FACTORS AFFECTING TRACTION COEFFICIENTS DURING INTERMITTENT SLIDING MOTION IN TEXTURED METAL-POLYETHYLENE BEARINGS

by

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Abstract

In cases of severe arthritis, a metal-on-ultra-high molecular weight polyethylene (UHMWPE) total joint arthroplasty (TJA) is the primary solution. Wear of UHMWPE is a concern as it causes poor bearing performance and a decrease in the device’s lifespan. In this study, UHMWPE surface texturing has been proposed as a way to improve tribological conditions. Surface texturing has been studied previously under steady-state conditions, which is not representative of the harsh kinematic conditions occurring in daily living activities. Therefore, the objective of this study is to investigate the hypothesis that the proposed novel texturing approach improves tribological conditions during intermittent stop-dwell-start (SDS) motion by measuring the traction coefficient during the SDS phases.

A custom waveform in a pin-on-disc friction and wear tester was created to simulate SDS loading conditions. Untextured and textured UHMWPE specimens were tested under three lubricating conditions (unlubricated, water and glycerin). Then, a method was developed to extract meaningful traction coefficient data from the SDS test results. Lastly, factors affecting the tribological conditions in the metal-UHMWPE system were investigated based on traction coefficient and wear analysis observations.

The factors affecting the traction coefficient and wear were the introduction of texturing and the viscosity of the lubricant. The presence of a lubricant dominated when attempting to reduce the traction coefficient and wear. A significant reduction in traction coefficient was observed with both water and glycerin compared to unlubricated conditions in all phases of SDS motion, regardless of the surface geometry. Also, the higher the lubricant’s viscosity, the lower the traction coefficient and amount of wear.

The introduction of the textured surface resulted in a significant reduction or no change in traction coefficient in the stop and start phases in the unlubricated and glycerin conditions. Also, no additional wear was observed when the surface was textured compared to untextured. Therefore, when the bearing system is properly lubricated, texturing is a promising approach to reduce traction and wear. It is therefore proposed that textured UHMWPE be further investigated as a solution to extend the lifespan on TJA.
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Chapter 1

Introduction

1.1 Problem Definition

Articular cartilage covers the surfaces of bones to promote smooth articulation of a joint. In cases of major cartilage damage caused by severe arthritis, a total joint arthroplasty (TJA) is the primary solution to restore joint function and alleviate pain. Typically, the bearing design is a metal CoCr component on an ultra-high molecular weight polyethylene (UHMWPE) counterface [1]. Wear of UHMWPE in TJA is a concern as it can lead to the generation of debris and consequently the deterioration of bearing performance. Debris produced by wear of UHMWPE can cause implant loosening and osteolysis, which may lead to a decrease in the device’s lifespan and a need for revision surgeries [2].

Factors affecting wear in TJA include tribological conditions such as lubrication, wear, friction, mechanical loading conditions and UHMWPE material properties [3], [4]. While these factors are common in all TJA, the primary factors affecting the degradation of UHMWPE in hip and knee arthroplasty are fundamentally different due to differing joint geometries and kinematic conditions. Studies have focused on improving UHMWPE wear properties by highly cross-linking the polymer, which reduces its susceptibility to oxidation and its tendency for delamination under high contact stresses [5], [6]. However, highly cross-linked UHMWPE experiences creep and abrasive wear [7]. Since debris generated from abrasive wear of UHMWPE deteriorates bearing performance, tribological studies have examined the effects of friction and lubrication in orthopaedic bearing systems with the goal of reducing wear and improving long-term durability.

Results of wear simulations are commonly based on tests conducted under steady-state conditions, focusing on the hydrodynamic effects in the system; however, steady-state conditions
do not accurately represent the harsh kinematic conditions occurring during daily living activities. Clinical studies have reported that an average total hip replacement patient typically walks in bursts of 10 steps before pausing or changing to another activity such as stair climbing or sitting, with a typical pause duration of 2-5s between activities [8]. This finding is consistent with the assumption of intermittent stop-dwell-start (SDS) motion and recent studies suggest that these loading conditions increase wear rates by up to 490% due to the deterioration of the lubricant film when motion stops and starts [9], [10]. There can be many variations in dwell duration and walking cycles between dwells in SDS motion. In this study, a short dwell duration was used in consistence with the observations made by Morlock and colleagues, as well as to avoid the influence of lubricant film starvation and viscoelastic effects of the UHMWPE.

To reduce friction and wear in the polymeric component of TJA, UHMWPE surface texturing has been proposed as a potential approach to retain fluid and promote lubrication within the joint. UHMWPE surface texturing has been reported to influence tribological behaviour in sliding bearings by controlling surface contact area and increasing hydrodynamic pressure [11]–[13], entraining fluid [14], and isolating wear particles [15]. Uniformly texturing bearing surfaces is common practice in machine bearings [16], and has also seen promising results when used in orthopaedic bearings in in vitro studies [17]. Steady-state experiments have reported enhanced lubrication between the articulating surfaces, and reduced friction and wear [18]–[20]. However, the effect of UHMWPE texturing under SDS conditions is not known.

A textured UHMWPE surface pattern has been designed by Kamil [17], and the approach has been predicted to reduce stress in the polymer. This is expected to improve the tribological conditions in the stop and start phases of SDS loading conditions, and thus reduce the coefficient of friction during SDS motion [17]. It is hypothesized that with improved lubrication over less contact area, friction and wear of the polymeric component of TJA will be reduced.
1.2 Objective

The long-term objective of the study is to improve wear performance in metal-polymer TJA during SDS motion. A specific modification is considered in which the UHMWPE component is textured using a process developed at Queen’s University.

The aim of this study is to investigate the effects of the proposed surface texturing approach on the tribological conditions during intermittent SDS motion. The specific objectives include:

1. Modifying an existing device to produce SDS loading conditions in metal-UHMWPE systems in a friction and wear testing machine,
2. Developing a method to extract meaningful coefficient of traction information from the simplified SDS test, and
3. Investigate the factors affecting the tribological conditions in the metal-UHMWPE system.

1.3 Impact

The results of the study will determine whether texturing the surface of UHMWPE affects the coefficient of friction in metal-polymer TJA during SDS loading conditions. To the author’s knowledge, this is the first study of its kind aimed at minimizing the coefficient of friction under SDS conditions. Thus, obtaining results that predict equal or lower friction coefficients for textured UHMWPE compared to untextured UHMWPE would be considered a positive outcome. Results of this kind would provide motivation to continue to research wear in metal-polymer joint replacements under SDS conditions.
1.4 Outline

This thesis explores a novel approach to extend the lifespan of metal-polymer TJA.

Chapter 2: Literature Review: outlines the need for and limitations of TJA, as well as the need for improvements to TJA.

Chapter 3: Materials and Methods: provides an overview of the UHMWPE texturing process, the development of the simplified SDS test and the experimental design.

Chapter 4: Results: covers the development of the method to extract meaningful traction coefficient data representative of the SDS phases, the traction coefficient data, and the wear analysis of the worn UHMWPE specimens.

Chapter 5: Discussion: examines the factors affecting the traction coefficient and wear of the UHMWPE, and a conceptual model is developed to explain certain events of interest during the SDS phases.

Chapter 6: Conclusions: outlines the key findings of the study and suggests future work in further understanding the mechanism of lubrication in textured bearings and their application to TJA.
Chapter 2

Literature Review

Severe osteoarthritis is commonly treated with metal-polyethylene TJA. Wear of the polyethylene component is a limiting factor on the lifespan of successful implants, and kinematic conditions greatly affect wear rates. Although a number of improvements have been implemented to improve the wear properties of polyethylene, it is unknown whether these improvements would be successful in situations of intermittent motion. Uniformly texturing the surface of the polyethylene has seen success in reducing wear in hip replacements in steady-state wear studies and is suggested to be successful in intermittent motion conditions as well.

Wear studies are particularly challenging to execute due to the duration of testing and measurement of small amounts of wear particulates, so friction studies are often used as an indicator for potential wear in orthopaedic bearing systems. This chapter will explore the need for and challenges of total hip arthroplasty (THA), causes of wear in TJA, steady-state wear simulations and the need for more realistic simulations, UHMWPE surface texturing, and the current progress of the research group’s proposed texturing approach.

2.1 Osteoarthritis

2.1.1 Articular Cartilage
Articular cartilage covers the surfaces of long bones in diarthroidal joints (Figure 2.1a) [21]. The main functions of articular cartilage include transmitting loads across the articulating surfaces, absorbing impacts, and promoting smooth articulation within the joint by providing lubrication and low friction [22]. The coefficient of friction between the surfaces of a natural, healthy joint ranges from 0.005 to 0.023 [23].
Figure 2.1: Hip Anatomy
(a) Healthy articular cartilage covers the femoral head and acetabulum of the hip; (b) Osteoarthritic articular cartilage exposes the bone and decreases the joint space, causing joint pain.

