricant groups, the materials used to produce the lubricant solutions are detailed in Chapter 3 along with the results. Please refer to the appropriate lubricant group for the list of materials. A sampling of the lubricant groups is provided below:

1) Distilled water
2) Bovine serum

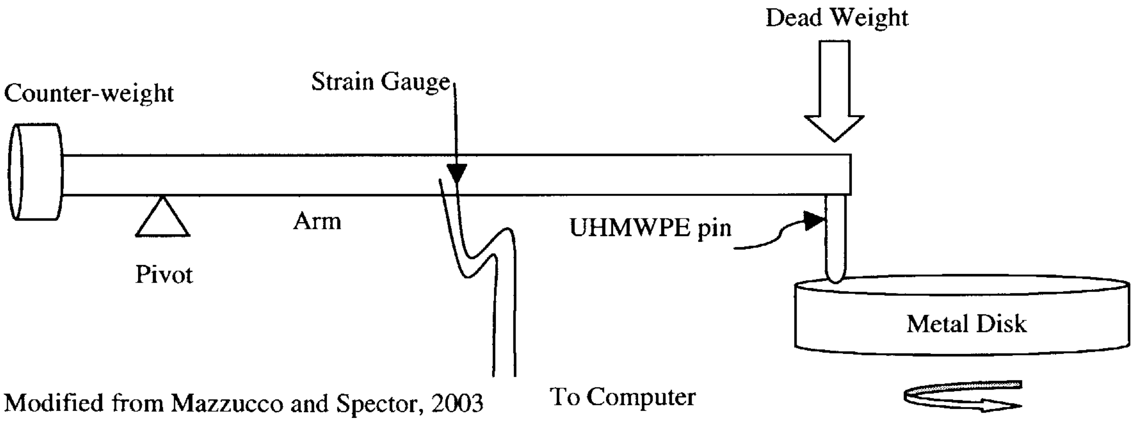
3) Dilutions of bovine serum
4) Bovine serum with additives
5) Phosphate Buffered Saline (PBS) and PBS with HA
6) Petroleum-based oils
7) Dry
8) Joint fluid samples

2.2 Experimental Setup

2.2.1 Pin-on-Disk Tribometer

PE pins on metal disks were chosen because a metal pin would continually deform a PE disk due to a viscoelastic effect of PE deformation.[42] A metal pin on a PE disk may be the optimal combination, since the PE surfaces in TJA are always concave. However, the viscoelasticity of PE and the consequential changes in contact stress would have caused too many variables. The PE pins deformed only once when the load was initially applied, eliminating the concerns of viscoelasticity.

Pin-on-disk tribometers have been used to conduct traditional wear testing. For these wear tests, the pins were made up of the wearing material, and the disk consisted of the more wear resistant counterface. Before the start of testing, pins with spherical tips underwent a "running-in" process where the tip is gradually worn away. During the process, the contact area grew while the load remained the same, thus changing contact stresses and other parameters dependent on geometry.[78] However, the wear rate of PE is known to be relatively good, which is why they are employed in knee arthroplasty. The short testing time in addition to the low wear rate made it unlikely that a gross, macroscopic change in geometry occurred. Considering these points, the choice of PE pin on metal disk was the preferred combination.



Modified from Mazzucco and Spector, 2003

Fig. 2.1.3.1. Schematic of Pin-on-Disk Tribometer All friction values were obtained from this tribometer setup. A pin-on-disk apparatus is used widely for friction and wear measurements. The rotating motor beneath the metal disk was not included. The well on which the metals sits and that also contains the lubricant was also omitted.

Since the parameter of importance in this study was friction and not wear, the gradual wear of the PE pins was a concern. The Hertzian contact stress and the real area of contact would constantly change due to the wearing away of the spherical tip. Thus, PE pins were examined under the microscope after testing to ensure integrity of the "roundness." After the pins had been used for twelve tests, visible damage under the microscope was observed. Thus, it was qualitatively determined that a maximum of six tests would be run on any PE pin to be moderately assured that the Hertzian contact stress level would not drastically fluctuate.

2.2.2 Hertzian Contact Stress

Real area of contact and average contact stresses were calculated using Hertzian analysis.[66] The average contact pressure calculation for 3 mm diameter pins under 590 g normal load is provided.

Material properties of 1000 MPa for the PE elastic modulus (E_{PE}) and 0.4 for the Poisson's ratio (υ_{PE}) were assumed.[33] The reduced radius, R', for the spherical tip was half the radius of the sphere, or 0.75 mm. Since the metal surface is stiffer than the PE surface, the following equation estimates the reduced modulus:

$$E' = 2\,E_{PE} / (1 - \upsilon_{PE}^2) = 2 \text{ x } 1.0 / (1 - 0.4^2) = 2.4 \text{ GPa}$$

Equation 2.2.2.1

The contact area (A) is given by πa^2, where

$$\begin{aligned} a &= (3WR'/E')^{1/3} \\ &= (3\,(5.77\text{ N})\,(0.75\text{ mm}) / (2.4 \text{ x } 10^4\text{ MPa}))^{1/3} \\ &= 0.18\text{ mm} \end{aligned}$$

Equation 2.2.2.2

and W is the normal load acting on the pin. The estimated real area of contact is thus A = 0.097 mm^2. The average contact stress is the normal load divided by the area, which equals 59.2 MPa.

These calculations are the same as those used in the Mazzucco study,[37] which argues the validity of the assumptions of Hertzian contact stress[16] in this case. The contact is described by a continuous polynomial, and the surfaces are isotropic and exist at quasi-equilibrium. Stress is centered on the zone of contact with no normal stress outside the zone of contact. Integration of the normal stress in the contact zone equates to the applied normal load. According to Mazzucco, two assumptions that may not be satisfied are 1) zero distance between two articulating surfaces (due to separation caused by the lubricant), and 2) zero tangential stress (due to frictional tangential force generated by disk rotation). Thus, the calculation for average contact stress is utilized as an estimate to demonstrate that appropriate combination of loads and pin geometry were used in comparison to typical stresses experienced in hip and knee arthoplasty.

The average Hertzian contact stress of 59.2 MPa exceeds the stresses estimated in finite element models in hip and knee arthroplasty models.[4] However, since many models estimate stress in normal walking conditions, higher contact stress in more rigorous activity conditions will alter those estimates. These walking wear tests are usually conducted at contact pressures above 10 MPa.[57] Also, wear particle generation is more likely to occur in higher load conditions. Thus, tests at around 40 MPa (maximum for typical ASTM standards for pin-on-flat apparatus) have been conducted as well, which exceed the tensile yield stress of PE of 21 MPa.[12] Furthermore, although the mechanisms for wear in knees are not definitively established, the predominant types of wear exhibited in both simulator-tested and retrieved UHMWPE tibial inserts are delamination and pitting. The cause of these wear mechanisms is the result of fatigue, where subsurface cracks propagate beneath and parallel to the surface until the cracks meet.[67] Relatively large portions of PE break off. Due to these subsurface cracks, stresses at the edges of the cracks within the PE surface (around 1-3 mm beneath surface) exceed the tensile yield stress of PE.[14] Finally, the friction tests in this study are short tests, so relatively extreme conditions may be necessary. And since the goal of this study is to observe the effect a lubricant has on the frictional assay, lubricant performance in extreme conditions will likely identify differences between them.

2.2.3 Calibration

The pin-on-disk apparatus was calibrated daily to ensure a proper relationship between the strain gauge displacement readings outputted by the apparatus to the voltage readings inputted to the computer. A string and pulley were attached to the end of the cantilever arm. The modified Atwood machine was setup so that the weight hanging from one end of the pulley would apply a known load in the direction of the frictional force.

The pin was free-floating and did not rest on the disk. Five different masses at 10 g increments from 0 g to 50 g (total of 6 mass readings, including 0 g) were used to establish the relationship between the applied force and the computer voltage reading. The computer recorded data every 25 ms for around 7 seconds (40 points per second) when the mass was at rest. The data were averaged, and each corresponding point was plotted to establish a proportional relationship. The mass (force) to voltage input was linear.

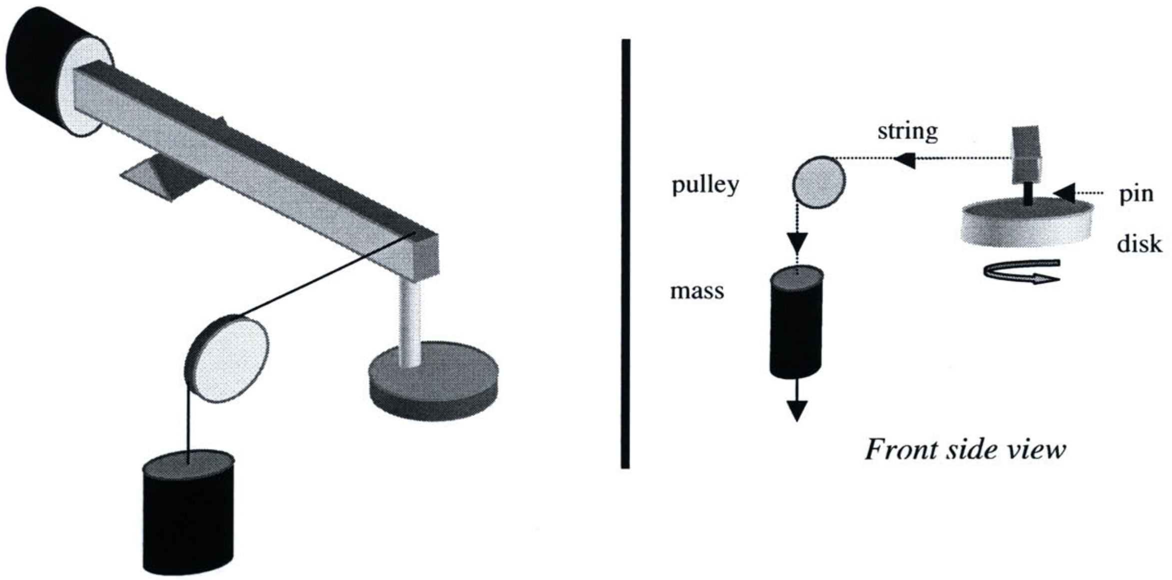


Fig. 2.2.3.1 Schematic of Calibration of Pin-on-Disk Overview (left), front-side view (right). The mass exerts a force transverse to the disk surface. The pin does not rest on the disk surface during the calibration procedure. Six different masses (0g, 10g, 20g, 30g, 40g, and 50g) were calibrated to the voltage readings recorded by the computer. This procedure was performed before every test group (usually 6 samples), to ensure accuracy.

This calibration procedure was performed before every group of tests. Usually, each group consisted of 6 individual tests. Since even a slight error in the calibration could skew the friction coefficient measurements, and the basis for this study examines slight changes in friction, the frequency of calibration was deemed necessary. See Appendix D for examples on the calibration process.

2.2.4 Surface Roughness

As described in Section 2.1.2, the Co-Cr metal disks were carefully polished and cleaned prior to each test. The disks were visually inspected to have a mirror finish. However, surface profilometry was performed to document surface roughness of the Co-Cr disks. ASTM recommends that the surface roughness be examined using a profilometer before testing.[3]

A Tencor P-10 Surface Profilometer with a 2 μm diamond tip was used to scan the surface of the Co-Cr disks. These measurements were performed at random to verify sufficient polish. The results ranged from a roughness of R(a) 0.0040 μm and RMS 0.0050 μm to a roughness of R(a) 0.0160 μm and RMS 0.0250 μm. A well-polished metal surface for prosthetic use has surface roughness R_a of 0.005 μm.[2]

Cho *et al.*[15] reported that when roughness was below 0.1 μm, the surface roughness did not affect the coefficient of friction. The samples used in this study were all below this surface roughness.

2.3 Experimental Protocol

2.3.1 Testing Procedure

The protocol used in this study was adapted from the friction measurement protocol employed by Mazzucco.[37] While Mazzucco experimented with varying loads, pins, and disks, one combination was used for this paper. A load of 590 g was applied by a 3 mm spherical tip PE pin onto a polished Co-Cr metal disk. This load was chosen in particular due to Mazzucco's preliminary studies showed that for loads from 60 g to 590 g, differences among lubricants were larger and more significant at higher loads. Thus, the 590 g load was chosen since this study relies on the ability of the friction apparatus to distinguish different friction values between lubricants. Additionally, the Hertzian contact stress of 59.2 MPa was reasonable.

Once a Co-Cr disk was placed within the lubricant well and a PE pin was secured to the pivoting arm, the calibration procedure as previously described was performed. 1 to 3 ml of lubricant was then spread onto the disk by a pipette, allowing exposure of the metal surface to the lubricant and its contents. The pivoting arm with the PE pin was subsequently placed onto the metal surface and loaded. The metal surface was kept clean and left untouched throughout the whole process, to eliminate any chance of foreign contamination.

The disk was rotated in reverse underneath the pin for at least one revolution, to standardize any preload or offset in the arm. It also allowed for a quick "run-in" period as described previously. The reverse rotation was stopped briefly to begin data capture on the computer. Forward rotation was then immediately commenced. Maximum static friction (μ_s) was determined as the highest recorded value with 0.25 seconds of the beginning of forward rotation. Data was recorded at 40 ms intervals. After achieving steady state following 30 seconds of forward rotation, mean dynamic friction (μ_d) was calculated taking the 1000 data points obtained at 40 ms intervals for 40 seconds. Thus, the duration of each individual test was a total of around 70 seconds. For each test, one μ_s value and one μ_d measurement (mean and standard deviation) were obtained.

The speed of rotation of the Co-Cr disks was set to 20 mm/s. ASTM standards for pin-on-flat tests recommend speed levels between 20-40 mm/s. The DC motor had a variable speed control, which allowed adjustment of the rotation rate. For all tests, the diameter of the circular test track was fixed at 41.5 mm. Thus, the disk rotated around once every 6.5 seconds. Mazzucco[37] showed that friction was independent of velocity, so other velocities of 10 and 40 mm/s were not used.

Overall, the voltages recorded on the computer demonstrated a similarity in the general output behavior amongst all lubricant groups. Although the voltage values varied from case to case, the general shape and behavior of the curve was similar. Since the disk was rotated in reverse prior to the start of the test, voltage readings were negative at first. Upon commencement of the test (rotation in the forward direction), voltage readings increased rapidly into the positive region immediately. Within the first 0.25 seconds, a maximum voltage value was reached. This value was corresponded as related to the static friction. Once this maximum was reached, the voltage readings gradually reduced and eventually came to a steady-state value. As described earlier, dynamic friction voltage readings were recorded once steady-state was achieved, which was at 30 seconds. Voltage readings at 40 ms intervals were recorded for 40 seconds. These readings were averaged to obtain the dynamic friction reading.

The oscillations of voltage readings (corresponding to the friction values) are not abnormal.[36] A closer look at the "steady-state" data reveals periodic oscillations coincident with the rotation of the disk. The oscillation values are also much higher than the noise present in the apparatus. Noise present in the strain gauge was calculated using the standard deviation of the calibration data, and it was found to be ±0.002 V. The oscillation is in the range of ±0.005 V. Thus, the oscillations seem to be caused by more than strain gauge noise. Friction mechanisms may be responsible.