Articular cartilage is composed of chondrocytes embedded in an extracellular matrix that consists of a mostly collagen type II network, containing high molecular weight proteoglycans, aggrecan and water (Figure 2.2) [24]. The collagen type II fibrils provide articular cartilage with the tensile strength necessary to resist shear loads during articulation [25], and the water-laden proteoglycans exert a swelling pressure which provides articular cartilage with the ability to evenly distribute contact stresses across the bone as well as generate a lubricating film on the bearing surfaces [26].

Figure 2.2: Structure and composition of articular cartilage.
Chondrocytes are in ECM that is composed of collagen, proteoglycans, aggrecans and water.
Since articular cartilage is an avascular, aneural and alymphatic tissue, it has limited potential for self-repair [22]. Demanding use, acute trauma and anatomic misalignment are all factors that can lead to the degeneration of articular cartilage, which is referred to as osteoarthritis (OA) and is characterized by the gradual loss of cartilage matrix content, loss of structural integrity and the eventual erosion of the articulating surfaces (Figure 2.1b) [27]. This joint disease is common in the aging population and is related to lower collagen production and the gradual reduction in cartilage health [28]. Symptoms of OA include chronic joint pain, restricted motion, joint cracking and joint effusions [29].

In the most severe stages of OA, the joint space between the articulating surfaces is reduced due to the degradation of cartilage leading to bone-on-bone contact and causing a chronic inflammatory response (Figure 2.1b). In this case, there is high friction between the joint surfaces and pain during use.

2.2 Osteoarthritis Treatment

There are many tissues in the body that are able to be naturally or surgically repaired, however this is not possible for articular cartilage. Therefore, synthetic replacements are used to repair damaged articular cartilage.

2.2.1 Total Joint Arthroplasty

In cases of severe OA, TJA is the primary solution. The most joint replacements are total knee arthroplasty (TKA) and total hip arthroplasty (THA). TJA encompasses a surgical procedure in which the damaged joint is removed and replaced with a prosthesis that is designed to relieve patient pain and restore joint function in a durable and reliable way [30]. Over 95% of patients report relief of hip pain post-operation [30].

In the United States, there are currently five types of THA available, which are categorized by their femoral head material and their liner material: metal-on-polyethylene, ceramic-on-polyethylene, metal-on-metal, ceramic-on-ceramic and ceramic-on-metal [31]. The
most common type of THA is a metal CoCr femoral head on an UHMWPE liner, mainly due to its low cost, self-lubrication ability and high resistance to wear and impact [32]. The typical friction coefficient in this material combination for THA is 0.07 [33].

A typical CoCr-UHMWPE THA has four components: a stem, femoral head, acetabular cup and acetabular liner. The stem is implanted into the femur with the femoral head attached, and the acetabular cup and liner are inserted into the acetabular. The femoral head fits into the acetabular cup to restore hip joint function (Figure 2.3). Clinical studies have reported survival rates of 90% after 10 years [34]–[37] and 80% after 20 years [38] depending on patient age, size, activity level, type of implant and the reason for replacement.

![Schematic of THA components](image)

**Figure 2.3: Components of a metal-on-polyethylene total hip replacement.**

### 2.2.2 UHMWPE

UHMWPE is a classification of polyethylene, which is manufactured from gaseous hydrocarbon, ethylene, and has the chemical formula, -(C₂H₄)ₓ⁻, where 𝑛 is greater than 100,000 [33]. Conventional UHMWPE used in orthopaedics is synthesized from ethylene, then sterilized with gamma irradiation to a dose between 25-40kGy in air, inert gasses such as nitrogen, or in a vacuum depending on the test or medical application [6], [7], [39]–[41].
Figure 2.4: Chemical structure of polyethylene.

(A) Ethylene monomer used to form polyethylene. (B) Polyethylene structure.

Approximately 50% of the polymer is crystalline which acts like a solid and 50% is amorphous which contains mobile polymer chains [42], making UHMWPE a linear semi-crystalline polymer. The crystalline phase contains chains folded into highly oriented lamellae that are 10-50nm thick and 10-50μm long. The lamellae are oriented randomly within the amorphous phase with tie molecules linking the individual lamellae layers to each other [33]. Figure 2.5 shows the crystalline and amorphous regions of UHMWPE.

Figure 2.5: TEM micrograph of crystalline and amorphous regions of UHMWPE [33].

UHMWPE is made up of very long, unbranched chains of PE compared to high-density polyethylene (HDPE), that are all aligned in the same direction giving it a molecular weight of 3.5-7.5 million g/mol compared to 0.05-0.25 million g/mol for HDPE. Its impressive strength (21-28MPa) is due to the length of each individual chain because the longer chains transfer the load more effectively to the polymer backbone by strengthening intermolecular interactions [33].
2.3 Challenges with TJA

2.3.1 Reasons for Revision Surgeries

While success rates for THA are over 90%, complications still occur. Wear of UHMWPE in TJA is a concern because of the release of polymeric debris that leads to the deterioration of bearing performance. Debris produced by wear of UHMWPE can cause implant loosening and osteolysis, which was the cause of approximately 32.8% of the hip replacement revision surgeries between 2013-2014 in Canada (Figure 2.6) [43]. Osteolysis is the end result of a biological process where the number of particles generated in the joint space exceeds the joint capsule’s capacity and the residual particles stimulate a macrophage-induced inflammatory response that leads to bone loss. The loss of bone mass causes aseptic loosening, which is defined as the failure of the bond between an implant and bone in the absence of an infection [2].

![Figure 2.6: Reasons for THA revisions, Canadian Joint Replacement Registry 2013-2014 [43].](image)
2.3.2 Wear of UHMWPE

Factors affecting wear in TJA include tribological conditions (friction, lubrication and wear in bearings), mechanical loading conditions and UHMWPE material properties [3], [4].

The Stribeck curve (Figure 2.7) is an important tool in tribology. It maps the relationship of the coefficient of friction between two sliding surfaces separated by a fluid film to the relative speed between the surfaces [44]. There are three regions of the Stribeck curve and they are associated with different lubrication modes. In the boundary lubrication region occurring at low speeds, friction is invariant with speed and surface-on-surface contact is observed. In the mixed lubrication mode occurring at intermediate speeds, the coefficient of friction decreases with increasing speed [45]. In the hydrodynamic lubrication mode, the two surfaces are completely separated by sufficient hydrodynamic pressure between the surfaces [46]. Unsworth et al. [47] indicates that the lubrication mode in knee joint bearings, in accordance with the Stribeck curve, is likely a mixed lubrication regime during steady state motion, which is affected by both surface asperity interactions as well as fluid flow [48]. That is, there is a lubricant film generated, but it is not thick enough to completely separate the surface asperities on the articulating surfaces during motion. However, hydrodynamic effects are still present. Since there is not complete separation of the two surfaces, the surface asperities interact causing friction.

Friction coefficients are highly dependent on the lubrication regime present between the two sliding surfaces in TJA. Factors influencing the coefficient of friction include adhesion between surface molecules of the two materials, interlocking of asperities on the surfaces, and ploughing of the bulk of one surface through the other [49]. While the friction coefficient describes the interaction between two surfaces rubbing together in dry contact, it does not explain the complex interactions occurring when a lubricant is introduced such as the dragging forces associated with the fluid moving between the counterparts or the deformation of the material. The traction coefficient, defined as the frictional force and dragging forces divided by the applied load.
encompasses these influencing factors and provides more detail into the tribology and deformation occurring at the sliding surfaces [50].

![Striebeck Curve](image)

**Figure 2.7: Striebeck curve with boundary, mixed and hydrodynamic lubrication modes.**

### 2.3.2.1 UHMWPE Wear Mechanisms

Surface damage of UHMWPE occurs via multiple wear methods at different depths when cyclically loaded [6]. From a study examining 48 retrieved TKA, Hood *et al.* [51] classified seven modes of articulating surface damage: pitting, embedded debris, scratching, delamination, surface deformation, burnishing and abrasion/adhesive wear.

1. **Pitting.** Surface craters 2-3mm in diameter and 1-2mm deep characterize the surface of the UHMWPE, liberating millimetre-sized pieces of wear debris from the articulating surface.

2. **Embedded debris.** Bone chips, bone cement fragments or metallic fragments from the surface of the metal component could become embedded in the UHMWPE, which can result in third body wear of both the UHMWPE and
metallic surfaces. Additionally, embedded debris can scratch the metallic surface, resulting in further abrasive wear of the UHMWPE.

3. **Scratching.** Linear indentations are featured on the articulating surface produced by microscopic asperities on the opposing metallic surface or by third party asperities. Scratching is considered a type of abrasive wear.

4. **Delamination.** Sheets of UHMWPE are removed from the articulating surface as a severe result of fatigue wear.

5. **Surface deformation.** Permanent, irrecoverable damage occurs to the surface geometry of the implant. This plastic deformation does not result in the removal of material and thus does not strictly correspond as wear, however it can lead to undesirable kinematic conditions that result in wear.

6. **Burnishing.** Characterized as “wear polishing,” burnishing is a result of adhesive/abrasive wear. Burnishing produces wear debris that are within the size range that can stimulate an osteolytic response.

7. **Abrasion.** The UHMWPE surface is shredded producing micrometre-sized debris.

These modes of degradation are common in all TJA, however the primary degradation mechanism of UHMWPE components in TKA and THA are fundamentally different. In the knee, with non-conforming CoCr femoral and UHMWPE tibial surfaces, the most significant modes of wear are pitting and delamination in the regions of contact [52]–[54]. During pitting, wear debris produced are too large to provoke an osteolytic response and pitting is therefore considered a more benign wear mechanism than adhesive/abrasive wear. In short-term explanted tibial inserts, pitting has been attributed to third body damage and plastic deformation, rather than fatigue wear of the surface. Furthermore, during delamination, sheets greater than 0.5mm have been reported to have been removed from the UHMWPE surface in TKA [7], [55]. This failure is caused by the
initiation and propagation of subsurface cracks that eventually connect with the surface of the polymer [40], [55]. If the tibial component is sufficiently thick, the UHMWPE under the delaminated sheets can still serve as a functional bearing surface. However, if the tibial component is thin and/or is brittle due to oxidation, delamination can result in catastrophic wear of the UHMWPE [33], [51].

The main wear mechanisms in a hip, with a conforming CoCr femoral head and UHMWPE liner, are adhesive and abrasive wear [1], [56], [57]. Adhesive/abrasive wear occurs through the rubbing action of the hard asperities on the surface of the metal component or third body particles, such as bone chips, bone cement particles or metal fragments. This type of wear results in the removal of small wear debris on the order of a few micrometers or less in size [55]. The mixed lubrication mode present in orthopaedic joint bearing promotes adhesive wear due to contact of surface asperities during motion.

2.3.2.2 Effect of Joint Kinematics on UHMWPE Wear
The kinematics of the articulating surface of metal-polymer orthopaedic bearings are suggested to affect wear, but no correlation has been found between wear and coefficients of friction [33], [40], [55]. For example, with early Charnley metal-on-PTFE (Teflon®) THA, there was low friction but very high wear rates of up to 0.5mm/month observed in implanted hips, leading to intense foreign body reactions [58], [59].

There is low adhesive wear during sliding motion (one surface moving while the other is stationary) as seen in THA. Contrarily, in TKA, during which rolling and gliding motions (both surfaces move with respect to each other) are present, the amount of wear is greater. There is also evidence of delamination which is promoted by the non-conformity of the components of total knee replacements [3].

While this thesis is intended to investigate the tribological conditions in a diversity of TJA, the remainder of this report will focus on the events in the hip and THA.
2.3.2.3 Effect of Chemical Degradation on UHMWPE Wear

The material properties of UHMWPE affect chemical degradation, which occurs via oxidation and accelerates mechanical wear. Oxidation may occur due to the sterilization process of UHMWPE. The most common process is gamma radiation, which has the objective to kill pathogenic agents on the surface or in the bulk of the UHMWPE by destroying the pathogens’ structures [39]. The energy of gamma radiation causes scission of some of the chemical bonds, forming free radicals [41]. Irradiation of UHMWPE in the presence of oxygen increases the occurrence of chain scission and therefore the density of crystallinity of the material [60]. The increased crystallinity and the reduction in the number of tie molecules connecting crystallites leads to increased brittleness, and therefore delamination [40].

Furthermore, irradiation produces free radicals in UHMWPE. Some of these free radicals are used to crosslink polymer chains in the amorphous region, however the free radicals in the crystalline phase remain trapped. The trapped free radicals are long-lived and cause oxidation of the material over time as they migrate to the crystalline-amorphous interface [61].

2.4 Wear Simulation

Since there are limited opportunities and ethical concerns for observing the wear of implanted THA, in vitro simulations are conducted instead. Hip simulators provide clinically relevant data regarding wear of THA by replicating in vivo loading and gait kinematics for 2 million cycles in continuous motion (Figure 2.8). Simulated gait motion is typically controlled by flexion/extension, internal/external rotation and/or abduction/adduction. Loads are usually applied in the vertical axis for simplicity. Components of the hip replacements can be periodically removed and examined to measure wear, which is not possible for implanted THA. ISO14242 is the standard test protocol for loading and displacement parameters for hip wear testing machines. Figure 2.8 shows a hip simulator machine and the load, flexion/extension and internal/external rotation for one walking cycle in ISO14242.
Figure 2.8: A typical hip simulator as well as load and motion inputs for a standard walking cycle in hip simulator, ISO 14242 [62].

Most *in vitro* wear studies are carried out under steady conditions. When steady-state results have been compared to explanted hip replacements, much lower wear rates have been observed [63], [64]. Various studies suggest that this is due to the continuous nature of simulator testing compared to the varying motion patterns of typical patients [63]. It has been suggested that the variances in daily living activities causes a breakdown of the lubricating film between the bearing surfaces leading to increased wear, whereas the continuous motion of a hip simulator allows for a more optimal lubrication regime between the bearing surfaces, resulting in less wear.
2.4.1 Stop-Dwell-Start Motion

Since wear results from steady-state hip simulator tests are not consistent with those observed in vivo, an approach more representative of the demanding kinematic conditions that occur during activities of daily living has been suggested. Clinical studies have reported that an average total hip replacement patient typically walks in bursts of 10 steps before pausing or changing to another activity such as stair climbing or sitting, with a typical pause duration of 2-5s between activities [8]. This finding is consistent with the assumption of SDS motion. During SDS motion, the speed of the articulating surfaces decreases to zero, dwells for a period of time under a constant compressive force, and then increases again to a nonzero value [65].

Figure 2.9 contains the load, flexion/extension and internal/external rotation inputs for an SDS walking cycle for a hip simulator developed by Hadley that was adapted from the ISO14242 test, shown in Figure 2.8. The five cycles indicated in the plots in Figure 2.9 could be programmed in different combinations and durations depending on the desired test specifications.

Recent studies suggest that SDS loading conditions increase wear rates by up to 490% [9]. Hadley et al. [10] suggests that this increased wear is attributed to the deterioration of the lubricant film between the surfaces during the dwell phase when entraining motion tends towards zero. When motion resumes, the surfaces are assumed to be operating at a less effective lubrication regime than normal, leading to increased surface wear. The study also concluded that the duration of the dwell phase between gait cycles did not significantly affect the wear rate, though a significant increase in wear was observed as the number of gait cycles between dwell phases was reduced.
Figure 2.9: Load and motion inputs for five cycles of an SDS test in a hip simulator. Gait cycle phases and dwell are depicted based on hip flexion angles [66].
In the case of the current study where the effects of SDS motion were being investigated using a pin-on-disc friction and wear tester, the changes in joint angles were converted to linear speeds. To represent hip joint motion, pure sliding was desired due to the conforming nature of hips. Therefore, in these new terms, SDS motion is defined as a sliding contact decelerating over a fixed distance, pausing for a duration of time and then accelerating over another fixed distance, all under a constant compressive load. The dynamic kinematic conditions including sliding speed, rate of acceleration, dwell duration, load magnitude, etc., can be varied to form different SDS patterns.

2.5 Improving Wear Performance of UHMWPE in TJA

Attempts have been made to improve the material properties of UHMWPE to reduce wear by oxidation, which occurs when free radicals generated by irradiation react with oxygen [6], [7], [67]. Gamma-sterilization of polyethylene inserts and storage in inert gasses are today’s standard in minimizing oxidation during shelf storage [7]. Highly cross-linking UHMWPE has been suggested to increase the wear resistance of TJA in vivo [68]. In a hip simulator study by Dumbleton et al. where conventional UHMWPE was highly cross-linked by gamma-irradiation, a reduction in the free radical count and in the oxidation index\(^1\) from 1.7 to 0.05 was observed [39]. Furthermore, a reduction in wear rate of 41.8mg/million cycles was observed in the same hip simulator study. Overall, clinical results of cross-linking indicate a reduction in adhesive wear and little to no delamination under steady-state, lubricated loading conditions. However, some mechanical properties such as the toughness, modulus and tensile strength of UHMWPE were observed to have decreased [7], [67].