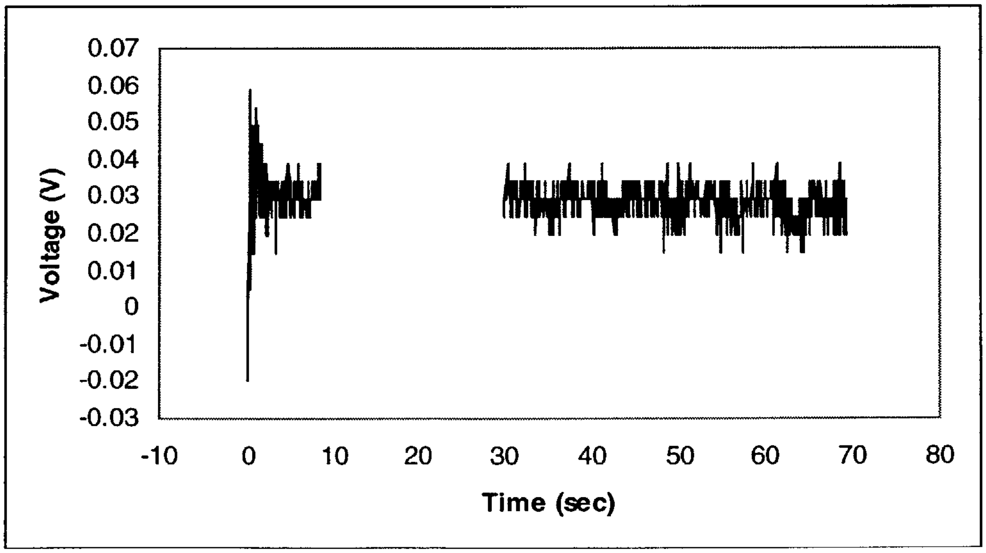


Fig. 2.3.1.1 Friction output versus time for a sample friction test The voltage output was recorded onto a computer. The maximum value of the initial output measured static friction. From 30-70 seconds, dynamic friction was obtained by averaging the recorded points. The voltages were converted to friction values using the calibration procedure.

2.4.2 Statistical Methods

Tests were in general conducted in separate lubricant groups. Each disk was tested only once. Disks were re-polished before undergoing another test. The mean dynamic friction was extrapolated from the μ_d data for each of the individual Co-Cr disks. These values were gathered into lubricant groups. Subsequently, mean and standard deviation values of the group were calculated. The mean coefficients of frictions for these lubricant groups were then compared for statistical significance using a two-tailed unpaired Student's t-test. A 20% difference in coefficient of friction (with $\alpha = 0.05$ and $\beta = 0.05$) could be determined with 95% confidence between two groups with a 10% coefficient of variation for a sample size of n=6.[39] In some cases, a complete set of six tests could not be completed due to the limited quantities of certain lubricants. However, since a smaller sample size can still show statistical significance given appropriate standard deviations and coefficient of variation, most of the data was useful. A power calculator was used to quickly determine statistical significance and appropriate sample sizes. See Appendix E for an explanation of the power calculation. Unless otherwise noted, the Student's t-test is the default tool used for analysis in this paper.

ANOVA tests were also used to determine the significance of the data. The Fisher least squares protected difference (LSPD) post-hoc test was also used for selected data to determine statistically related groups in the data sets. Statview and a power calculator made available by the Statistics Department of University of California, Los Angeles (www.stat.ucla.edu) were used to perform these tests.

CHAPTER 3: RESULTS AND ANALYSIS

3.1 Response of Pins and Disks to Test

The POD friction test was a very brief and rapid test that did not significantly alter test material. The testing procedures did not drastically affect the pins or disks, due to the relatively short testing period and the use of competent lubricants. The innocuousness and the short timeframe of the test was one of the considerations and driving forces behind this study, so that a relatively quick and easy friction test could be used as an assay to determine the effectiveness of a lubricant as compared to a more time-consuming and destructive wear test. Pins were inspected under an optical microscope to look for scratches or other damage to the spherical tip. Since the pins were used only a maximum of six times, no damage was observed.

Disks were inspected for scratches or other artifacts along the wear path. Evidence for wear tracks was examined on the surfaces. In general, when PE is used in a tribological system, PE forms a layer on top of the opposing surface in order to allow PE to slide over PE, rather than PE sliding over metal. From visual observations, a PE transfer film did not appear on the surfaces. When distilled water was used as the lubricant, there was no evidence of scratches or surface contaminants. For other lubricants, such as NCS, residuals of what appeared to be components of the fluid were adhered to the surface. The possible contaminants were proteins or phospholipids. For the bovine serum case, what appeared to be a visible transfer film remained on the surface once the pin articulated across the surface. Inspection of the track did not support this theory, however, since little damage occurred to the PE pin, and the transfer film track did not appear to be PE. Rather, the film appeared to be composed of proteins or other substances in the serum that adhered to the surface. Again, there was no evidence of PE transfer.

When joint fluids were used as lubricants, a transfer film was also noted along the wear track path. However, the film was very thin and weak in intensity when compared to that of NCS. An outline of the edges of the wear track was visible, but the middle portion of the wear track film was very thin and almost not visible. The transfer film again did not appear at all to be PE. Visual inspection of the surface showed what appeared to be wet precipitates.

It is unlikely that a visible wear track of PE will form on the surface. The test period lasted only about 70 seconds in entirety. In order for a PE layer to form in that short amount of time, the PE must wear at an extremely fast rate. Therefore, the wear tracks that were observed were not transfer films or wear tracks of PE, but rather precipitates of proteins or phospholipids. The wear tracks were only observed when lubricants with proteins or phospholipids (bovine serum and joint fluid) were tested. In all other occasions, no transfer film was observed.

3.2 Lubricant Group Results

Numerous lubricant groups were tested to compare dynamic friction values. There were statistically significant groups between the lubricants. Results are presented in lubricant groups, in which statistical analyses are likewise calculated for that group. Within each lubricant group section, a short discussion on the results immediately follows to organize the rather large amount of data. General discussions on the overall data are presented in Chapter 4.

All of the data presented below are dynamic friction values. Although static friction was recorded as described in Section 2.3.1, the results were widely variable and unreliable. Preliminary evaluations of static friction revealed little significance in data due to the variability. Therefore, they were not included.

The results that follow were tested in a semi-logical manner. First, friction using water and undiluted bovine serum were compared to serve as standards. As described in Chapter 1, water serves as the historical lubricant of choice until bovine serum, which has a lower wear rate, started to gain popularity due to similarities to *in vivo* wear rates and wear particle morphologies. Varying concentrations of bovine serum were then tested, since wear simulations are typically conducted with diluted lubricants. The protein and phospholipids concentrations of the bovine serum are high compared to natural joint fluids. Thus the serums were diluted, and the effects of fluid concentration on friction are presented. Next, the effects on friction of additives to bovine serum, some of which are used as preservatives, were examined, which were then followed by proteinase digestion of proteins to determine the role of proteins in the friction. A dry test without lubricants was also performed, partly to determine what a high friction value in a non-lubricated environment would be, and also partly to look for a transfer film. Next, PBS, which does not have proteins or phospholipids, was compared to water. HA was then added to PBS to determine if changes in viscosity (and fluid film lubrication) affected the friction. In order to test boundary lubrication contributions, results for petroleum-based oils were presented. All of these lubricants were used primarily to determine the mechanisms of friction and the behavior of PE on Co-Cr due to varying lubricants and properties. Once these observations were made, joint fluid samples were tested and analyzed. Appendix F contains a chart compiling the dynamic friction results for the lubricant groups discussed below.

3.2.1 Distilled Water and Bovine Serum

Distilled water and bovine serum were used as standards to compare to other lubricants. Mazzucco[37] previously demonstrated that the frictional apparatus distinguished between bovine serum and distilled water using a spherical pin.

Lubricant Material

Distilled water was obtained from Building 13 of the Department of Materials Science and Engineering at MIT. This "lubricant" was used as a control group.

Newborn bovine calf serum (catalog number 16010-159, lot number 498797; Invitrogen Corporation, Grand Island, NY) was used as the base fluid for bovine serum study. The concentration of bovine serum was varied through dilution with distilled water and other chemicals.

Results

Using the described statistical method, this study demonstrated that there was a statistical significance between distilled water and bovine serum (μ_d, $p < 0.0001$). The dynamic coefficients of friction for water and bovine serum were $\mu_d = 0.041 \pm 0.007$ (n = 47) and $\mu_d = 0.053 \pm 0.007$ (n = 39).

There is an important note to consider in the presented results. As described in Section 2.1.2, two different cleaning techniques were employed following the polishing process. The first process (Group 1) skipped a detergent cleaning process, while the second (Group 2) used a detergent to ensure a contaminant-free Co-Cr surface. Roughly half of the lubricants tested employed the first cleaning technique, while the rest used the second. Thus, tests were run to determine if the cleaning procedure would have any impact on the dynamic friction. Since distilled water and bovine serum (or NCS) were the standards or controls, these lubricants were tested.

For distilled water, there was a significant difference (μ_d, $p= 0.0002$) between Groups 1 and 2. The dynamic coefficients of friction for Groups 1 and 2 for water were $\mu_d = 0.042 \pm 0.006$ (n = 42) and $\mu_d = 0.031 \pm 0.005$ (n = 5). There was also a statistical significance for bovine serum as well (μ_d, $p= 0.007$). The dynamic coefficients of friction for Groups 1 and 2 for NCS were $\mu_d = 0.054 \pm 0.005$ (n = 30) and $\mu_d = 0.046 \pm 0.006$ (n = 8).

The detergent cleaning was effective in reducing friction for water and NCS. Since the detergent cleaning step significantly affected at least one of the two standards, two separate standard groups were created: those that did not add the detergent cleaning step used Group 1 for water and NCS as their standards, while those that did employ detergent used Group 2. If the detergent cleaning affected water as indicated, then other lubricants could possibly have been affected as well.

In order to alleviate any confusion in the results, all data were segregated into Groups 1 and 2. Since water and NCS are used as standards to compare the tested lubricants in most cases, the corresponding Group 1 and 2 standards are presented in subsequent sections. The water and NCS groups are labeled as Water I and NCS I for Group 1, and Water II and NCS II for Group 2.

Lubricant	All	Group 1	Group 2
Water	0.041 ± 0.007 (n=47)	0.042 ± 0.006 (n=42)	0.031 ± 0.005 (n=5)
Bovine Serum	0.053 ± 0.007 (n=39	0.054 ± 0.005 (n=30)	0.046 ± 0.006 (n=8)

Table 3.2.1.1 Coefficient of Friction for water vs. bovine serum

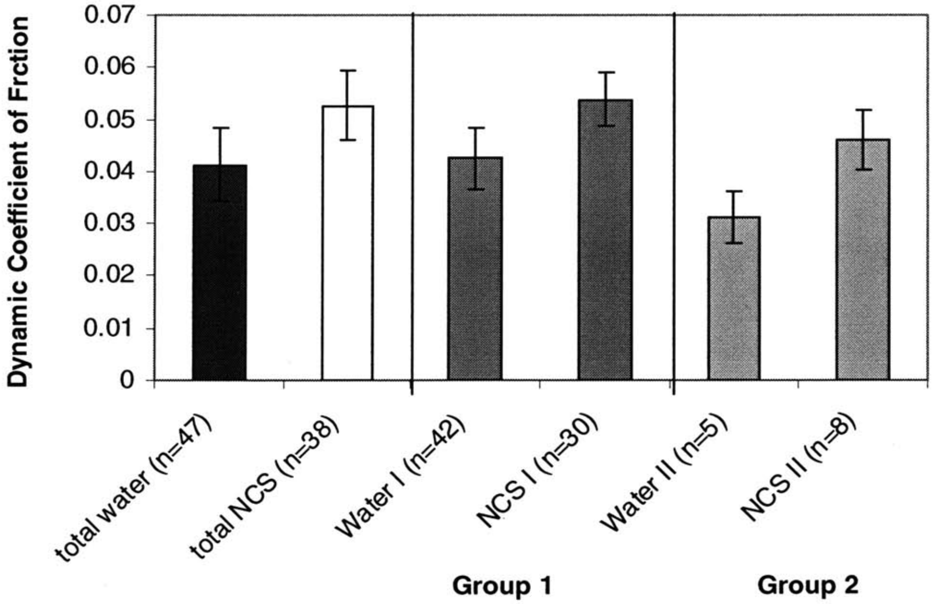


Fig 3.2.1.1 Distilled water vs. bovine serum The first group is a combination of the two groups. A detergent-washed disk was not used in Group 1, while a detergent-washed disk was used for Group 2. The bars indicate standard deviation. In all groups, water was significantly lower than bovine serum (NCS) (μ_d, $p < 0.001$). Additionally, the water and bovine serums between Groups 1 and 2 were significantly different to each other as well. Therefore, the cleaning process had an effect on the friction. Subsequent data is presented with the corresponding standard lubricant Group depending on the cleaning method used for the data collection.

Discussion

Originally, the data supplied by Mazzucco indicated a significant increase in the friction for water compared to bovine serum. Thus, when the dynamic coefficient of friction for water in this current research showed significant reduction in friction compared to bovine serum for both Groups 1 and 2, concerns about whether the experimental procedure adopted in this study was the same as those used by Mazzucco arose. Additionally, the polishing and cleaning procedures were revisited and scrutinized step-by-step to ensure mimicking of the original process. The surfaces were cleaned and sealed to prevent contamination before testing. Tests were even conducted to determine the effect of surface roughness on friction values. The Co-Cr disks were therefore roughened to determine if there would be an effect. Tests showed that surface roughness had little impact on the frictional response for water and bovine serum. This finding was substantiated by Cho *et al.*, that found that when surface roughness was less than 0.1 μm, coefficients of friction were not affected in PE on zirconia pin-on-disk tests.[15] In order to further ensure validity of the tests, the strain gauge readings were calibrated daily.

Considering the wear rate data between water and bovine serum,[7,19,22,40] where bovine serum caused considerably less wear particle production that water, it seemed as if water should have a higher value than bovine serum for friction. The rationale as outlined in Section 1.5.4, that friction should correlate to wear generation due to energy dissipation in asperity deformation and removal, supports the view that water should have a higher coefficient of friction than bovine serum since water has the higher wear rate. However, even after scrutinizing every polishing, cleaning, and calibrating procedure, all bovine samples continued to have higher friction values to that of distilled water.

Recently, a similar investigation was conducted by Yao *et al.*[79] using a PE and Co-Cr pin-on-disk apparatus. A comparison of bovine serum and distilled water was conducted at 50 mm/s, with hemispheroidal tip of 12.7 mm, and with 4.9 N of load. They similarly found water to have a lower coefficient of friction than both 100% and 25% bovine serum with statistical significance, which strongly supports the results of this thesis. Another study by Scholes, *et al.* suggested that the use of bovine serum as the lubricant significantly increased the friction in both metal-on-plastic and ceramic-on-plastic joints.[61] These tests were conducted on a hip joint similarly using stainless steel as the metal.

Additionally, the presence of a transfer film was important to consider. A clearly visible transfer film-like wear track was present for bovine serum (as well as in all groups of lubricants using bovine serum in the subsequent sections). The water lubricant test did not reveal any transfer film. Since analysis of the wear track was not conducted, it is not certain whether the wear track was a track of PE that adhered during the friction process or if it was a layer of proteins or other lubricant components precipitating out and forming a layer across the track. Contrarily, other studies have indicated that transfer of PE does not usually occur for bovine serum.[2,59] A typical transfer film would involve PE transfer onto the surface, causing high levels of wear. It is hypothesized that proteins and other lubricant components that adhere to the surface would prevent PE transfer. Thus, since tests to determine the makeup of the film transfer material observed due to bovine serum are necessary, the transfer film may be composed of PE, precipitates, or some other change on the surface due to the articulation over the boundary lubricated surface. As argued in Section 3.1.1, the wear track is likely not composed of PE, but rather precipitates due to the short timeframe of the tests.

One difference was noted between this study and the previous study by Mazzucco. The bovine serum was not diluted before testing, while Mazzucco pre-diluted the serum to 40% by volume with distilled water. Therefore, tests needed to be conducted at 40% NCS and compared to verify the results.

Overall, even though the coefficient of friction of bovine serum was nearly 150% of water, the actual difference in coefficient magnitude was merely 0.01. These differences are slight. It is important to note that with this set of data and in those following, the coefficients of friction are extremely low. The determination of the actual causes and mechanisms of these slight differences are not so clear-cut. When coefficient of friction values are so low, small difference and changes to the mechanisms contributing to tribology can have a large impact.

3.2.2 Bovine Serum Concentrations

Lubricant Material

Several varying concentrations of NCS were prepared to test concentration effects on friction.

- 100% NCS.
- NCS diluted to 40% volume to volume in distilled water.
- NCS diluted to 20% volume to volume in distilled water.
- NCS diluted to 5% volume to volume in distilled water.
- NCS diluted to 1% volume to volume in distilled water.
- NCS diluted to 90% volume to volume in 20 mM solution of ethylene-diaminetetraacetic acid (EDTA) (catalog number ED-1KG, Sigma-Aldrich, St. Louis, MO).

Results

Two separate experiments were conducted at different times to investigate the effects of concentration on friction. The first set was run when the Co-Cr disks were not cleaned with detergent (Group 1 conditions) while the second was performed under Group 2 conditions. The results of the first test, as detailed below, were somewhat peculiar, which prompted a second set of tests.

In the first set, NCS was diluted to several concentrations using distilled water: 40%, 20%, 5%, and 1%, all in volume-to-volume ratios. A fifth concentration of 90% was diluted with a solution of 20 mM EDTA. Pins were inadvertently reused for tests between different concentrations in the first set.

Statistical analysis showed that for the NCS concentrations by volume of between 90% to 1%, pre-dilution had no effect (μ_d, *p = 0.7023, ANOVA*). Furthermore, the Fisher's PLSD post-hoc analysis showed that none of the concentrations were statistically significant to each other as well, with the 90% NCS and 40% NCS tests having the best chance for significance (μ_d, $p =$ 0.2228, ANOVA). This result suggested that although pre-dilution of bovine serum is effective in wear simulations, it may have little effect in friction tests. Since protein precipitation is dependent on concentration, time and temperature, it is likely to have little effect. The duration of friction tests were short, which also affected the likelihood that high temperatures would not be reached to produce high levels of precipitation.

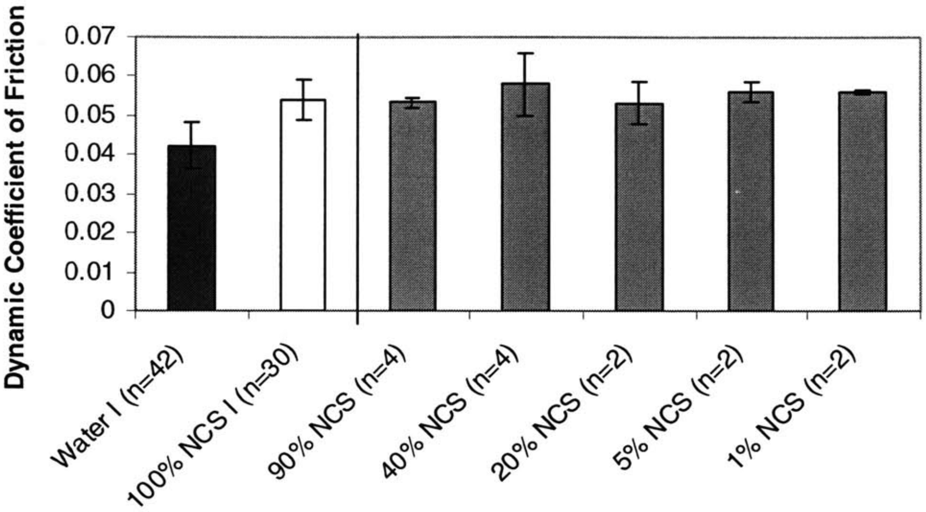


Fig 3.2.2.1 Bovine serum concentrations, Group 1 Bovine serum was diluted with distilled water to the different concentrations. The bars indicate standard deviation. A change in concentration did not affect friction (μ_d, *p = 0.7023, ANOVA*).

Visual observation of the Co-Cr disks after testing showed lubricant components adhered to the surface (wear track not of PE). Even in the case of the 1% NCS concentration, a thin layer of a substance lightly coated the surface.

A second set of tests were run under Group 2 conditions. Only two pre-diluted solutions, one at 40% NCS and the other at 5% NCS (volume-to-volume concentration) were tested. New pins were used for each concentration.

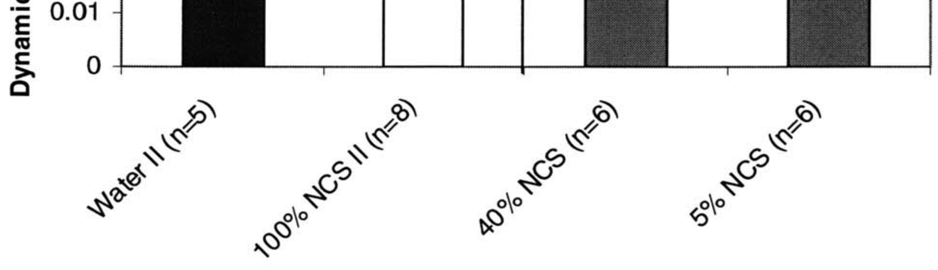


Fig 3.2.2.2 Bovine serum concentrations, Group 2 Bovine serum was diluted with distilled water to the different concentrations. The bars indicate standard deviation. This was a similar test to 3.2.2.1. This time, changes in concentration affected the dynamic friction coefficient (μ_d, *p = 0.0032, ANOVA*). The 40% NCS and the 5% NCS were not significant to each other (μ_d, *p = 0.3*).

Lubricant	μ_d	n
Water – Group 2	0.031 ± 0.005	5
Bovine Serum – Group 2	0.046 ± 0.006	8
40% NCS - Group 2	0.039±0.004	6
5% NCS - Group 2	0.037±0.003	6

Table 3.2.2.1 Bovine serum concentrations, Group 2

In complete contrast to the Group 1 experiment, changes in concentration affected the dynamic friction coefficients between the undiluted, 40%, and 5% NCS lubricants (μ_d, *p = 0.0032, ANOVA*). Both the 40% and 5% NCS concentrations were individually significant to the 100% NCS concentration. The 5% and the 40% NCS were not, however, significant to each other (μ_d, *p = 0.3*).

Discussion

The first set of data revealed no significant difference due to changes in volume concentration. This did not seem likely, since protein and phospholipids concentration levels would drop to near negligible levels at 1% NCS by volume concentrations. The re-using of pins for tests of different concentrations may have affected the first results. If the pin used to make the 1% NCS friction readings was used to make the 20% NCS readings earlier, the data is likely questionable. Protein or other deposits responsible for the higher friction may already have adhered to the PE pin. The bovine serum tests of Section 3.2.1 showed that its friction is higher than that of water, so there is some component of the lubricant that is raising the friction by adhering to the surface.

In contrast to the first, the second set of data showed statistical significance, demonstrating that the dilution of bovine serum was important to the frictional response. In the experiment by Yao *et al.* which showed statistical difference between the lower frictional measurements for water vs. the bovine serum, two different concentrations of bovine serum were tested. The 25% concentration had a slightly higher friction than the 100% concentration, though they were not significant.[79] Thus, when going from 100% bovine concentration to 0% concentration, the Yao *et al.* data increased and peaked at some point with a dilution concentration in between before decreasing to the 0% bovine concentration, or distilled water. The study in this thesis suggested a slightly different model, in which the frictional value consistently decreased as the concentration of bovine serum decreased. The small set of data points basically only allowed a weak confidence in establishing this trend. However, since the protein concentration was decreasing, there may have been less friction as well.

The decrease in bovine serum concentration seems to correlate with a collective decrease in protein and phospholipids concentration, which are indicated as candidates for the cause of good boundary lubrication characteristics. Proteins display good adsorption rate performance at particular concentration of proteins, due to a lack of crowding in high concentrations. However, a high concentration may promote crowding, which may aid in boundary lubrication. The increased boundary lubrication will decrease wear, but may increase friction (as discussed in more detail in Chapter 4).

The higher statistical significance of the 40% bovine serum to distilled water is of importance since Mazzucco's work used the 40% by volume concentration. His research suggested a statistical significance with a lower frictional coefficient for bovine serum than water.

3.2.3 Bovine Serum Additives

Lubricant Material

Bovine serum has become the standard lubricant in wear simulator tests. Nevertheless, some investigators are still not convinced of its ability to simulate joint fluid. The debate on what concentration of a serum is appropriate to simulate a human joint, and on other lubricants that may be more appropriate continues. In order to test the effect that certain additives have on friction, NCS solutions as used by Liao *et al.*[34] in hip joint simulator tests were prepared for testing. The 0.2% sodium azide and 20 mM EDTA solution is a recommended ASTM standard for joint simulator and pin-on-flat tests. This solution was not filtered on 0.2 μm filter paper to remove particulate material as suggested by ASTM. Three solutions with varying additive combinations were formulated.

- NCS diluted to 90% by volume in 20 mM solution of ethylene-diaminetetraacetic acid (EDTA) (catalog number ED-1KG, Sigma-Aldrich, St. Louis, MO).
- NCS diluted to 90% by volume with 9% by volume of 20 mM solution of EDTA and 1% by volume of 0.2% sodium azide (catalog number S8032-25G, Sigma Aldrich, St. Louis, MO).
- NCS diluted to 99% by volume with 1% by volume of 0.2% sodium azide.

The addition of EDTA minimizes the precipitation of calcium phosphate onto the femoral balls in wear testing.[35] These precipitates artificially roughen the surface and increase wear, and may consequently have an effect on friction. Additionally, sodium azide is used as a preservative so that the lubricant would maintain its integrity throughout the test.

Results

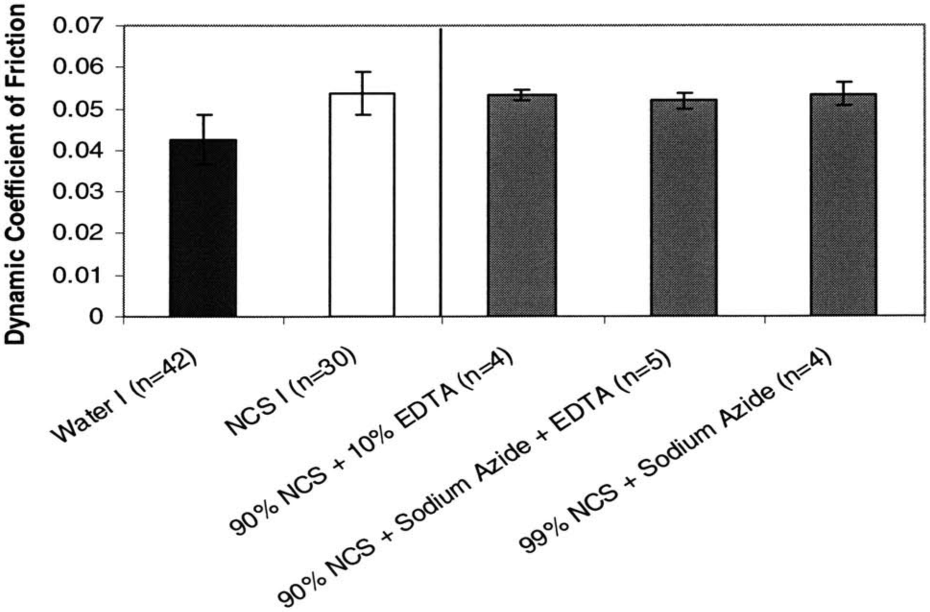


Fig 3.2.3.1 Bovine serum additives Bovine serum (NCS) was diluted with additive solutions. The bars indicate standard deviation. Additives to bovine serum used in wear simulators were tested. The additives had no significant effect on the friction (*μ_d, $p = 0.5$, ANOVA*). None of the individual solutions with additives were significant to 100% bovine serum (μ_d, $p > 0.3$).

The addition of additives again had little effect to friction in NCS when comparing the untreated NCS with the three treated NCS lubricants (μ_d, *p = 0.5, ANOVA*). None of the lubricants have statistical significance (μ_d, $p > 0.3$) to NCS.

ANOVA analysis showed there was an effect between the additives (μ_d, *p = 0.02, ANOVA*). Tukey/Kramer showed that the lubricants with sodium azide were related, while the lubricant with just EDTA added was unrelated to the rest. However, since none of these values were significant to NCS, distinguishing between additives was not important. These tests were run to ensure that the addition of these additives did not significantly alter friction performance.

Discussion

Precipitates are not likely to play a major role in a short friction test. In a 70 second test, the addition of EDTA to decrease the amount of calcium phosphate that precipitates onto the Co-Cr surface is not too important. Additionally, the solution was not filtered as suggested by ASTM. Therefore, the addition of EDTA should affect the friction much in a short test. Also, as long as sodium azide does not directly affect any of the proteins, phospholipids, or other components present in lubricants and strictly is used for preservative purposes, it should have little effect on a friction tests as well. If the friction results changed significantly, the use of sodium azide as a benign supplement should have been reconsidered.

3.2.4 Proteinase Digestion of Bovine Serum

Lubricant Materials

NCS was treated by a protease to destroy all proteins. For this digestion, 3.5 mg proteinase K (catalog number P-6556, lot number 081K8623, Sigma-Aldrich, St. Louis, MO) was added to 10 ml of NCS. The solution was heated to body temperature (37° C) and incubated for 16-24 hours.

In order to determine which molecule in human joint fluid and bovine serum is responsible for low friction in PE-on-Co-Cr articulations, Mazzucco[37] formulated various lubricants from various components of joint fluid. After testing several lubricants, he determined that a protein that was unaccounted for could be responsible for decreased friction. One particular protein, Lubricin, was found to be effective in cartilage-on-cartilage articulations,[69] thereby promoting the idea of the presence of a protein responsible for reduced friction on PE on Co-Cr articulations. Thus, the proteins in bovine serum were digested using protease, in order to test the hypothesis that if a protein is responsible for lubrication, the friction will change when proteins are digested.

Results

Lubricant	μ_d	**n**
Water – Group 1	0.042 ± 0.006	42
Bovine Serum – Group 1	0.054 ± 0.005	30
Bovine Serum + Proteinase	0.060 ± 0.004	6

Table 3.2.4.1 Proteinase digestion of bovine serum

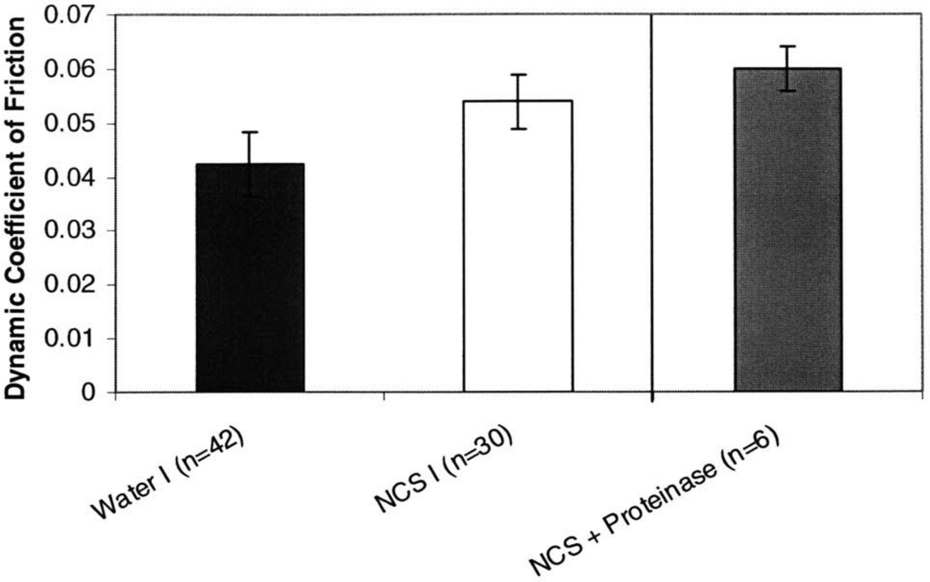


Fig 3.2.4.1 Proteinase digestion of bovine serum Bovine serum (NCS) was digested by protease. The bars indicate standard deviation. Digestion of proteins significantly increases friction compared to bovine serum (μ_d, $p = 0.02$).