---

1 Fourier transform infrared spectroscopy (FTIR) is used to quantify the extent of oxidation in UHMWPE components by quantifying carboxyl groups formed by oxidation of PE as a reaction to oxygen from the environment with free radicals formed by gamma irradiation. The oxidation index is calculated by normalizing the height under the carboxyl peak [106].
2.6 Uniformly Textured UHMWPE Surfaces

With UHMWPE as a standard bearing surface in TJA, other methods of reducing wear are being examined. UHMWPE surface texturing has been proposed as a potential approach to retain fluid and promote lubrication in the joint in an effort to reduce wear. Surface texturing involves applying a pattern of cavities machined on a surface with prescribed shapes, sizes and distributions [50].

Success in reducing friction by improving hydrodynamic pressure distribution and time-dependent clearance between articulating surfaces has been observed when the surface of mechanical bearings are textured [69]. It is expected that similar success be seen in orthopaedic bearings by controlling surface contact area, increasing hydrodynamic pressure, entraining fluid and isolating wear particles [55]. Additionally, surface texturing of UHMWPE could help overcome the hydrophobicity of the polymer.

2.6.1 Surface Texturing in Orthopaedic Bearings

The application of texturing the surface of orthopaedic bearings has been explored. Zhang et al. [20] mimicked articular cartilage surface morphology on the surface of the UHMWPE, as described by Clarke [70]. The textured UHMWPE articulated against a metal counterface showed a reduction in the coefficient of friction of 67-86% using water as a lubricant and under steady-state motion.

Sawano et al. [19] introduced dimples ranging from 0.25-4.4μm in diameter onto the surface of the metal component of a THA, and the results of a 2-axes pin-on-plate steady-state sliding test with Co-Cr-Mo alloy plates showed a 52% reduction in UHMWPE wear compared to non-textured surfaces when using water as a lubricant. Reduced wear was observed when the dimple diameter was approximately 1μm because the wear particles were trapped in the dimples and could not scratch the bearing surfaces. The study’s analysis predicted that the lifetime of a THA with the proposed micro-dimple pattern could be increased from 15 to 33 years.
Kustandi et al. [71] introduced a 1µm grating structure pattern into the surface of UHMWPE using nanoimprint lithography (NIL), which is a simple low-cost and high-resolution patterning method to produce micro and nano-structures in polymers. Linear reciprocating wear tests using a ceramic ball in a tribometer resulted in an 8-35% reduction in coefficient of friction under dry conditions.

In a study by López-Cervantes et al. [50], square arrays of dimples were machined into the surface of UHMWPE with two different diameters, \( D = 0.397 \text{mm} \) and \( D/2 = 0.199 \text{mm} \), and centre-to-centre spacing of \( 1.5D \). The effects of the dimples on the traction coefficient, which is defined as the frictional and dragging forces divided by the applied force, were observed. It was expected that the cavities would expand the range of the hydrodynamic lubrication regime observed in the Strubeck curve. The study examined the effects of dimple size, load, mean speed and sliding-to-rolling ratio (SRR) compared to plain surfaces by conducting a ball-on-disc test comprising of a steel ball and flat UHMWPE disc with distilled water as a lubricant. A higher SRR ratio would be more representative of the kinematics in THA, and a lower SRR value would be more representative of the kinematics in TKA. In all cases, the traction coefficient was smaller when the surface was textured than when it was untextured. Textured surfaces with diameter, \( D/2 \), exhibited the largest reduction in traction coefficient. Furthermore, the study reported that the traction coefficient was significantly less at lower loads regardless of speed and SRR. This is because the amount of direct contact between the metal and plastic components of the bearing system was reduced. At greater loads when there is more surface contact, texturing was only effective in extreme kinematic environments such as at low speeds and very high or low SRR. At greater speeds, the traction coefficient decreased for both untextured and textured surfaces because of the enhanced hydrodynamic effects. Lopez-Cervantes suggested that the lower traction coefficients experienced with textured surfaces could improve the performance of UHMWPE in orthopaedic applications. The most important benefit of texturing is the reduction in direct metal-
on-plastic contact occurring at low speeds and low SRR, which is consistent with the kinematic conditions entering and exiting the dwell phase of SDS motion, and when wear is most likely to occur.

While all of the studies discussed in this section show promising results for texturing the surfaces in orthopaedic bearings, all of the experiments were conducted under steady-state conditions. Therefore, the effects under SDS loading conditions are unknown and must be studied further. A surface texturing approach proposed by Kamil will be examined under these conditions [72].

2.6.2 Recent Texturing Method for SDS Applications
Recent work in the laboratory has resulted in the production of a novel textured surface that has been predicted to reduce the coefficient of friction and improve the tribological conditions in the transition into and out of the dwell phase of SDS motion [17].

Figure 2.10 outlines how the proposed textured metal-on-polymer system functions. It is hypothesized that under quasi-static conditions, dimples in the surface will be entrained with fluid (Figure 2.10a). When the polymer is loaded, the metal upper surface will displace the polymer (Figure 2.10b). The loaded area with fluid-filled dimples develops locally pressurized regions under loading normal to the polymer surface (Figure 2.10c). The stress distribution in the polymer contact areas (B, B’) depends on the viscoelastic properties of the bulk, entrained materials and the geometry of the dimples. It is expected that the stress in the fluid ($\sigma_1$) will be higher than the contact stress in the polymer ($\sigma_2$) due to a higher structural stiffness in the region under the indentation, which occurs during the manufacturing process. This reduction in contact stress in the polymer is referred to as stress shielding.
Figure 2.10: Model for textured polymer-metal contact with entrained fluid.

(a) Undeformed state showing the entrained fluid in the dimples; (b) The surface deflects the amount, $\delta$, due to the displacement of the metal upper surface under the applied load; (c) Resulting contact stress in a dimple and its adjacent area due to the normal load application; (d) Fluid gap created during motion start-up.

Furthermore, during the stopping or starting phases of SDS motion, improved tribological conditions are expected. Normal synovial fluid is non-newtonian with marked shear-thinning behaviour related to the presence of hyaluronic acid [73]; therefore, the fluid in the indentations will have a higher viscosity than the fluid in the polymer contact regions due to lower shear stresses experienced. Once motion resumes, the shear stress will increase in the indentations inducing flow into the gap to help generate a continuous fluid layer between the two articulating surfaces under a large range of stress and motion conditions (Figure 2.10d). Improved lubrication between the articulating surfaces of the bearing should reduce friction and wear. A similar mechanism is expected for the stop phase in which the loss of fluid in the gap is delayed.

Studies were undertaken using a finite element model of textured systems in the dwell phase of SDS motion under a constant load. The metal surface was assumed to be rigid, the UHMWPE was assumed to be linearly elastic and the fluid retained in the dimples was assigned an arbitrary high modulus to approximate incompressibility [17].

Stress reduction, $S_R$, was used as an indicator for performance and was defined as the reduction in stress in the polymer contact regions ($\sigma$) compared to the expected nominal average stress in untextured regions ($\sigma_F$) such that;
\[ S_R = \left(1 - \frac{\sigma}{\sigma_f}\right) \times 100\% \]

A range of semi-spherical dimples of varying diameters, spacing and patterns were analyzed [72]. Results showed that significant polymeric stress reduction occurs in the range of \(0 < c/d < 2\), with stress shielding as high as 75\% observed for \(c/d = 1.09\) when the dimples are arranged in a hexagonal pattern. However, low \(c/d\) ratios represent unrealistic configurations in practice since the size of the contact region between the dimples would be small. Practical configurations were suggested in the range of \(1.2 < c/d < 1.6\) which corresponds with stress shielding from 10-45\% [7]. The proposed geometry is shown in Figure 2.11, which has semi-spherical dimples in a hexagonal pattern with diameter, \(d\), and centre-to-centre spacing, \(c\).

Figure 2.11: Schematic representation of the hexagonal geometry pattern. The dimples have a diameter, \(d\), and there is a distance, \(c\), between adjacent dimples.

Specimens with the proposed hexagonal dimple geometry can be produced and a manufacturing method has been optimized to fabricate these polyethylene components achieving 96\% of the desired dimple diameter [74]. Previous studies have also suggested that stresses in the polymer surface can be reduced with the introduction of dimples during a compression test using a flat punch when the dimples are entrained with fluid [75]. For stress shielding to be observed, a
sufficient seal between the metal and polyethylene must be achieved. In order for this to occur, the dimples must be completely filled with fluid and the viscosity of the fluid must be high.