The results show a slightly higher protease digestion friction value compared to undigested NCS. This value is significant (μ_d, $p = 0.02$). The coefficient of friction of the NCS + Proteinase was $\mu_d = 0.060 \pm 0.004$, which was a significant increase from bovine serum who had a $\mu_d = 0.054 \pm 0.005$.

Discussion

The digestion of proteins in bovine serum was motivated by the claim that a protein is responsible for the lubricating qualities of fluid. Lubricin, as detailed in Chapter 1, may be a protein that reduces friction and wear. Some others claim that it is merely a carrier for phospholipids, which they insist are truly responsible for reduced friction.

The protein digestion resulted in a statistically higher friction value than undigested bovine serum. Mazzucco yielded similar results. From this finding, conclusions may logically be drawn that a protein is in fact responsible for improved friction, since digesting proteins increased friction. However, in complete contrast, the water vs. bovine serum test demonstrates that the addition of proteins increased the friction. It has also been suggested that protein conformation and polymer surface hydrophilicity on protein adsorption has an effect on the friction in the boundary lubrication regime.[45] De-natured proteins, especially those of protein albumin, preferentially adsorb to hydrophobic polymer surfaces and form a compact layer that increases sliding friction.

Although these concepts are seemingly contradictory, it is likely that proteins have some role in the friction, even though the relationship may not entirely be clear. The cases of an increase in friction due to an increase in protein content vs. the increase in friction due to a digestion of proteins may actually not be so contradictory, as the products of digested proteins may behave in a manner similar to de-natured proteins and form a layer across the surface that increases friction. If that is the case, the claim that Lubricin is a protein that reduces friction in an undigested serum may still be valid, though not conclusively, since Lubricin may well be reducing friction, but is counteracted by the adsorption layer of proteins that raises friction.

3.2.5 Dry

Lubricant Material

The articulating surfaces of a TKA system will almost certainly never be used without lubrication. However, dry tests were conducted to determine what the maximum friction coefficient is likely to be in this PE-on-Co-Cr frictional assay, assuming that no lubricant will raise friction higher than a dry case. In essence, this test was run to note the range of frictional response for this assay. Additionally, this test was also conducted to look for a wear track. Only the two articulating surfaces and no lubricant were used in this test.

Results

The mean coefficient of friction for the PE pin sliding over a Co-Cr surface was μ_d = 0.155 with standard deviation = 0.01. Therefore, using water as a lubricant reduces the friction coefficient by three to four times. There was also no visible wear track on the surface following the brief 70 second test.

Discussion

This result clearly demonstrates the effectiveness of using lubricants. Even water is capable of performing as a lubricant, by performing some of the roles of typical lubricants which include 1) prevention of particle agglomeration, 2) removal of particles from the interface, 3) prevention of adhesion between surfaces, 4) reduction in heat due to plastic deformation, and 5) creation of a gap between surfaces. Water is typically not used as a lubricant for its great boundary lubricant qualities.

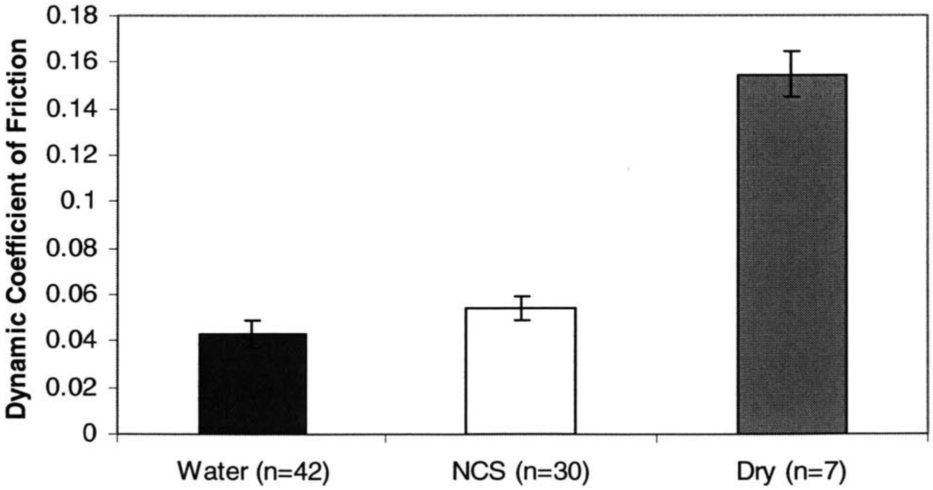


Fig 3.2.5.1 Dry No lubricant was added. The bars indicate standard deviation. The dry articulation had a dynamic coefficient of friction of μ_d = 0.155 with standard deviation = 0.01. Using lubricants such as water significantly reduced friction by three to four times.

However, on a hydrophilic surface like Co-Cr used in this test, even a thin layer of water may be enough to greatly lower the friction between PE and Co-Cr, as this test indicates, despite that fact that water does not have long chains. Although the effect of hydrophobic vs. hydrophilic metal surfaces were not tested for water, a hydrophobic surface may have a higher friction value than a hydrophilic, though not as high as dry conditions since the water will still perform some of the lubricant roles listed above.

Additionally, this dry test shows that a true transfer film of PE onto the metal surface will raise the coefficient of friction. In a dry articulating situation, a layer of PE coats the metal surface much like a transfer film, thereby encouraging PE on PE sliding rather than PE on metal.[67] Thus, a true transfer film on lubricated surfaces will cause PE-on-PE sliding, which will raise the friction coefficient. However, a transfer film was not observed in this short test. Therefore, when a wear track-like deposit formed on the bovine tests, the deposit was not likely to be PE.

3.2.6 Phosphate-Buffered Saline

Lubricant Materials

Dulbecco's Phosphate-Buffered Saline (PBS; catalog number 14191-144, lot number 1192635, Invitrogen Corporation, Grand Island, NY) was evaluated mainly to compare with water. Two PBS groups were examined:

- 100% PBS.
- PBS supplemented with sodium hyaluronate (HA) with viscosity average molecular weight 1.76 x 10^6 Da (catalog number 80190, Lifecore Biomedical, Chaska, MN). The solution had HA concentration of 2.45 mg/mL.

Phosphate-buffered saline was used to compare friction values to those of distilled water. Since both water and saline do not have any proteins, HA, or phospholipids that are thought to have influence on the tribology of lubricated articulating surfaces, it was hypothesized that water and PBS would share similar friction performance. Since PBS is a solubilized, ionic solution and is not substantially physically different from water such as in viscosity, water and PBS should lubricate similarly.

Once the PBS test was completed, HA was added to PBS to determine its effect on friction. The test was conducted with the expectation that the addition of HA would raise the viscosity (Mazzucco[37] determined a positive correlation between HA concentration and viscosity), which would affect the fluid-film lubrication characteristics of the fluid.

Results

Lubricant	μ_d	**n**
Water – Group 1	0.042 ± 0.006	42
Bovine Serum – Group 1	0.054 ± 0.005	30
PBS	0.040±0.007	8
PBS + HA	0.036±0.005	7

Table 3.2.6.1 PBS

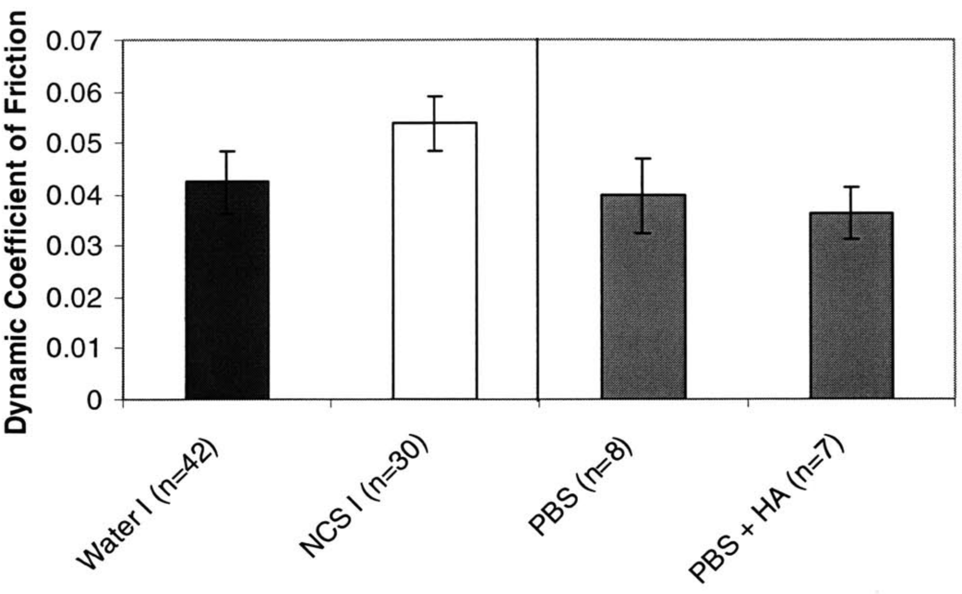


Fig 3.2.6.1 Phosphate-buffered saline Phosphate-buffered saline (PBS) was the main lubricant in the group. The bars indicate standard deviation. PBS performed similarly to that of water (μ_d, $p = 0.2685$) and was significantly different from bovine serum (μ_d, $p < 0.0001$). The addition of HA to PBS slightly reduced the friction to that of PBS (μ_d, $p = 0.25$).

PBS did perform similarly to water ($p = 0.2685$) and was significantly different from NCS ($p < 0.0001$). The addition of HA reduced the friction slightly, but not significantly to that of PBS ($p = 0.25$). It did have a significant difference to NCS ($p < 0.0001$).

Discussion

As expected, PBS performs similar to water. There are no proteins or phospholipids to affect friction. The solubilized ions should not have an immediate affect on the friction of a short-term test. Interestingly, Sawae reported the formation of a transfer layer of PE on stainless steel when using saline as the lubricant.[59] At initial readings of his study, friction was very low, at around 0.02. However, as time progressed, a transfer film formed due to surface plastic deformation of PE, leading to an increase in friction to above 0.15. This particular value is similar to those found in the friction values of dry conditions. Mazzucco[37] described similar results for water and PBS.

The addition of HA slightly reduced the friction value, though not significantly. Sawae *et al.* also reported that friction and wear between PE pins and counterfaces dropped with the addition of HA. Mazzucco, however, found that the addition of HA increased friction, which was quite puzzling. It is expected that with the addition of HA, the fluid-film effect should be enhanced since the viscosity of the solution increases with the addition of HA. Mazzucco[37] noted a positive correlation of HA concentration and viscosity. The Stribeck curve also substantiates that an increase in viscosity encourages fluid-film lubrication. A lower friction due to the addition of HA supports the argument that the tribology of PE on Co-Cr in POD tests is influenced in part by fluid-film lubrication, since fluid film lubrication is affected by viscosity.

3.2.7 Petroleum-based Oils

Petroleum-based oils were tested to determine their effectiveness on arthroplasty surfaces. Although these lubricants will likely never be used in a human body, petroleum-based lubricants are used in everyday appliances and machines to reduce friction and wear.

Lubricant Materials

Miscellaneous oils, such as mineral oil and lubricating oil purchased over-the-counter was used to gather relative friction values. Mineral oil, a mixture of hydrocarbons, is commonly ingested as an emollient or lubricant laxative. It is also commonly found in body lotions. Mineral oil was purchased over-the-counter at a local supermarket.

Lubricating oil is a machine lubricant for application to moving joints and hinges. Its role is to largely reduce friction coefficient. This oil was likewise purchased at a local supermarket.

Results

The friction value of mineral oil and lubricating oil were about 200% of that of water, and about 150% of that of NCS (μ_d, $p < 0.0001$). The oils had roughly the same friction coefficient, and were not significantly different (μ_d, $p > 0.9$).

Lubricant	μ_d	**n**
Water – Group 1	0.042 ± 0.006	42
Bovine Serum – Group 1	0.054 ± 0.005	30
Mineral Oil	0.083±0.015	6
Lubricating Oil	0.083±0.004	2

Table 3.2.7.1 Petroleum-based Oils

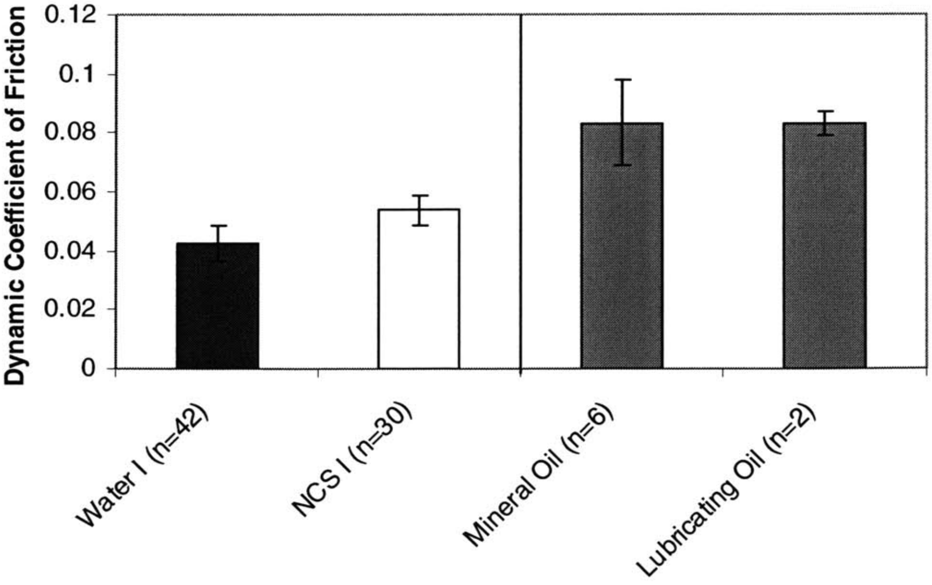


Fig 3.2.7.1 Petroleum-based oils Mineral oil and generic lubricating oil were tested. The bars indicate standard deviation. The friction value of mineral oil and lubrication oil increased to twice that of water (μ_d, $p < 0.0001$). The oils were not significantly different from each other (μ_d, $p > 0.9$).

Discussion

The frictional values recorded were relatively high compared to the rest of the lubricant groups. Since petroleum-based oils or even lipids are typically considered as the lubricant of choice to reduce friction in conventional tribology, it was not expected that the friction would be so high. Not only was the friction coefficient higher than the standards, it was about double that of water, which is normally not considered as a lubricant. Both of these oils are used in conventional applications to decrease friction and wear, in order to increase performance. Mineral oil is used to facilitate movement of substances through the gastro-intestinal tract when used as a laxative, and lubricating oil is used to decrease friction and ultimately wear particle generation when used on mechanisms with frequent cycling. Water is not usually the lubricant of choice to reduce wear and friction. But in this case, water clearly has the lower friction.

One thought that resulted from this observation was that, based on evidence from Section 1.3.4, components of the lubricant that adhere to the surface may be interacting with the articulating surface and raising the friction. In the case of the oils, chains of hydrocarbons adhere to the surface of hydrophilic Co-Cr. These chains may be the source of a resistive force against the PE pin when it slides across the surface which the tribometer interprets as frictional force. This is a highly speculative conjecture that needs further review. If this concept is true, it may begin to explain the higher coefficient of friction value in bovine serum compared to water. Denatured proteins and phospholipids, and other components in the system, may be increasing the apparent friction as the pin slides across the adhered surface. Water is simply just small molecules without long chains, thereby minimizing the possibility of surface contaminant resistance that may raise the friction.

Additives of long, unbranched fatty acids and alcohols that are attracted to hydrophilic metal surfaces are introduced to industrial oils as additives. Similarly, as suggested by Liao *et al.*,[35] proteins in bovine serum may precipitate out and form a protective layer on the surface. This layer may raise the friction, but it may also lower the wear rate by preventing asperity contact against hard surfaces. Thus, the ideas explored here bring attention to more variables to consider in understanding wear and friction response and their relationship to each other using different lubricants. A boundary layer may raise what appears to be the friction of a surface as the pin glides across the surface.

3.2.8 Joint Fluid Samples

Lubricant Materials

Joint fluid was obtained from New England Baptist Hospital through approval from the Institutional Review Board. An orthopedic surgeon removed the fluid during surgery by exposing the knee and extracting as much fluid as possible from within the joint before opening up the synovium. A syringe with a needle was used to penetrate the joint and remove the fluid. Of the twenty-two procured samples, only two were noticeably tainted with blood. The fluid samples were stored in a stopped 15 ml glass test tube and frozen at -20°C. In preparation for testing, frozen samples were thawed at room temperature in a water bath. Additionally, all testing was performed at room temperature (~22°C)

There were a total of twenty-three joint fluid samples collected for friction testing. Two were discarded due to large amounts of blood mixed with the fluid. These cases were mostly associated with revision, rather than with primary total knee arthroplasty (TKA). For more details on joint fluid samples and characteristics, see Appendices A, B and F.

Results

Sixteen of the twenty-one tested lubricants were from OA cases, while four were from revision surgery. One case was unknown. In the following charts, primary TKA cases are shaded, while revision cases are striped.

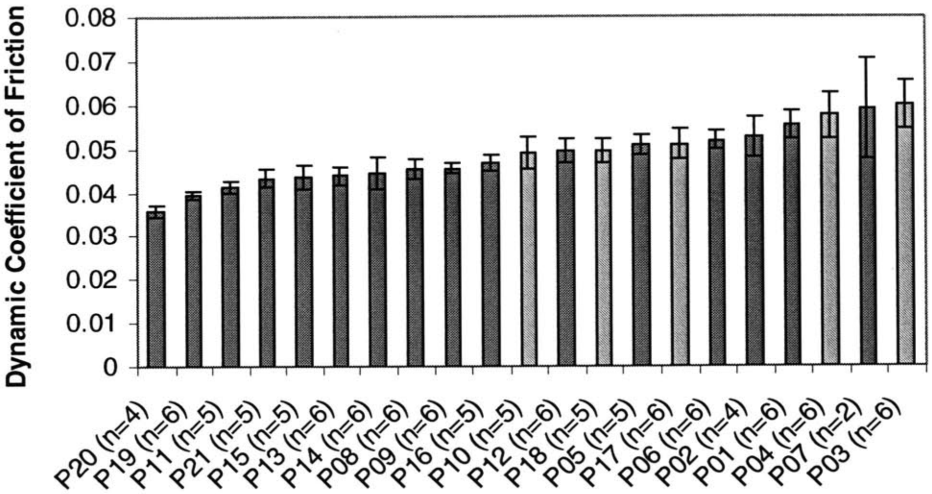


Fig 3.2.8.1 Joint fluid compilation Compilation of the 21 tested joint fluids. The bars indicate standard deviation. The darker-shaded boxes are fluids taken from OA patients for primary TKA. The lighter-shaded boxes are fluids taken from patients undergoing revision. The range of values is from $\mu_d = 0.035$ to 0.060, for a difference of 0.015. The variation is significant, (μ_d, $p < 0.0001$, *ANOVA*). The variation of the fluid properties causes a large variation in friction.

See Appendices A and B for charts and specific information including μ_d on the joint fluids.

The twenty-one joint fluid values were distributed across a wide range of friction values, from $\mu_d = 0.035$ to 0.060. Taking the mean values, the overall mean of the joint fluids is 0.048 with a standard deviation of 0.006. ANOVA analysis indicates that the joint fluids do vary and have an effect on the friction (μ_d, $p < 0.0001$, *ANOVA*). Fig. 3.2.8.2 compares the joint fluid group to water and NCS. The joint fluid group falls right between the water and NCS groups.

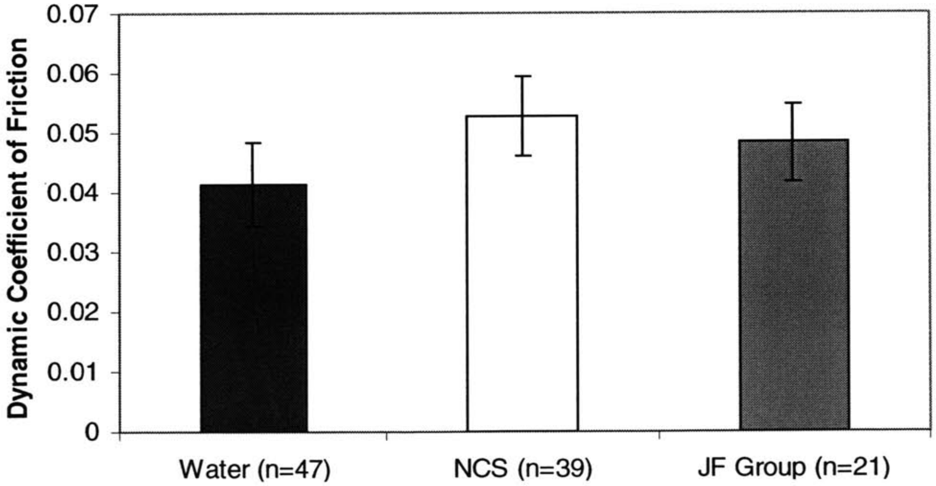
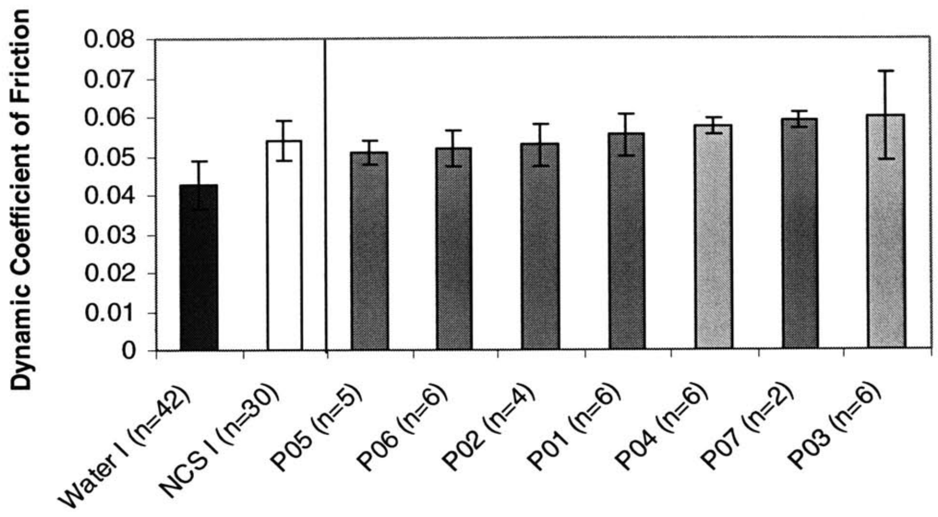


Fig 3.2.8.2 Mean of all joint fluid samples The mean was taken of all 21 tested joint fluids. The bars indicate standard deviation. This graph incorporates both Group 1 and Group 2 cleaning methodologies. Therefore, the results may not be relevant to one another.

However, this graph is a bit misleading. The two different cleaning methods used throughout this study may have impacted these results. The joint fluid results were therefore segregated as well, since joint fluid tests were conducted throughout the year.



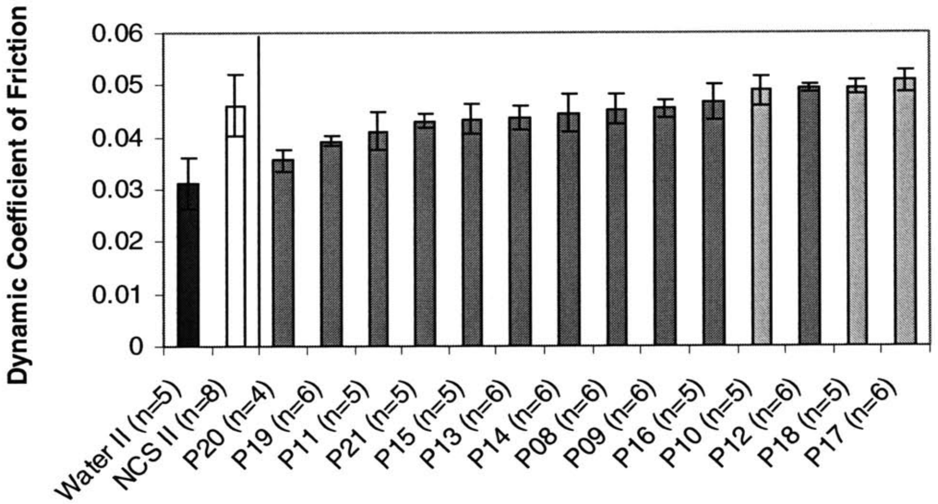


Fig 3.2.8.3 Joint fluids in groups The 21 joint fluids were separated into groups according to their cleaning process. The top graph refers to Group 1, and the bottom refers to Group 2. Boxes that are darker-shaded are fluids taken from OA patients for primary TKA. The lighter-shaded boxes are fluids taken from patients undergoing revision. The bars indicate standard deviation. The differences in fluid in Group 1 (top) caused a significant variation in friction (μ_d, *$p = 0.016$, ANOVA).* The fluid from revision patients were on the two of three highest values.

The differences in fluid in Group 2 (bottom) caused a significant variation in friction as well (μ_d, *$p < 0.0001$, ANOVA).* The fluid from revision patients were three of the top four highest friction values. Also, none of the joint fluids had friction less than water, nor were any similar to water.

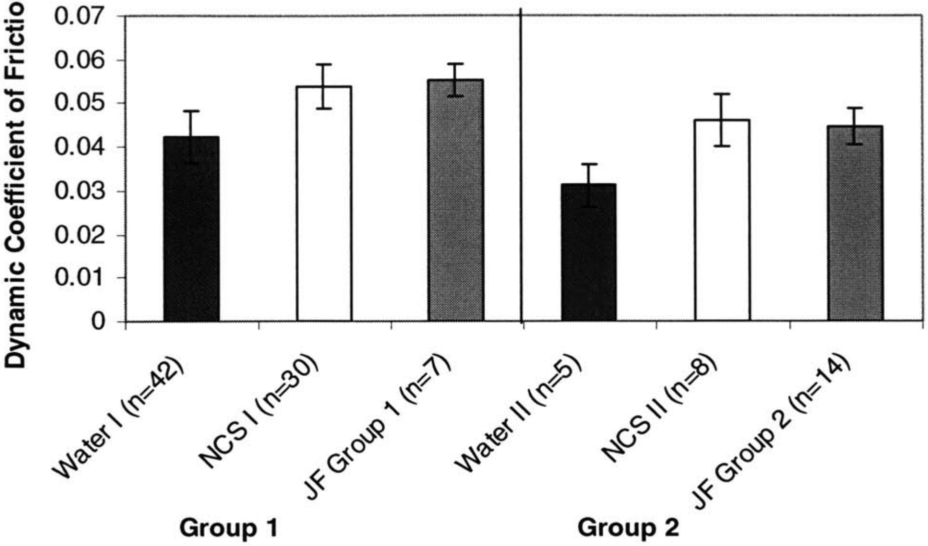


Fig 3.2.8.4 Group means of joint fluids in cleaning groups The means were taken of the groups formed in Fig. 3.2.8.3, according to their cleaning process. The bars indicate standard deviation. The dynamic friction for both joint fluid groups were not significantly different to bovine serum (*μ_d, $p = 0.75$, Group 1) and (μ_d, $p = 0.18$, Group 2)*. The dynamic friction was significantly different to water for both groups *(μ_d, $p = 0.0005$)*.

When the joint fluids are compared to each other, statistical significance indicates a factor causing the variance in Group 1 *(μ_d, $p = 0.016$, ANOVA)*, as it does in Group 2 *(μ_d, $p < 0.0001$, ANOVA)*. A comparison of the group of fluids of Group 1 and Group 2 as in Fig 3.2.8.3 shows statistical significance *(μ_d, $p < 0.0001$)*. Additionally, the joint fluids in each group are statistically significant to the water, but not to the bovine serum. In Group 1, joint fluids are distinct from water *(μ_d, $p < 0.0001$)*, but not to bovine serum *(μ_d, $p = 0.75$)*. Group 2 behaves similarly, as joint fluids are again different from water *(μ_d, $p = 0.0005$)*, but similar to NCS, though it is slightly lower *(μ_d, $p = 0.18$)*. From this information, joint fluid does not seem to behave differently from bovine serum in relation to friction. Fig. 3.2.8.4 shows that for both groups, the coefficient of frictions for the joint fluids in both groups hover near the coefficient of friction for bovine serum.

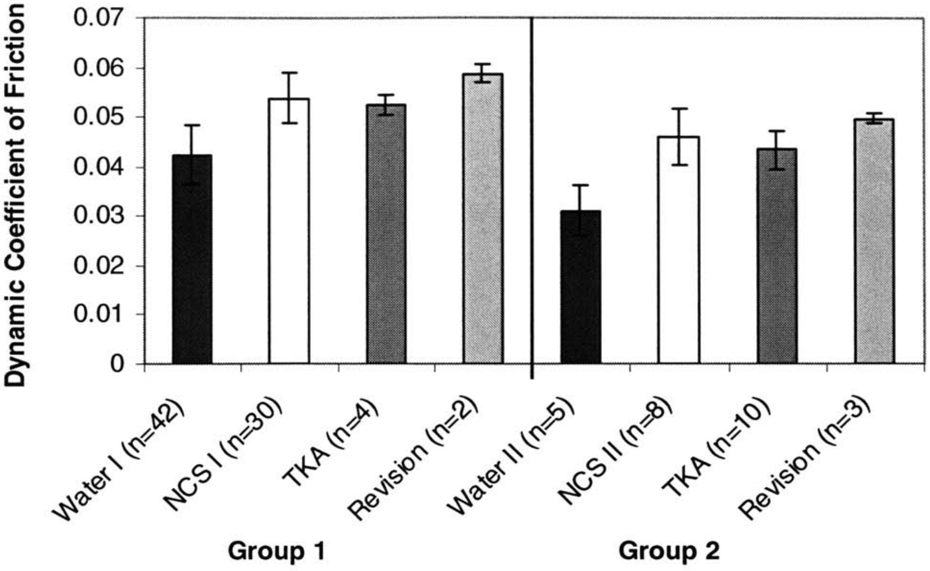


Fig 3.2.8.5 Means of the two groups separated into Primary TKA and Revision cases In each group, the fluids were separated into regrouped into primary TKA (OA) and revision cases (wear). The means were taken and graphed as above. The bars indicate standard deviation. The darker-shaded boxes refer to primary TKA, and the lighter-shaded boxes refer to revision cases. The friction values were significantly different between TKA and Revision for both Groups 1 and 2 (μ_d, *$p = 0.02$ for both)*. The coefficient of friction difference was ~ 0.006 between TKA and Revision for both groups. The friction for Revision was higher than bovine serum for both cases, and the friction for NCS was lower than bovine serum, though not significantly.