2.7 Summary

Metal-on-polyethylene are the most common material pairing in THA, and while over 90% successful 10 years post-operative, wear mechanisms persist producing UHMWPE wear debris that causes aseptic loosening and ultimately failure of the artificial joint.

Most wear studies of TJA are done under steady-state conditions, although joint kinematics are recognized to affect wear rates. Recent hip simulator studies investigating the effects of intermittent SDS motion on metal-on-metal hip replacements have reported wear rates to increase significantly compared to steady-state walking.

Many studies have been conducted proposing approaches to improve wear of the polymeric component of TJA. Uniformly texturing the surface of the UHMWPE to entrain fluid to reduce friction and wear has been found successful under steady-state conditions, however has not been studied in intermittent motion conditions.

A surface texturing method proposed by Kamil has been reported to reduce stress in the plastic by entraining fluid in the dimples that can assume a portion of the load when the plastic is deformed. Less stress in the plastic would theoretically reduce wear of the plastic [17].

The objective of this study is to develop a testing regime to produce an SDS kinematic pattern and measure the corresponding traction coefficient for both textured and untextured UHMWPE surfaces under different lubricating conditions.
Chapter 3

Materials and Methods

3.1 Experimental Design

This study was motivated by the research question of whether uniformly texturing the surface of UHMWPE improves tribological conditions in orthopaedic bearings under SDS conditions. A fabrication method was developed to uniformly texture the surface of UHMWPE by imprinting the surface of blank commercial grade UHMWPE using a micro-embossing process. UHMWPE specimens were subjected to wear tests under SDS motion in a pin-on-disc friction and wear testing machine, in which the traction coefficient and wear patterns were observed. Six conditions were tested for 6,000 cycles each: (1) untextured unlubricated, (2) untextured water lubrication, (3) untextured glycerin lubrication, (4) textured unlubricated, (5) textured water lubrication and (6) textured glycerin lubrication.

3.2 Friction Measurement System

The UHMWPE specimens were tested in an AMTI OrthoPod™ (AMTI, Watertown, MA) six station pin-on-disc friction and wear testing machine, in which different paths can be generated by rotations of the pin and disc to simulate unidirectional and bidirectional sliding (Figure 3.1). There are two main components of the machine: the top head and the base. The top head contains the pin actuators, which can be loaded up to 445N using pressurized air and the base contains the discs holding the UHMWPE specimens. The machine is connected to a computer that can rotate and load the pins and discs under manual control, or be programmed to do so. All of the pins move simultaneously and all of the discs move simultaneously. The pins and discs move in cyclic motion independently of each other (Figure 3.2). Relevant data acquired from programmed tests include pin and disc location, pin load, forces and moments in the x, y and z-directions on the
pins, and the coefficient of friction, which are acquired by the proprietary data acquisition system from the machine using Pod software on a Windows 98 platform\(^2\).

There are three legs on the machine that each contain three-component force sensors, which allow for the frictional analysis. The force sensors were calibrated by hanging 10lb weights from the legs in the \(x\), \(y\) and \(z\)-directions. According to the manufacturer, the accuracy of the calibrated measurement system is ±4N for \(F_x\) and \(F_y\), and ±8N for \(F_z\).

![Figure 3.1: OrthoPod\textsuperscript{TM} pin-on-disc friction and wear tester machine](image)

This pin-on-disc tester is comprised of the top head containing the metal pins, the base containing the discs and the UHMWPE specimens, computer containing the OrthoPod\textsuperscript{TM} software and the data acquisition cable connecting the machine and the computer.

\(^2\) There were some unfortunate experiences with this legacy device. Tragedy struck at the beginning of data collection. The motherboard crashed in the Windows 98 computer, for which support or know-how is no longer available. Luckily, a replacement motherboard was located, and a month and a half later, the antique computer was restored.
The pins and discs rotate independently in both directions to produce the desired path of motion. All of the pins must follow the same path and all of the discs must follow the same path.

3.3 Experimental Preparation

The pin-on-disc wear tests were conducted by articulating a flat cylindrical stainless steel pin on flat untextured and textured UHMWPE samples. The processes to manufacture and prepare the pin and discs are outlined in Sections 3.3.1 and 3.3.2.

3.3.1 UHMWPE Specimens

The blank UHMWPE specimens were waterjet cut from a commercial-grade UHMWPE sheet (McMaster Carr, Aurora, OH) into 1.25 x 0.75 x 0.25 inch pieces with a notch on one end for orienting the specimens in the OrthoPod™ (Figure 3.3). The specifications for the UHMWPE sheet can be found in Appendix A.
UHMWPE specimens with the hexagonal texturing pattern developed by Kamil [72] were manufactured with a $c/d$ ratio of 1.5 ($d=433\mu m$, $c=650\mu m$) using a hot embossing manufacturing process by pressing a die into the blank UHMWPE specimens. This process was optimized in a previous study to achieve 96% of the desired dimple diameter [74] (Appendix B).

A die was first formed by drilling the hexagonal pattern of the desired $c$ and $d$ dimensions over a 24 x 12 mm area into a flexible aluminum sheet, $d/2$ thick, using a Microlution™ 363-S 3D micro-milling machine (Microlution™, Chicago, IL). Precision 316-stainless steel balls (Abbott Ball Company, West Hartford, CT) with diameter, $d$, were press fit into the holes in the aluminum plate (Figure 3.4a). Then, the aluminum plate was fixed between two steel blocks and pressed together to ensure the stainless steel balls were fixed into the holes. The aluminum plate was attached to a polished stainless steel block with the same dimensions as the UHMWPE specimens using Loctite A234 adhesive with Loctite 075 adhesive activator (Henkel Corporation, Düsseldorf, Germany) to produce the completed die. The manufacturer reports that the adhesive is at 15% strength at 100°C compared to room temperature, however since the system is under compression during the hot embossing process, it is assumed that this is sufficient for adhering the aluminum plate to the steel base even at the elevated temperatures experienced [76]. The surface of the completed die can be seen in Figure 3.4b.

Figure 3.3: UHMWPE specimen dimensions.
To texture the UHMWPE specimens, an EVG® 510HE hot embosser (EV Group, Austria) was used. The hot embosser consists of an upper and lower stage with the top stage being able to move in the vertical direction via a piston mechanism. The die was placed on the lower stage and the blank UHMWPE specimen was on top of the die as shown in Figure 3.5.

The hot embosser chamber (top and bottom plates) heated up to 110°C, which is above the glass transition temperature (-160°C) and below the melting temperature (137°C) of UHMWPE Specimen
UHMWPE [33]. The chamber was evacuated to a vacuum. Then, the upper plate was lowered to press the die into the UHMWPE specimen until 1800N was reached, which is above the yield strength of the polymer (~5MPa at 100°C, or 1400N based on the dimensions of the specimen) [77]. The load was held for 60 minutes and then the chamber was cooled to 20°C at a rate of 5°C/minute. Lastly, the top plate was lifted and the vacuum was removed. The hot embosser protocol can be found in Appendix C.

3.3.1.1 Specimen Measurement Verification
A completed textured UHMWPE sample is shown in Figure 3.6. Dimple diameter and centre-to-centre distance were measured 15 times randomly across each sample upon completion by taking photos at 2x magnification using an optical microscope (Olympus Canada Inc., Toronto, ON) and measuring using Motic Images Plus 3.0 (Motic, Richmond, BC) to verify that the desired dimensions were achieved.

![Figure 3.6: Formed specimen](image)

3.3.2 Pins
A 6mm diameter flat cylindrical stainless steel pin, polished to a mirror finish (Figure 3.7B) was articulated against a flat UHMWPE specimen. Stainless steel was used instead of CoCr due to
material availability and ease of manufacturing. The pin was formed from a 0.375” diameter stainless steel rod. The rod was cut to length and lathed to the desired 6mm diameter at the bottom. Full pin dimensions are depicted in Figure 3.7A. Additionally, the articulating edge of the pin was bevelled by hand on a lathe to approximately 45° to avoid the pin delaminating the surface of the UHMWPE.

The articulating surface of each pin was polished prior to each test. Three different slurries were used in polishing the pins in the following order: 6µm diamond spray, 0.05µm alumina slurry and 0.05µm colloidal silica solution. All polishing was carried out on rotating polishing wheels using a pin holder to keep the pins perpendicular to the grinding surface. Each slurry was sprayed on cotton cloth-wrapped rotating discs and the pins were ground for 3-5 minutes. Following each step in the polishing process, the pins were washed with warm water and soap, and wiped dry with a cotton ball. In Figure 3.7B below, the pins with their polished surface can be seen after 6,000 SDS cycles.