For both Groups 1 and 2, Fig. 3.2.8.4 shows that the Revision cases (mostly due to wear) tend to be on the higher end of the group in regards to friction. Although the sample sizes are relatively small (with two and three cases for Groups 1 and 2, respectively), data was used to create Fig. 3.2.8.5. Student's t-test between TKA and Revision cases for Groups 1 and 2 show statistical significance for both Groups 1 and 2 (μ_d, *$p = 0.02$ for both)*. It is speculated that a larger sample size of revision cases can more confidently indicate significance of a higher friction value for revision fluids.

Discussion

The friction values for joint fluid range from values close to that of water to those of bovine serum. Statistically, since the collective groups of joint fluids do not show statistical significance to bovine serum but to water, the friction of joint fluid is similar to bovine serum. Individually, only one joint fluid (P03, Revision) was significantly higher than bovine serum in Group 1 (μ_d, $p = 0.01$), while four joint fluids (P11, P17, P20, P21, all primary TKA) were significantly lower than bovine serum in Group 2. In both groups, no fluid was similar to water. Since all of the fluids have friction higher than water, this result suggests boundary lubrication is taking place (See discussion in Chapter 4). Joint fluid consists of protein, phospholipids, and HA, and so it is possible that the protein and phospholipids are causing boundary lubrication and raising the friction.

Additionally, the ANOVA test of the set of joint fluid samples indicated that the fluids were in general dissimilar to one another. Some factor, which could be a physical or chemical quality, is causing the joint fluid to vary in friction.

Moreover, the highest joint fluid friction coefficient is 0.060, which is from a patient undergoing revision. In that joint, due to the damage incurred on the synovium during the initial implantation surgery, changes to the joint fluid likely occurred. As discussed in Chapter 1, the new synovium may not be as adept in filtering out proteins, as well as other complications that may occur to the joint fluid. It is interesting to note that the 0.060 value is similar friction obtained using the protein-digested bovine serum. The proteins in that lubricant were digested, and gave high friction values of about 0.06.

Finally, the range between the lowest and highest joint fluid frictions is 0.015. This difference is larger than the difference between water and bovine serum, which is 0.011. Wear studies using water and bovine serum as lubricants reveal higher wear rates for water as opposed to bovine, with some as high as fourteen times more.[7,19,40,75] Therefore, since a 0.011 change produces a large change in wear, the wear rate difference is expected to be high as well. Although a direct relationship is questionable since different mechanisms and lubrication conditions may exist as will be discussed in the following chapter, the significant differences in friction indicate tribologically significant events. The wear rates are likely to vary.

3.2.9 Compilation of Results

See Appendix F for a general overview of all the results on the effects of various lubricants on PE on Co-Cr articulating surfaces. A chart with the mean coefficient of friction values are provided.

CHAPTER 4: DISCUSSION

Due to the large amount data, discussions pertaining to the respective lubricant groups are jointly presented with the results in Chapter 3 for organization purposes. This chapter compares and discusses overall results between the lubricant groups.

4.1 General Discussions

4.1.1 Effect on Friction of Composition and Property Changes of Lubricant

The friction of PE on Co-Cr is clearly affected by changes to compositions and properties of lubricants. Several tests support this accepted hypothesis:

1. Bovine serum concentrations: Dilution of the bovine serum changes the protein and phospholipids concentrations. Fig. 3.2.2.2 clearly demonstrates a significant decrease in friction as the bovine serum is diluted.
2. Proteinase: The addition of proteinase to bovine serum digested the proteins. There is a definite change to the compositional makeup of the bovine serum. Fig. 3.2.4.1 illustrates the significant increase in friction of the proteinase-treated serum in relation to the standard.
3. PBS + HA: The addition of HA to PBS increases the viscosity of the fluid. Fig. 3.2.6.1 (as well as studies by Sawae *et al.*[59]) confirms that the friction decreases due to the addition of HA.

4.1.2 Boundary Lubrication and Fluid-Film Lubrication

Analysis of the lubricant groups indicates trends that show evidence of mixed lubrication behavior in TJA.

1. The bovine serum vs. distilled water test (Section 3.2.1) shows an increase in friction that may be due to the boundary lubrication of proteins or phospholipids on the surface. The test of petroleum-based oils in Section 3.2.7 also shows a significant increase in friction compared to water. Since water does not contain molecules that coat the surface as bovine serum and petroleum oils do, it is not a good boundary lubricant. The small water molecules may provide some lubrication effects on the highly polished, hydrophilic surface and may even enter fluid-film lubrication, but it is not as effective in protecting the surface as long chain proteins and hydrocarbons do. Therefore, the boundary lubricants may be what are increasing the friction values from that of water. The data reveals that the PE on Co-Cr articulating surface is affected by boundary lubricants.
2. The fluid-film lubrication characteristic in this system is demonstrated by the HA-supplemented PBS test. Compared to the non-supplemented test, the addition of HA decreased the friction. Although there was not a significant decrease, Sawae *et al.*[59] reported a similar result that was significant of UHMWPE on alumina. Since HA increases the viscosity of the fluid (Mazzucco[37] noted a positive correlation of HA concentration and viscosity), which affects the fluid-film lubrication and not boundary lubrication, fluid-film lubrication affects PE on Co-Cr surfaces. Section

1.3.4 describes the types of fluid-film lubrication that occurs in natural joints. These variations such as elastohydrodynamic and weeping lubrication are not likely to occur in TJA systems due to the material properties of the surfaces. However, it is important to note that the friction of the PE on Co-Cr is affected in a POD test by some sort of fluid-film lubrication as demonstrated by the HA data.

3. Moreover, the tests of the varying concentrations of bovine serum (Section 3.2.2) indicate that as the concentration decreases, the friction decreases. Since a lower concentration of bovine serum equates to lower concentrations of protein and other components responsible for boundary protection, a thinner boundary layer is likely forming (although there are optimal rates of adsorption for specific concentrations to consider). The decreasing friction of decreasing concentration may be due to a thinner boundary layer as less resistance is exerted onto the passing pin.
4. Further support is provided by the joint fluid data. Figure 3.2.8.3 shows the individual joint fluid results for water and bovine serum. None of the joint fluids had friction less than water. Since joint fluids have proteins and phospholipids that act as surface lubricants, they adhere to the surface and cause a rise in friction. Therefore, none of the joint fluids should have friction below water due to the presence of proteins. If there is an abnormal case where a joint fluid does not have any proteins and phospholipids, then the friction may be at or below that of water (since a reduction in proteins indicates a rise in HA due to the negative correlation discovered by Mazzucco,[37] and therefore an increase in fluid-film lubrication, reducing the friction). Basically, if there is any boundary lubrication, the friction should not drop below that of water, which has little boundary lubrication effect. The Stribeck curve shows that boundary lubrication has friction higher than fluid-film lubrication. Therefore, Figure 3.2.8.3 supports this hypothesis.

As an additional note, the petroleum-based oils like the mineral oil had different viscosities than water. Normally, a higher viscosity should encourage fluid-film lubrication and lower friction. However, the friction increased for the petroleum oils, thereby implying that boundary lubrication had a more prominent role in the friction than fluid-film lubrication for those lubricants. This does not demonstrate conclusively that the PE on Co-Cr system is more affected by boundary lubrication, but that for these specific cases, the higher friction was due to boundary lubrication. Conceptually, in order for fluid-film lubrication to dominate, the fluid-film thickness (gap) should exceed the thickness of the boundary layer. The Stribeck Curve also indicates that the friction in the boundary lubrication regime is higher than those in the fluid-film regime (as well as in the mixed regime). This indicates that if there is any sort of boundary lubrication effect, its friction should be higher than a case that has minimal boundary lubrication.

Therefore, the hypothesis of the presence of both boundary and fluid-film lubrication effects is accepted. The contribution of boundary lubrication vs. fluid-film lubrication is dependent on the specific fluid and its components. The frictional behavior will furthermore vary in this mixed lubrication stage depending on the properties of the fluid. Since this discussion demonstrates that the PE on Co-Cr surfaces react to both boundary and fluid-film lubrication, it is possible for the friction value to change drastically if a lubricant that promotes boundary lubrication is applied.

4.1.3 Rejection of Correlation between Friction and Wear

Typically, good lubrication characteristics imply lower friction and lower wear. It does not intuitively make sense for good lubrication to give a rise in friction. However, in several of the lubricant groups tested in this thesis, friction increased using lubricants that are known to decrease wear compared to water. The data provides strong evidence that low wear can coexist with relatively higher friction.

Since the principle mode of failure in TJA is due to the biological response to wear particles generated from tribological failure, the ultimate goal is to reduce wear particle generation. Therefore, a good lubricant for this application would primarily have to reduce the wear rate. The original hypothesis of a friction and wear relationship is based on the concept that the two share common mechanisms, such as asperity deformation, particle plowing, and adhesion for friction, and abrasion, adhesion, and delamination for wear. The frictional force is related to the work done between just the two surfaces of the articulating materials, where an increase in friction indicates some plastic deformation or work done on the surfaces. This original hypothesis does not consider that other contributors to force not related to plastic deformation and ultimately wear particle generation could exist. An analysis of the data presented in this study does not support the original hypothesis.

There are several results to consider for this argument:

1. Water has a significantly higher wear rate than bovine serum.[7,19,22,40]
2. Fig. 3.2.1.1 clearly shows that water has a significantly lower coefficient of friction than bovine serum.
3. Fig. 3.2.2.2 indicates that an increase in concentration of bovine serum raises the friction.
4. Fig. 3.2.7.1 shows that petroleum-based oils that have boundary lubrication qualities have friction 200% larger than that of water.

The common thread in these four results is the presence of a boundary layer that is responsible for boundary lubrication. Water, however, is not a good boundary lubricant because it does not have any proteins or phospholipids or any other long chain molecules that form a layer over the surface. Water molecules just wet the hydrophilic surface, and rely more on the possibility of entering fluid-film lubrication to reduce friction when appropriate speeds, loads, and viscosities (e.g., addition of HA to PBS) are reached. It provides minimal protection to the surface, which facilitates high wear generation. In contrast, bovine serum contains proteins and phospholipids that adhere to the surface. These components that provide boundary layer protection reduce wear particle generation by preventing as much direct asperity contact as possible. Bovine serum has a significantly lower wear rate than water due to the boundary layer protection provided by the components.

The apparent discrepancy that emerges from the data is that even though the wear rate is lower for bovine serum, the friction coefficient is higher for bovine serum than water. Again, this is not intuitive. However, there are several suppositions to explain the conundrum.

1. For lubricants with components that adhere to the surface and provide boundary layer protection, the surface components may indeed prevent the two surfaces from making direct asperity contact, thereby reducing wear. However, the components on the boundary layer may interfere with the pin sliding across the surface and provide a

resistive force that is interpreted as friction. Therefore, this frictional force is not due to plastic deformation (and wear particle generation), but to the interaction of the pin cutting through the surface components. The example of the petroleum-based oils is also used as evidence, since these lubricants are design to encourage the formation of a heavy boundary layer of long chains. The corresponding friction of the oils was very high, even though they are commonly used lubricants to reduce wear.

2. The Stribeck curve illustrates that as a tribological system shifts toward the boundary lubrication region, the friction coefficient rises rapidly. Boundary lubrication has a much higher friction coefficient than fluid-film lubrication. The bovine serum concentration data shows that as the protein and phospholipids content increases with the increase in bovine serum concentration, the friction value rises. This increase is likely due to the increase in the boundary layer.

One study that directly supports the data collected in this thesis was performed by Saikko and Ahlroos,[57] who found that higher friction does not correspond to a higher wear factor. Albumin, γ-Globulin and serum were tested at various friction coefficients on a pin-on-disk tester, and the wear factor varied widely, with Albumin (capable of boundary protection) producing the least wear.

This discussion on the effect of boundary lubrication components on friction and wear may only be appropriate for short-term tests that are run in ideal, well-polished conditions. In the case of a water lubricant, PE pins will begin to wear out and PE wear tracks will form as the test progresses. These surface changes may exceed the limited boundary effect of water as well as interfere with fluid-film lubrication, thereby increasing friction. Studies have established this behavior using saline as the lubricant, where the friction increased significantly (to near dry conditions) from very low initial friction values as time progressed.[59] This boundary lubricant model on the role of a boundary layer on friction and wear is relevant for a discussion of the results presented in this paper, with the stated testing times and protocols. Additional loads, configurations, lubricants, articulating surfaces, etc. will need to be measured to obtain a more comprehensive understanding of the relationship between friction and wear.

As a result, the hypothesis that friction and wear have a direct relationship is rejected due to the data and the supporting evidence collected in this study. The boundary layer protects the surface from wear, but may be contributing a resistive force as the two surfaces slides against each other. Especially in a situation where the coefficients of friction are so low, even a small contribution of friction may indeed be the dominating component.

One note of importance is that even though a direct relationship cannot be established between friction and wear, the results of the study confirm that a change is friction is responsible for some sort of significant change in wear behavior. This is a more general statement than making a direct correlation of an increase in friction leading to an increase in wear. This claim is substantiated by the bovine and water tests that indicate a significant difference in friction. Since earlier studies generally accept that bovine serum has far lower wear rates than water, this substantiates that even a slight change in the friction (in this case a 0.01 change in the magnitude of the coefficient of friction) can cause a large change in wear behavior. Again, although the direct relationship cannot be established, the change in friction reveals that there was some change to the tribology of the system. This indicates that a different mechanism is at work, leading to a change in tribological response.

4.1.4 Effects on Friction due to Variation in Joint Fluid

The friction changes significantly when tested with varying joint fluids. Analysis of Fig. 3.2.8.1 suggests that variations in the joint fluid property are causing significant differences in the friction response.

Friction using revision fluids are in general higher than the fluids from patients undergoing primary TKA (Fig. 3.2.8.3). Visual, qualitative inspection of the fluid (Appendix B) suggests that revision fluids tend to be less viscous and have less color. The properties of the revision cases may be due to the reduction of production of products by synoviocytes and the increased inflammatory response of the knee, as well as the reduced filtration capabilities of the synovium, which encourages large protein infiltration into the joint fluid. Other factors as discussed in Section 1.2.3. All of these factors, including the presence of de-natured proteins that may also be present in the revision cases,[2] contribute to the formation of a thick boundary layer on the surface that could explain the high friction.

Additionally, joint fluid composition studies by Mazzucco[37] indicate that joint fluids display certain concentrations of proteins, phospholipids and HA for different indications, such as OA and RA. Appendix C provides the data that shows that Revision patients have the highest proteins and phospholipids concentrations, followed by OA, and then by healthy patients. HA is inversely correlated to both proteins and phospholipids. Combining this composition information of higher protein and phospholipids concentrations in revision patients with the data from Fig. 3.2.8.3, which indicate higher friction for Revision patients, a conclusion is reached that the concentration of joint fluids has an effect on the friction. The hypothesis is therefore accepted that the variance in friction is due to the variance in joint fluid composition and properties from patient to patient.

4.1.5 POD Friction Test as Assay

Although a direct relationship between friction and wear was rejected, the POD friction test is nonetheless still valuable in determining wear behavior using joint fluids. The POD device provides quick and reliable friction information. The preceding discussions endorse the value of the POD apparatus in obtaining meaningful and significant friction values for joint fluids. The value of the POD apparatus is obvious, but the value in the friction data is the question.