![Figure 3.7: (A) Schematic of pin with dimensions; (B) Photograph of pins after 6,000 SDS cycles.](image)

The pins were inserted into the top head of the pin-on-disc tester by press fitting them into the pin holders. The pins were randomized for each test to avoid bias. A nut with a plastic washer inside was fastened onto the pin holders to help align and contain the pins. To inspect the
alignment of the pins, they were manually loaded to 150N before testing with a Fujifilm™ pressure sensitive paper to observe the stress distribution. If the stress distribution on the paper was uniform, it was assumed that the pin was flat and the test set-up was continued.

Once the pins were in place, the desired fluid was added, the pins were sent to their zero location, and then manually lowered until the pins were almost touching the surface of the UHMWPE. The amplifiers were balanced before each test and the SDS waveform was initiated.

### 3.4 Development of SDS Motion Profile on OrthoPod™

A custom waveform was created using Learn Mode in the OrthoPod™ control software, which allows the machine to be taught a path by “sketching” it using the manual controls. First, the intended trajectory is drawn on paper using standard graphical precision, then placed on the specimen holder of one channel. Using Learn Mode, the pin and disc are moved manually to a desired location and the coordinates are added to the waveform. This process is repeated until each point in the waveform has been added. The software creates a waveform from the “sketched” points. Next, a cycle time must be indicated for the waveform such that the time between each programmed point is the same. This is an advantage when a specific speed is desired, such as during the stop and start phases of SDS motion. Therefore, if the speed is known then the necessary distance between each programmed point can be determined and sketched using the Learn Mode to create the desired SDS motion profile.

The SDS waveform developed for this study has a cycle time of 2s and contains 26 points, making the time between each point 0.08s. There are four distinct sections in the waveform: stop, dwell, start and return, as shown in Figure 3.8. In the stop phase (Points 1-7), the pin and disc system slows to a stop from 32.5mm/s over 0.48s. Next, the pin and disc system pauses for 0.8s during the dwell phase (Points 7-17), and then it speeds up again to 41.3mm/s over 0.4s during the start phase (Points 17-22). The pin and disc system returns to the origin (points 22-26) over 0.32s along its own path to ensure unidirectional motion of the SDS pattern.
While Figure 3.8 is the pattern “sketched” in the OrthoPod, Figure 3.9 depicts the actual path followed by the pin and disc system on a worn UHMWPE specimen. The waveform developed for the simplified SDS test is depicted in Figure 3.8 and detailed in Section 3.4.3.

**Figure 3.8: SDS motion pattern on OrthoPod™.**

Each circle represents a pin location programmed into the SDS waveform created in the Learn Mode function. There are a total of 26 points programmed into the waveform to form 25 motion segments.

**Figure 3.9: Actual motion followed by pin and disc system in the OrthoPod™ shown on worn UHMWPE specimen.**

The arrows indicate the direction of motion. The pin does not follow the exact rectangular path in the return phase; however, no measurements are taken during this time.
The region of interest in this study is detailed in Figure 3.10, which contains the 22 points that make up the SDS section of the waveform. There is special interest in the mixed-SDS region (yellow region in Figure 3.10) where all of the SDS events occur.

![Figure 3.10](image)

**Figure 3.10: Scaled schematic of SDS sections of OrthoPod™ motion pattern.**

Each circle represents one of the 22 programmed pin locations during the SDS section of the OrthoPod™ waveform. The red circles are the pin locations during the stop phase, the yellow area is the dwell phase and the green circles are the pin locations during the start phase. The schematic has been scaled 10:1.

### 3.4.1 Stop and Start Phases

The stopping and starting kinematics for the SDS waveform in the pin-on-disc tester were based on an SDS motion protocol for a hip simulator developed by Hadley [10]. The distance between each programmed point was determined by converting the changes in flexion angle in the hip simulator into linear displacements for the SDS waveform on the OrthoPod™ pin-on-disc tester.

The linear motion was based on the flexion angles from Figure 3.11 and Figure 3.12 developed by Hadley, which are load and angular motion input graphs for the SDS motion hip simulator protocol [66]. Only flexion angles were considered because abduction/adduction was not used in the hip simulator study and internal/external rotation was minimal. Firstly, flexion
angles (in degrees) were extracted from Figure 3.11 and Figure 3.12 at every 5% of the cycle while deceleration in the stop phase and acceleration in the start phase was occurring. These flexion angles are depicted by the labelled points inside the blue boxes. These points were plotted versus time at 0.1s time steps and then fit with a quadratic. Further analysis was carried out to calculate the distance from an origin on the OrthoPod™. The procedures are outlined in Sections 3.4.1.1 and 3.4.1.2 for the stop and start phases, respectively.

Figure 3.11: Load and motion inputs for the stop phase of SDS motion in hip simulator testing protocol proposed by Hadley et al. [66], with permission
3.4.1.1 Stop Phase

The stop phase sequence was based on Figure 3.11.

1. Flexion angles, $\theta_{\text{stop}}$, in degrees from the SDS hip simulator input waveform as a function of time, $t$, in seconds was fitted with a quadratic where $R^2=0.997$.

$$\theta_{\text{stop}} = 38.147t^2 - 66.174t + 28.504$$

2. $\theta_{\text{stop}}(t)$ was differentiated to obtain the angular velocity, $\omega_{\text{stop}}$, in degrees/s.

$$\omega_{\text{stop}} = 76.294t - 66.174$$

3. Linear velocity, $v_{\text{stop}}$, in mm/s was calculated based on the use of a hip replacement with an 36mm diameter femoral head ($r=18$mm).
4. The distance from the origin (Point 1) is calculated in mm where the first point, $d_1=0$.

$$d_{2\text{stop}} = \left| \left(\frac{v_2 + v_1}{2}\right)(t_2 - t_1) + d_1 \right|$$

The distance from the origin (Figure 3.8, Point 1) for the stop phase and the preceding calculated values are displayed in Table 3.1.

**Table 3.1: Flexion angle (°), angular velocity (°/s), linear velocity (mm/s) and distance from the origin for the stop phase of the OrthoPod™ SDS waveform sketch**

<table>
<thead>
<tr>
<th>Point #</th>
<th>Time, t (s)</th>
<th>Flexion Angle, $\theta_{stop}$ (°)</th>
<th>Angular Velocity, $\omega_{stop}$ (°/s)</th>
<th>Linear Velocity, $v_{stop}$ (mm/s)</th>
<th>Distance from Origin, $d_{stop}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>28.0</td>
<td>-66.17</td>
<td>-20.79</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>23.5</td>
<td>-58.54</td>
<td>-18.39</td>
<td>1.96</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>16.6</td>
<td>-50.92</td>
<td>-16.00</td>
<td>3.68</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>11.6</td>
<td>-43.29</td>
<td>-13.60</td>
<td>5.16</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>7.9</td>
<td>-35.66</td>
<td>-11.20</td>
<td>6.40</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>4.5</td>
<td>-28.03</td>
<td>-8.80</td>
<td>7.40</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>2.6</td>
<td>-20.40</td>
<td>-6.41</td>
<td>8.16</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>1.3</td>
<td>-12.77</td>
<td>-4.01</td>
<td>8.68</td>
</tr>
<tr>
<td>9</td>
<td>0.8</td>
<td>0.5</td>
<td>-5.14</td>
<td>-1.61</td>
<td>8.96</td>
</tr>
<tr>
<td>10</td>
<td>0.9</td>
<td>0.0</td>
<td>2.49</td>
<td>0.78</td>
<td>9.00</td>
</tr>
</tbody>
</table>
3.4.1.2 Start Phase

The same procedure was followed to calculate the location of the programmed points for the start phase as the stop phase. The start phase was based on Figure 3.12 and the resulting equations are shown below.

1. \[ \theta_{start} = 43.983t^2 - 8.7195t + 0.5573 \]

2. \[ \omega_{start} = 97.966t - 8.7195 \]

3. \[ v_{start} = \frac{(18mm)\pi}{180^\circ} (97.966t - 8.7195) = 27.635t - 2.739 \]

4. \[ d_2 = \left( \frac{v_2 + v_1}{2} \right) (t_2 - t_1) + d_1 \]

Table 3.2 contains the distances for each programmed point from the initial point of the start phase, which is the dwell location in this case (Figure 3.8, Point 17). The table also contains the results of each step of the procedure listed above.

Table 3.2: Flexion angle (°), angular velocity (°/s), linear velocity (mm/s) and distance from the dwell location for the start phase of the OrthoPod™ SDS waveform sketch

<table>
<thead>
<tr>
<th>Point #</th>
<th>Time, t (s)</th>
<th>Flexion Angle, ( \theta_{start} ) (°)</th>
<th>Angular Velocity, ( \omega_{start} ) (°/s)</th>
<th>Linear Velocity, ( v_{start} ) (mm/s)</th>
<th>Distance from Dwell, ( d_{start} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>-8.72</td>
<td>-2.74</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>0.5</td>
<td>0.08</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>1.0</td>
<td>8.87</td>
<td>2.79</td>
<td>0.14</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>2.1</td>
<td>17.67</td>
<td>5.55</td>
<td>0.56</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>4.2</td>
<td>26.47</td>
<td>8.31</td>
<td>1.25</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>7.0</td>
<td>35.26</td>
<td>11.08</td>
<td>2.22</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>10.5</td>
<td>44.06</td>
<td>13.84</td>
<td>3.47</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>15.8</td>
<td>52.86</td>
<td>16.61</td>
<td>4.99</td>
</tr>
<tr>
<td>9</td>
<td>0.8</td>
<td>22.3</td>
<td>61.65</td>
<td>19.37</td>
<td>6.79</td>
</tr>
</tbody>
</table>
3.4.2 Dwell Phase

The dwell phase duration was determined based on two principles. Firstly, studies suggest that the longer the pause before motion resumes, the greater the static friction at start-up will be due to fluid starvation [78]. However, Hadley did not observe a significant increase in wear when the dwell phase of SDS motion was increased [66].

Secondly, stress relaxation tests of UHMWPE by Waldman et al. [79], reported that approximately 10s are required for appreciable deformation of the UHMWPE surface. Therefore, with a short dwell in the pin-on-disc SDS waveform, the effects of lubricant film starvation and viscoelastic effects of the material can be limited so only the effects of stopping and starting are observed. Ten pin locations were programmed into the SDS waveform for a total of 0.8s.

3.4.3 Final SDS Waveform

The SDS waveform used for pin-on-disc experimentation contained 26 points to produce 25 separate motion segments of 0.08s, each with its own desired speed. The stop and start phases were based on an SDS hip simulator study by Hadley and the distances between each programmed point were calculated. Between the stop and start phases, the pin and disc system dwells for 0.8s, which is intended to avoid fluid film starvation or viscoelastic effects, and focus on the frictional effects of the material pairing.

However, during the sketching process there were limitations in that accurate measurements could only be made to approximately 0.5mm. Therefore, every neighbouring pair of points were summed to create six motion segments for the stop phase and five motion segments for the start phase spanning approximately 10mm each. Figure 3.13 and Figure 3.14 depict the data extracted from Figure 3.11 and Figure 3.12 as linear velocities, as well as the change from Hadley’s waveform to the OrthoPod™ SDS waveform. A further breakdown of the transition between the original angle data to the linear velocities can be found in Table 3.3. The
red sections are the points contained in the stop phase, the yellow sections contain the points making up the dwell phase and the green sections contain the points making up the start phase.

The first section, “Hadley,” contains the linear velocity calculated from step 3 of the SDS waveform procedure for the entire SDS profile. The second section, “Hadley @ \( dt=0.08\) s,” contains the linear velocity calculated from step 3 using 0.08s time steps, which is the time step used in this study. Then, after combining displacements, the sketch was drawn and re-measured. The measurements and their resulting speeds are contained within the third section of Table 3.3, “OrthoPod™ Sketch.” The speeds in the “OrthoPod™ Sketch” section are to be compared to the speeds calculated from the Hadley hip simulator flexion angles.

The magnitude of the velocities from the sketch are greater than those calculated from Hadley’s hip simulator study. Also, while the stop and start in Hadley’s profile occur over 1 sec, they occur in 0.48 sec in the OrthoPod™ waveform. The limitation of measurement resolution caused the waveform to differ from Hadley’s protocol, and in the future a more precise measurement tool should be used to sketch the SDS waveform to program the OrthoPod™ pin-on-disc tester.
Figure 3.13: Stop profile of the SDS waveform.

The dashed line is the stop phase of Hadley’s waveform with 0.08s time steps and the solid line is the stop phase in the OrthoPod™ waveform with the programmed point numbers indicated.

Figure 3.14: Start profile of the SDS waveform.

The dashed line is the start phase of Hadley’s waveform with 0.08s time steps and the solid line is the start phase in the OrthoPod™ waveform with the programmed point numbers indicated.
Table 3.3: Final OrthoPod™ waveform from linear velocities in hip simulator.

<table>
<thead>
<tr>
<th>Point #</th>
<th>Hadley</th>
<th>Hadley @ $dt=0.08s$</th>
<th>OrthoPod™ Sketch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (s)</td>
<td>v (mm/s)</td>
<td>Time (s)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>-20.79</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>-18.39</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>-15.99</td>
<td>0.16</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>-13.60</td>
<td>0.24</td>
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<tr>
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<td>0.4</td>
<td>-11.20</td>
<td>0.32</td>
</tr>
<tr>
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<td>-8.80</td>
<td>0.40</td>
</tr>
<tr>
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<td>-6.41</td>
<td>0.48</td>
</tr>
<tr>
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<td>0.7</td>
<td>-4.01</td>
<td>0.56</td>
</tr>
<tr>
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<td>0.8</td>
<td>-1.61</td>
<td>0.64</td>
</tr>
<tr>
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<td>0.9</td>
<td>0.78</td>
<td>0.72</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>0.00</td>
<td>0.80</td>
</tr>
<tr>
<td>12</td>
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<td>0.00</td>
<td>0.88</td>
</tr>
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<td>1.2</td>
<td>0.00</td>
<td>0.96</td>
</tr>
<tr>
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<td>1.3</td>
<td>0.00</td>
<td>1.04</td>
</tr>
<tr>
<td>15</td>
<td>1.4</td>
<td>0.00</td>
<td>1.12</td>
</tr>
<tr>
<td>16</td>
<td>1.5</td>
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<td>19</td>
<td>1.8</td>
<td>0.00</td>
<td>1.44</td>
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<tr>
<td>20</td>
<td>1.9</td>
<td>0.00</td>
<td>1.52</td>
</tr>
<tr>
<td>21</td>
<td>2.0</td>
<td>-2.74</td>
<td>1.60</td>
</tr>
<tr>
<td>22</td>
<td>2.1</td>
<td>0.02</td>
<td>1.68</td>
</tr>
<tr>
<td>23</td>
<td>2.2</td>
<td>2.79</td>
<td>1.76</td>
</tr>
<tr>
<td>24</td>
<td>2.3</td>
<td>5.55</td>
<td>1.84</td>
</tr>
<tr>
<td>25</td>
<td>2.4</td>
<td>8.31</td>
<td>1.92</td>
</tr>
<tr>
<td>26</td>
<td>2.5</td>
<td>11.08</td>
<td>2.00</td>
</tr>
<tr>
<td>27</td>
<td>2.6</td>
<td>13.84</td>
<td>2.08</td>
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<tr>
<td>28</td>
<td>2.7</td>
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<td>2.16</td>
</tr>
<tr>
<td>29</td>
<td>2.8</td>
<td>19.37</td>
<td>2.24</td>
</tr>
</tbody>
</table>
3.5 Experimental Protocol

3.5.1 Tests Conditions

Four tests were conducted for each experimental condition: (1) untextured unlubricated, (2) untextured water lubrication, (3) untextured glycerin lubrication, (4) textured unlubricated, (5) textured water lubrication and (6) textured glycerin lubrication, for a total of 24 tests. Each condition was tested on each of the four OrthoPod™ stations used to avoid any station bias. Prior to testing, the UHMWPE discs were soaked in a 1% detergent solution (Liqui-Nox®, Alconox Inc., White Plains, NY) and rinsed with deionized water. In the lubricated tests using water, 10mL of deionized water (viscosity = 8.9x10^-4Pa·s) was used and in the glycerin tests, 10mL of 99% glycerin (viscosity = 1.0Pa·s) was used (McMaster Carr, Aurora, OH). These fluids were chosen as lubricants because their viscosities span the range of viscosities observed with synovial fluid.

All tests were carried out at room temperature (24°C). The set-up for a station can be seen in Figure 3.15. The 6 mm diameter flat stainless steel pins were articulated against the flat UHMWPE discs. For each test, a load of 150 N was applied, resulting in a nominal average contact stress of 5.3MPa, which is representative of stresses observed in THA during normal gait [80]. The pins were articulated against the UHMWPE discs in the pattern shown in Figure 3.8 with a cycle time of 2s. The pin was loaded the entire duration of each cycle to avoid any artifacts during the beginning and end of the SDS section.
Figure 3.15: Experimental set-up for one station in the OrthoPod™.