As the preceding section 4.1.4 indicates, the variation in joint fluid composition is directly related to the friction values. Also, the correlation of the proteins, phospholipids and HA in joint fluid concentrations has a general behavior related to patient disease where for example higher protein and phospholipids concentrations exist for revision cases. A table is provided in Appendix C that relates component concentrations to other indications. Accordingly, Fig. 3.2.8.3 shows that the fluids from Revision patients tend to be clustered at the higher end of the joint fluid sample friction readings. Therefore, a direct relationship is established between concentrations of joint fluid components and friction response.

This relationship is very important to the possible establishment of a relationship between friction and wear. Although the direct relationship between friction and wear was rejected, there is still the possibility that the composition of joint fluid could be related to the wear behavior. This new hypothesis is highly likely, since this thesis has shown that joint fluid compositions alter boundary lubrication and fluid film lubrication effects, which also was show to have effects to wear. Additionally, since it has been established that a small change in friction could cause large changes in wear, a change in joint fluid composition will cause large changes in wear since friction is affected by composition. Moreover, the establishment of the correlation between the three components of joint fluid responsible for lubrication implies that the variation in joint fluid composition is limited, since a change in proteins indicates that the other two components have changed as well.

Taking all this into consideration, the wear rate will be affected by the limited joint fluid composition change. And since there is a relationship between friction and composition, a new hypothesis is formed that an establishment of indirect relationship between friction and wear is possible through the creation of a "friction map." Since the friction of disease indications appear to cluster together, and the joint fluid compositions are correlated together, the information is naturally clustered. Therefore, the "friction map" is created by testing a known fluid in a particular regime (such as the Revision regime) for wear and correlating that wear value back to the tested regime. It is hypothesized that the wear behavior for fluids within the same regime will be similar since the joint fluid concentrations should also be similar in the same regime due to their correlation. Appendix G provides an example of a friction map.

The POD has great potential to be a reliable assay in determining wear behavior if the indirect relationship between friction and wear is established. The "friction map" could be used as the reference to allow a brief POD friction test to predict wear behavior. Therefore, this hypothesis is not rejected, but is also not entirely accepted.

As a final note, the variability in content concentration data is high. Therefore, the "friction map" is limited in its precision. It should be used as a quick test to approximate the fluid content concentration from the friction, and not as a precise table. The fluid from this test should then be analyzed on a more precise wear simulator for verification. See Appendix G for a simple illustration of the "friction map."

4.2 Potential Future Work

The preceding sections discuss several opportunities for future work. The creation of a "friction map" that correlates friction, fluid content concentration and wear is promising, since there appears to be a correlation between friction and fluid content concentration. Since the components of joint fluid are also correlated, a change in wear due to a change in fluid content is likely since a change in one component of joint fluid such as protein changes the other components as well. Since the tribology of surfaces is dependent on more than just the lubricant content, correlations between viscosity and other properties important to tribology should be verified. A verification of this hypothesis will allow POD friction tests to function as assays to approximate wear behavior in PE on Co-Cr.

Additionally, a new tribo-rheometry apparatus[29] can be used to expand on the POD friction tests used in this thesis. This device can determine characters important to both rheology and tribology. The effect of normal load, gap changes, and surface roughness changes can be examined while varying load and velocity continuously. Since this thesis suggests the boundary lubrication and fluid-film lubrication contributions to friction by joint fluids, this apparatus may be very valuable as it outputs Stribeck curves as well.

4.3 Limitations of the Study

One of the principal limitations of this study is that the static coefficient of friction was not considered. Although most studies do not report static friction due to the difficulty is obtaining precise and accurate data, it is an important consideration since static friction may contribute to wear. Static friction values were recorded during testing but are not reported in this thesis due to wide variations and general unreliability of the results.

Moreover, the length of test time is a limitation as well. In clinical settings, lubricant concentrations change over time. Proteins also undergo conformation change on surfaces over time. These effects cannot be modeled in a short friction test. Also, since the surfaces used in this study were finely polished and clean, a short test under these conditions may not compare to *in vivo* or simulator tests. After long periods of time, gross changes occur to the surface, thereby causing large changes in tribological response.

Additionally, the joint fluid samples collected from the hospital were stored in a freezer for several days before testing. The changes that occur from freezing and thawing are not known. There may be molecular changes that happen or other instabilities may break down the joint fluid. Tests to determine molecular content immediate following fluid aspiration and after a freezing and thawing process will help to determine an optimal retrieval, storage and testing procedure.

Although the frictional measurements of twenty-three joint fluid samples are a considerable sample size, the number of patients from whom the fluids were collected from limited to types of indications that were studied – OA for primary TKA and wear for revision.

Finally, all of the sources referenced in this thesis did not use PE on Co-Cr in their studies. Since different materials and even material properties (such as surface roughness and hydrophobicity) can greatly friction, the meaningfulness of data is limited. Most of the materials were of like kind and application, thereby mitigating the relevancy of the data.

4.4 Significance

One of the aims of this study is to establish a relationship between friction and wear. The ability of tests to precisely predict wear behavior is important since wear is the most significant cause of TJA failure. Moreover, since wear simulation testers are expensive and time consuming, the development of a simpler yet comparably capable assay would help in TJA research. Since friction values are able to be measured quickly, this friction assay is proposed to reasonably predict wear through a relationship with friction. However, the hypothesis that the friction can directly predict wear is rejected through the data under the testing conditions as described. However, an alternative hypothesis of an indirect relationship was developed for future consideration.

At the very least, this thesis reveals variations in friction values for joint fluid. The fluid from patients undergoing revision, who have thus had damage incurred to their synovium due to surgery, have higher friction than those undergoing primary TKA for OA. This indicates that there are differences in the fluids from patient to patient. The range of joint fluid friction values (0.015) was also greater than the difference between the friction values due to bovine serum and water. Since the wear due to bovine serum and water vary greatly, the range of friction values demonstrates differences in wear rates between joint fluids. The differences in friction are significant, thereby indicating a substantial effect on tribology in general.

CHAPTER 5: CONCLUSIONS

A unidirectional pin-on-disk apparatus was used to evaluate the effects on friction of various lubricants, both conventional and biological, for PE on Co-Cr articulating surfaces for TKA. The POD device was capable of significantly distinguishing friction coefficients for numerous lubricants. Tests of varying composition and bulk properties of standard lubricants such as distilled water, bovine serum and PBS determined that these altered properties greatly influenced friction. Additionally, tests utilizing petroleum-based oils, PBS, and HA demonstrated both boundary lubrication and fluid film lubrication contributions on the tribology of PE on Co-Cr articulating surfaces.

A model for the effects of boundary lubrication on friction was discussed, contending that boundary lubrication components contributed greatly to frictional force measured in relatively low friction coefficient arrangements such as PE on Co-Cr. Data revealed that lubricants under fluid-film conditions which typically have higher wear rates (i.e., distilled water and PBS) recorded lower dynamic coefficients of friction than lubricants under boundary lubrication (bovine serum and petroleum-based oils). An increase in the concentration of a lubricant with primarily boundary lubrication dominance (i.e., bovine serum), and therefore lower wear rates, increased the coefficient of friction. Therefore, the hypothesis of a direct relationship of an increase in friction leading to an increase in wear was rejected. Nevertheless, an indirect relationship between friction and wear in joint fluids was proposed, including the supposition of a "friction map" that correlates friction, joint fluid component concentrations, and wear. Overall, friction from joint fluid lubricants displayed great variability. The variability (range) of the joint fluids exceeded the difference between water and bovine serum whose wear rates significantly vary, thereby demonstrating that wear rates and joint composition significantly differ from patient to patient. Finally, POD friction tests have the potential to be a relevant and reliable assay in determining wear behavior.

All in all, I have shown that PE on Co-Cr incorporates both boundary lubrication and fluid-film lubrication. I demonstrated that the friction values of PE on Co-Cr are also affected by varying compositions and properties of lubricants. I also determined that friction results cannot directly determine wear. Additionally, I showed that the friction of PE on Co-Cr using joint fluids vary widely, due to the large variations in joint fluid composition and properties. Finally, I showed that the POD test has potential in the future to show a relationship between friction and wear for joint fluids.

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APPENDIX A: PATIENT INFORMATION

Patient ID	Gender	Age	Height (in)	Weight (lbs)	Left/Right	Procedure	Indication	Aspiration Date
P02	M	86	-	-	R	TKA	OA	11/30/2004
P20	F	83	64	140	R	TKA	OA	10/27/2004
P15	M	82	-	-	L	TKA	OA	11/3/2004
P22	M	81	71	205	R	TKA	OA	11/3/2004
P10	F	78	-	153	R	Rev Tib	Wear	11/23/2004
P23	F	78	-	152	L	Rev Tib	Wear	11/23/2004
P18	F	74	-	-	R	Rev TKA	OA	11/17/2004
P19	F	73	-	165	L	TKA	OA	11/16/2004
P16	F	71	70	170	R	TKA	OA	12/7/2004
P11	F	70	70	175	R	TKA	OA	11/23/2004
P24	F	66	-	-	R	Rev Tib	Wear/OA	11/19/2004
P08	F	66	62	116	R	TKA	OA	12/15/2004
P03	M	64	-	-	L	Rev TKA	Wear	11/30/2004
P12	F	64	-	-	L	TKA	OA	-
P05	M	61	72	195	L	TKA	OA	11/17/2004
P06	M	61	72	195	R	TKA	OA	11/17/2004
P01	F	61	60	198	R	TKA	OA	11/10/2004
P17	M	61	-	-	L	Rev TKA	Wear	12/7/2004
P04	M	61	-	-	R	Rev TKA	Wear	11/30/2004
P09	F	61	63	175	L	TKA	OA	12/14/2004
P14	F	60	62	180	R	TKA	OA	11/3/2004
P21	F	58	63	260	L	TKA	OA	11/16/2004
P13	F	-	-	-	R	-	-	-

APPENDIX B: PATIENT DYNAMIC FRICTION DATA

Patient	Surgery	Indication	n	μ_d	Fluid Description
P20	Primary TKA	OA	4	0.036 ± 0.001	Yellow, medium viscosity, 5ml of fluid
P19	Primary TKA	OA	6	0.039 ± 0.001	Very viscous, not too yellow, bit cloudy, 9 ml
P11	Primary TKA	OA	5	0.041 ± 0.001	Yellow, cloudy
P21	Primary TKA	OA	5	0.043 ± 0.002	Chunky, yellow, viscous, 2 ml
P15	Primary TKA	OA	5	0.043 ± 0.003	Yellow, clear, watery, 12 ml
P13	-	-	6	0.044 ± 0.002	Reddish tint, clear, viscous, 5 ml
P14	Primary TKA	OA	6	0.045 ± 0.004	Yellow, almost clear, viscous, 6 ml
P08	Primary TKA	OA	6	0.045 ± 0.002	Little bloody, bit watery, chunky
P09	Primary TKA	OA	6	0.045 ± 0.001	Yellow, viscous
P16	Primary TKA	OA	5	0.047 ± 0.002	Yellow, clear, very watery, 13 ml
P10	Revision Tib. Insert	Wear	5	0.049 ± 0.004	Slighty bloody, watery, cloudy
P12	Primary TKA	OA	6	0.049 ± 0.003	Yellow, slighty cloudy, medium viscosity, 7 ml
P18	Revision TKA	OA	5	0.050 ± 0.003	Not cloudy, reddish tint, 10 ml
P05	Primary TKA	OA	5	0.051 ± 0.002	Yellow not cloudy
P17	Revision TKA	Wear	6	0.051 ± 0.003	Viscous to liquidy, cloudy, yellow, 12 ml
P06	Primary TKA	OA	6	0.052 ± 0.002	Reddish tint
P02	Primary TKA	OA	4	0.053 ± 0.004	Very little fluid, yellow, chunky, viscous
P01	Primary TKA	OA	6	0.055 ± 0.003	Very viscous
P04	Revision TKA	Wear	6	0.057 ± 0.005	Yellow w/ slight reddish tint, chunky
P07	Primary TKA	OA	2	0.059 ± 0.011	
P03	Revision TKA	Wear	6	0.060 ± 0.005	Watery, lots of fluid, yellow
P23	Revision Tib. Insert	Wear	N/A	N/A	
P24	Revision Tib. Insert	Wear/OA	N/A	N/A	

APPENDIX C: COMPONENTS OF JOINT FLUID

The table below is a compilation of previous work in components of joint fluid. This was adapted from D. Mazzucco (Ph.D. Thesis, Massachusetts Institute of Technology, 2003).

	Healthy	**OA**	**RA**	**TJA**
Protein	10-30 mg/ml	24-44 mg/ml	27-63 mg/ml	~35 mg/ml
Hyaluronic Acid	~ 2 MDa 2-4 mg/ml	M_w 2.4-3.2 MDa 0.5-1 mg/ml	M_n ~ 0.6 MDa 0.1-0.9 mg/ml	Unknown ~0.5 mg/ml
Phospholipids	~0.1 mg/ml	0.1-0.5 mg/ml	0.4-0.8 mg/ml	Unknown

Mazzucco followed up on this data, and found that for joint fluids, there was a positive correlation between protein and phospholipids. He also found a negative correlation between hyaluronic acid and with both protein and phospholipids. The three were all correlated, thereby suggesting that the synovium has a major impact on the joint fluid.

Mazzucco noted that the positive correlations between protein and phospholipids content were $R^2 = 0.47$ overall and as high as $R^2 = 0.87$ for revision cases. Both protein and phospholipids had a negative correlation with HA (protein, $R^2 = 0.25$; phospholipids, $R^2 = 0.34$). For revision cases, it rose to $R^2 = 0.66$).

APPENDIX D: CALIBRATION OF FRICTION APPARATUS

A calibration process was necessary to establish a relationship between the known load (force) acting in the direction of frictional force on the pivoting arm and the voltage readings recorded by the computer from the strain gauges attached to the pivoting arm. See Section 2.2.3 for schematic and detailed description of the setup. With no load applied to arm, the voltage input was adjusted and set to zero. Loads in increments of 10 g were placed on the pulley and recorded in the computer from 0 g to 50 g. A total of six measurements were taken. An example of the output graph is provided below.

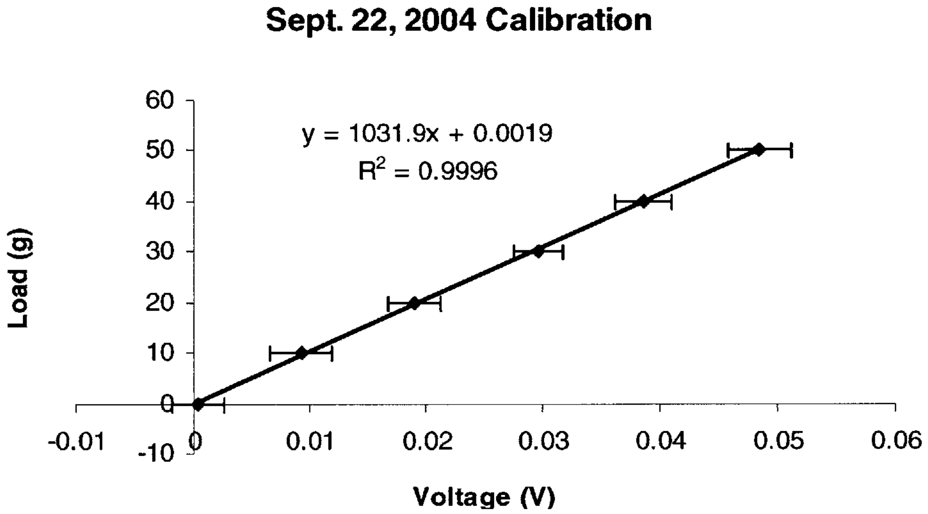

Fig. D.1. Calibration of friction apparatus This calibration was performed before testing every test group, typically (n=6). The bars represent standard deviation.

Error bars represent standard deviation. Calibrations were performed before the start of every test group. The frequency of the calibrations became necessary because the accuracy of the tests were important. The differences in the friction measurements were small enough that it was necessary to ensure the accuracy of each test group.

APPENDIX E: POWER CALCULATION

A power calculation is capable of determining an appropriate sample size to detect a statistical significance between data groups. Determining the power = 1 – β for the two sample t test is complicated. There is no simple way to use β curves.[1] The UCLA Statistics Department homepage (http://www.stat.ucla.edu) allows access to a power calculator. Using this calculator, known variables can be inputted to calculate the unknown.

μ_1 = Mean population 1
μ_2 = Mean population 2
n_1 = Sample size from population 1
n_2 = Sample size from population 2
δ_1 = Standard deviation of group 1
δ_2 = Standard deviation of group 2
α = Significance level of the test, or
Prob (reject null hypothesis (H_0: $\mu_1 = \mu_2$) given it is true)
$1-\beta$ = Power desired for the test, or
Prob (reject H_0 given that H_0 is true)

Inputting sample variables of $\mu_1 = 0.042$, $\mu_2 = 0.054$, $\delta_1 = 0.004$, $\delta_2 = 0.005$, $\alpha = 0.05$, and $(1-\beta) = 0.95$, the calculations for $n_1 = 4.44$ and $n_2 = 5.56$. Thus, $n = 6$ is an appropriate sample size to determine the statistical significance between distilled water and NCS.

FORMULA

Mazzucco calculated the sample size utilizing a formula as follows:[2]

$$n = 2(\sigma/\delta)^2(t_{\alpha,\upsilon} + t_{2\beta,\upsilon})$$

where:

n = sample size
σ = standard deviation
δ = desired difference to detect
α = desired significance level (probability of obtaining a false positive)
β = desired statistical power (probability of obtaining a false negative)
$t_{\alpha,\upsilon}$ = t statistic corresponding to significance level α and degree of freedom υ
$t_{2\beta,\upsilon}$ = t statistic corresponding to significance level 2β and degree of freedom υ

Both of power calculator and the equation assume that each sample group is normally distributed within its variance. The bottom equation is limited in assuming that the sample sizes and standard deviations are the same for both groups. This is not the case, thereby promoting the power calculator as the tool of choice to determine sample sizes and statistical significance.

1. J.L. Devore: *Probability and Statistics for Engineering and the Sciences*. pg. 370, Duxbury: Pacific Grove, CA, 2000.
2. Mazzucco, D.: Variation of Joint Fluid Composition and Its Effect on the Tribology of Replacement Joint Articulation. Ph.D. Thesis. MIT, 2003.

APPENDIX F: COMPILATION OF DYNAMIC FRICTION DATA

This chart is a compilation of all the lubricant test groups. Alike groups are shaded.

Lubricant	μ_d	n	Group
total water	0.041±0.007	47	1
PBS	0.040±0.007	8	2
PBS + HA	0.036±0.005	7	2
total NCS	0.053±0.007	38	3
90% NCS	0.053±0.001	4	3
40% NCS	0.058±0.007	4	3
20% NCS	0.053±0.005	2	3
5% NCS	0.056±0.002	2	3
1% NCS	0.056±0.001	2	3
40% NCS - Group 2	0.039±0.004	6	4
5% NCS - Group 2	0.037±0.003	6	4
90% NCS + Sodium Azide + EDTA	0.052±0.002	5	5
99% NCS + Sodium Azide	0.053±0.003	4	5
NCS + Proteinase	0.060±0.004	6	5
Mineral Oil	0.083±0.015	6	6
Lubricating Oil	0.083±0.004	2	6
Dry	0.155±0.010	7	7

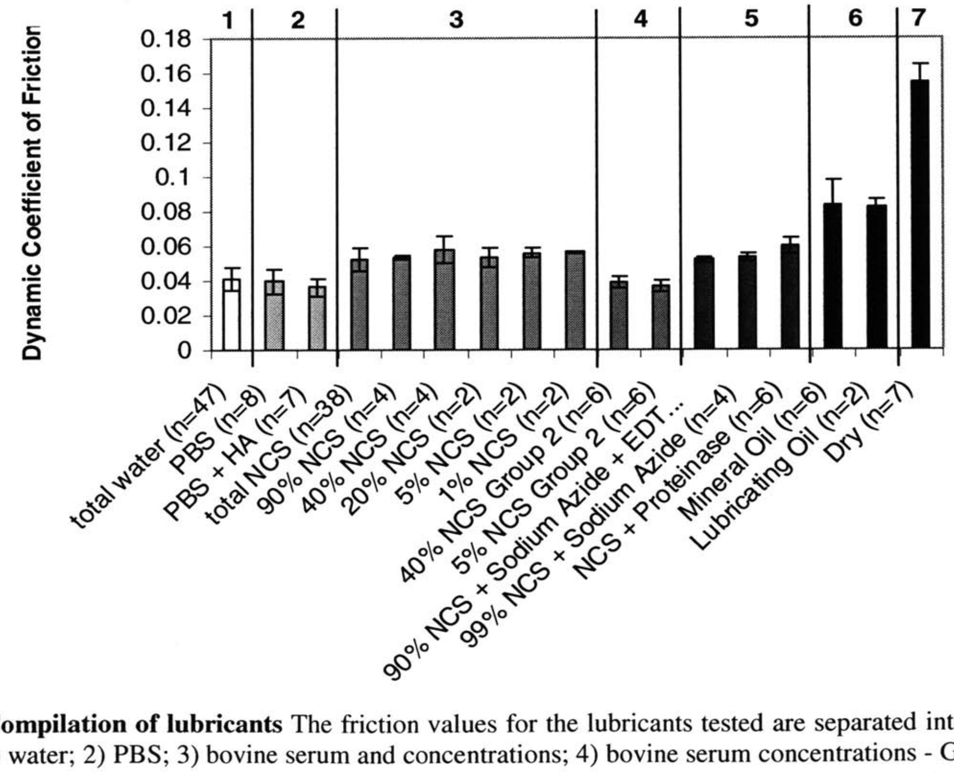

Fig. F.1 Compilation of lubricants The friction values for the lubricants tested are separated into seven groups. 1) water; 2) PBS; 3) bovine serum and concentrations; 4) bovine serum concentrations - Group 2; 5) bovine serum and additives; 6) petroleum-based oils; 7) dry. The bars indicate standard deviation. In general, water (Groups 1 and 2) has significantly lower friction than bovine serum (Groups 3, 4, 5). Group 4 used detergent-washed disks, and when compared to water that also used detergent-washed disks (not shown), the friction was higher. The digestion of proteins (Group 5) with proteinase in bovine serum significantly increases the friction. Group 6 is nearly two times greater than water, and exhibits boundary lubrication behavior. Group 7 is a dry case with no lubricants.

Joint Fluids	μ_d	n
P01 (Primary TKA)	0.055±0.003	6
P02 (Primary TKA)	0.053±0.004	4
P03 (Revision)	0.060±0.005	6
P04 (Revision)	0.057±0.005	6
P05 (Primary TKA)	0.051±0.002	5
P06 (Primary TKA)	0.052±0.002	6
P07 (Primary TKA)	0.059±0.011	2
P08 (Primary TKA)	0.045±0.002	6
P09 (Primary TKA)	0.045±0.001	6
P10 (Revision)	0.049±0.004	5
P11 (Primary TKA)	0.041±0.001	5
P12 (Primary TKA)	0.049±0.003	6
P13 (Primary TKA)	0.044±0.002	6
P14 (Primary TKA)	0.044±0.004	6
P15 (Primary TKA)	0.043±0.003	5
P16 (Primary TKA)	0.047±0.002	5
P17 (Revision)	0.051±0.003	6
P18 (Revision)	0.050±0.003	5
P19 (Primary TKA)	0.039±0.001	6
P20 (Primary TKA)	0.036±0.001	4
P21 (Primary TKA)	0.043±0.002	5

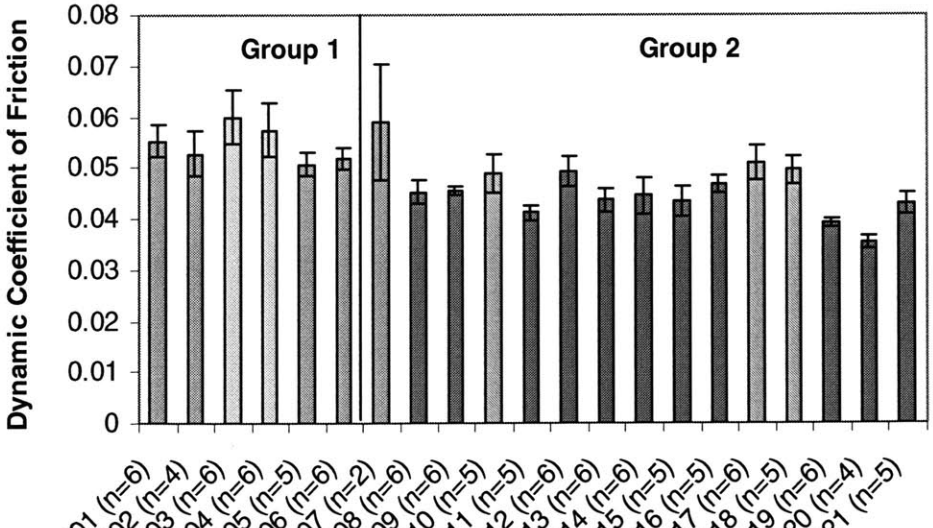

Fig. F.2 Compilation of joint fluid The friction values for joint fluids are separated into two groups: 1) Group 1, with no detergent-washed disks; 2) Group 2, with detergent-washed disks. Since the difference between the two groups is significant (Fig. 3.2.8.4), the groups are separated. The shaded regions are for fluids from primary TKA (OA) patients, and the dashed regions are for fluids from revision (wear) patients. The bars represent standard deviation.

APPENDIX G: "FRICTION MAP"

This is a concept described in Chapter 4, where the friction values of joint fluids are correlated to joint fluid component compositions. An argument for the correlation of friction and joint fluid composition is discussed in Chapter 4. Joint fluid samples from each regime are tested for wear, if sufficient fluid is available and the integrity of the fluid is not broken down through the length of the test. It is hypothesized that the joint fluid samples in each regime will elicit wear behavior that are clustered in their respective regimes. Although this thesis rejects the hypothesis of a direct relationship between friction and wear, analysis of the data support a relationship nonetheless. This is because the joint fluid concentrations of proteins, phospholipids and HA (which are responsible for the lubrication), are all correlated together, as observed by Mazzucco.[37] See Appendix C for some estimates of joint fluid content. And since his data showed that fluid from revision patients had the highest protein and phospholipids concentrations, thereby increasing boundary lubrication and eventually friction, a correlation to the high friction data of Revision fluids presented in this thesis is hypothesized. Therefore, since the compositional change relates to a change in friction with the data available, wear behavior is likely to change through compositional change since it was shown that friction was influenced by changes in lubrication mechanisms. This lubrication change in tribology behavior will affect the wear. Additionally, the resulting relationship between friction and wear is not expected to be direct.

A simple example of the "friction map" is developed using current joint fluid data.

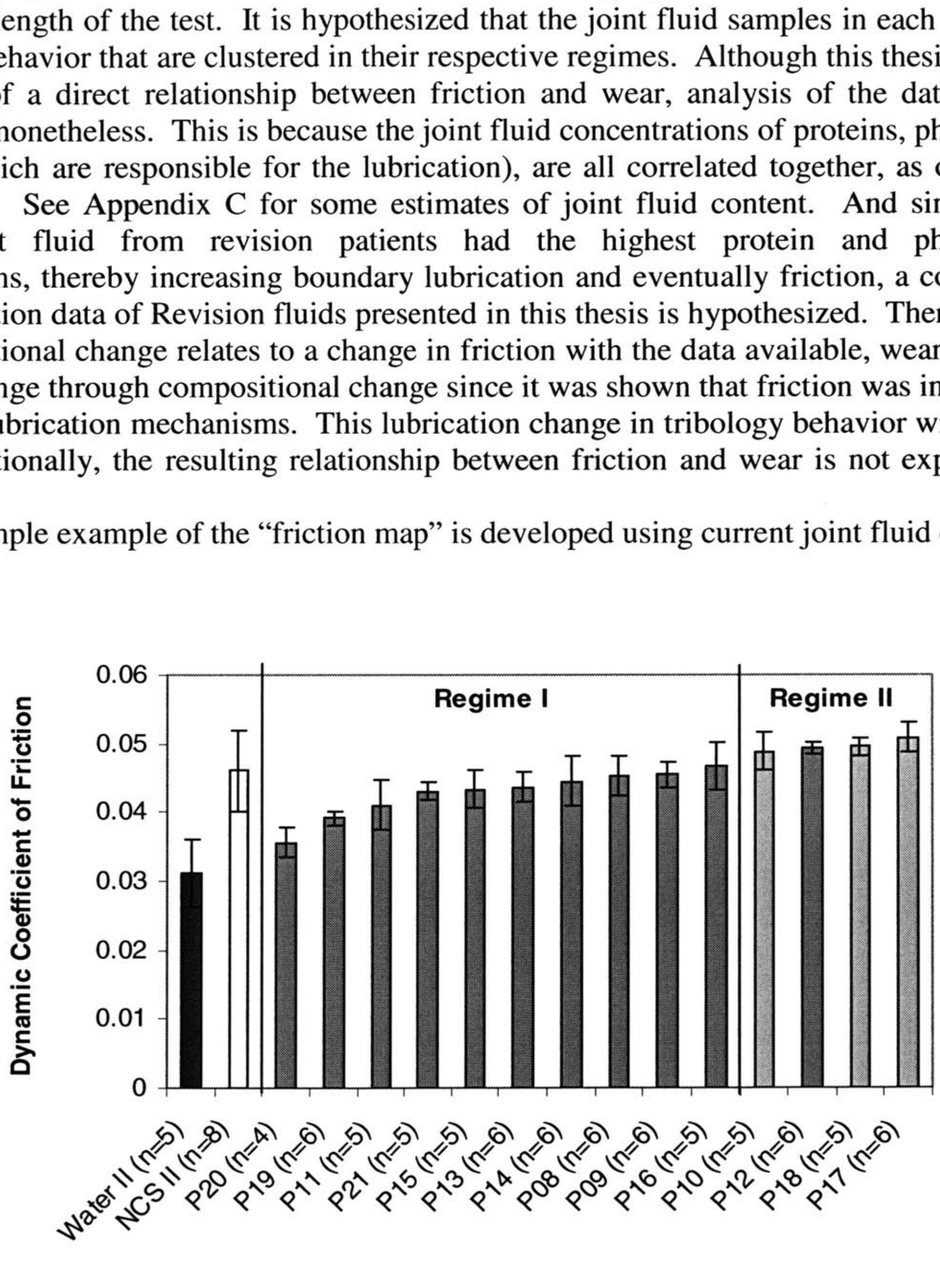

Fig. G.1 Example of proposed "friction map" Regime I is composed of all OA patients. Regime II is composed of mostly Revision cases. An increased sample set of joint fluids will increase the number of patient indications, and therefore the number of regimes. Fluids from within each regime will be tested for wear to obtain wear rates that are hypothesized to correlate to the regimes.

This hypothesis requires extensive future work. Since this current study observed only two patient indications, the correlation between friction and joint fluid composition is rather elementary. However, other disease indications may upset the correlation. Therefore, tests on more joint fluid samples of indications other than OA and wear for revision is required.