Four stations are used for each test. Only lubricated tests require the Plexiglas cup. The coordinate system is indicated in white and is fixed to the base which does not move.

3.5.1.1 Contact Conditions

A flat pin on a flat disc was used in this study. The major motive was the necessity to cover as many dimples as possible to be able to observe the effects of texturing. However, the stress distribution, \( p(x) \), under a flat punch has a region of high stress near the edge as depicted in Figure 3.16. When a punch is loaded normal to the surface, stress in the elastic half space, or in this case the UHMWPE, is increased at the edges, but is nearly uniform in the inner 90% of the contact region [81]. In addition, the edges of the pins were bevelled to reduce the severity of the edge effects, and resulted in an average stress of 5.3 MPa in the inner region.
3.5.2 Data Acquisition

The AMTI OrthoPod™ collects multi-component force data to calculate the friction coefficient, or in this case, the traction coefficient. The nine outputs from the machine are summed to provide a single value for the forces in the x, y and z-directions, where x and y are in the horizontal direction and z is in the vertical direction, as shown in Figure 3.15. The traction coefficient, $\mu$, was calculated to four decimal places based on the ratio of tangential and normal forces:

$$
\mu = \frac{F_t}{F_N} = \sqrt{\frac{F_x^2 + F_y^2}{F_z}}
$$

where $F_t$ is the tangential force and $F_N$ is the normal force.

Each test consisted of three loops of 2,000 cycles for a total of 6,000 cycles. The sampling rate was 300 data sets per second for a duration of 10 seconds, which produced four full cycles of data. This sampling rate was used due to a practical limitation of the data storage system. Data collected in the last 10 seconds of the last loop were used for analysis. A data
extraction and analysis process was developed based on experimental observations to compute traction coefficient data for the stop, dwell and start phases that are representative of what occurs during these phases. The process is outlined in Section 4.1.

3.5.3 Wear Assessment

A qualitative wear analysis was conducted examining the surface wear mechanisms present after 6,000 SDS cycles for all lubricant and texturing conditions. Photos were taken at 50x magnification using optical microscopes (Olympus Canada Inc., Toronto, ON). Further quantitative analyses were carried out for the textured specimens, specifically examining the effects of wear on the dimple diameter under the different lubricating conditions. Measurements were made using Motic Images 3.0 (Motic, Richmond, BC).
Chapter 4

Results

The method of determining traction coefficients from measured data is described and the traction coefficients for each test condition are presented. The effect of factors affecting the traction coefficient are proposed and compared to the corresponding wear mechanisms observed.

4.1 Determination of Traction Coefficient for Stop, Dwell and Start Conditions

A typical traction coefficient output for 10s of acquired data at 300 data sets per second is depicted in Figure 4.1. This shows periodic behaviour every 600 data points, resulting in four full cycles of data. Each cycle contains four distinct sections: stop, dwell, start and return (Figure 4.2).

![Figure 4.1: Typical raw traction coefficient data for an entire data acquisition cycle for the textured glycerin condition.](image)

The four cycles are indicated by the green boxes and the dashed green lines separate the four distinct phases of the SDS waveform (stop, dwell, start, return).
Figure 4.2: Typical traction coefficient plot for one SDS cycle for the textured glycerin condition.

The blue line depicts the coefficient of friction value for each data point. The vertical dashed green lines separate the sections (stop, dwell, start, return) and the blue circles represent each of the 26 programmed pin locations.

One cycle of a typical traction coefficient plot is presented in Figure 4.2. The four distinct sections have been indicated and the programmed pin locations are depicted across the top of the plot. Because the first programmed point is at a corner, the pin enters the stop phase at 0m/s instead of at a constant speed as would be desired and expected in vivo. Therefore, during the first motion segment, a spike in traction coefficient is observed due to high acceleration. The traction coefficient decreases again and is constant while the pin is decelerating until approximately the last two motion segments of the stop phase where the traction coefficient begins to increase.

During the dwell phase, the traction coefficient remains constant as expected since there is no movement. Entering the start phase, there is a sharp increase in traction coefficient consistent with the system overcoming static friction. As the system continues to accelerate, the traction coefficient increases linearly.
4.1.1 Data Extraction Process

Using a custom MATLAB script, the traction coefficient was calculated for the entire 10s data collection period. The traction coefficient data were separated into the four loops (each 600 data points), which are initiated when the pin and disk location are both 0°, or at the waveform’s origin (Figure 3.8, Point 1). The traction coefficient data are averaged across the four loops to obtain a vector of traction coefficient values. The traction coefficient vector is split into the sections of interest: the stop, dwell and start phases of SDS motion.

The SDS OrthoPod™ waveform is composed of 25 motion segments, each 0.08 seconds in length. The stop phase contains six motion segments and is 0.48s, the dwell phase contains 10 segments and is 0.8s, and the start phase contains five motion segments and is 0.4s. Therefore, as a percentage of each 2s cycle, the stop phase contains 144 data points, the dwell phase contains 240 data points and the start phase contains 120 data points out of the total 600 data points per cycle. There is a breakdown of each phase in Table 4.1

<table>
<thead>
<tr>
<th>SDS Waveform</th>
<th>Section Duration</th>
<th>Number of Data Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>(s)</td>
<td>Points</td>
</tr>
<tr>
<td>ONE CYCLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2s (600 points)</td>
<td>STOP</td>
<td>1-7</td>
</tr>
<tr>
<td></td>
<td>Dwell</td>
<td>7-17</td>
</tr>
<tr>
<td></td>
<td>Start</td>
<td>17-22</td>
</tr>
</tbody>
</table>

Once the data were sectioned, the traction coefficient for the stop, dwell and start phases were determined based on specific criteria for each phase.

Stop and Start Phases. From examination of Figure 3.10 and worn UHMWPE specimens, the majority of the stop and start phases occur in the same area as the dwell phase, creating the mixed-SDS region. This is the region of interest and only the traction coefficient data from this area are averaged to determine coefficient of traction value for that section. Therefore, the traction coefficients for the stop and start phases are taken as the average of the traction coefficient data where the surface area of the pin is more than 50% in the mixed-SDS region. For
the stop phase (Figure 4.3), this corresponds with the last three pin motion segments of the section, or the last 72 data points which are the points shown within the green lines. For the start phase (Figure 4.5), the pin area is more than 50% within the mixed-SDS region during the first three pin motion segments, or the first 72 data points which are shown within the green lines.

**Dwell Phase.** For the dwell section (Figure 4.4), a convergence test was carried out to determine how many points about the median should be averaged together to compute the dwell phase traction coefficient. The results of the convergence test indicated that 50 points above and below the median correspond with the lowest SEM. Therefore, a total of 101 points about the median are averaged to compute the dwell phase traction coefficient.

![Figure 4.3: Typical stop phase traction coefficient plot for textured glycerin conditions.](image)

The area between the vertical dashed green lines indicates the 72 data points averaged together to compute the stop phase traction coefficient. The blue circles indicated the seven programmed pin locations in the stop phase.
Figure 4.4: Typical dwell phase traction coefficient plot for textured glycerin conditions.
The area between the vertical dashed green lines make up the 101 points averaged to calculate
the dwell phase traction coefficient. The blue circles represent the 11 programmed pin
locations in the dwell phase.

Figure 4.5: Typical start phase traction coefficient plot for textured glycerin conditions.
The area between the vertical dashed green lines indicates the 72 data points averaged together
to compute the start phase traction coefficient. The blue circles indicated the seven
programmed pin locations in the start phase.
4.2 Coefficients of Traction

Traction coefficients were calculated using the data extraction process set out in Section 4.1.1 for the stop, dwell and start phases for each of the six conditions tested. Standard deviations were calculated across the four tests carried out on each of the four OrthoPod™ stations used during testing. Figure 4.6 shows the traction coefficients for each tested condition for the stop, dwell and start phases. The data within Table 4.2, Table 4.3 and Table 4.4 contain the corresponding traction coefficient values for each bar in Figure 4.6. The bottom row contains the difference in traction coefficient between the textured and untextured conditions, with * indicating significance at the $p=0.05$ level and † indicating significance at the $p=0.1$ level. Two $p$ levels were used to detect statistical significance because this is the first test of its kind and whether the testing practices used were promising enough to continue being studied was attempting to be determined.

Figure 4.6: Traction coefficients (± SEM) for the six conditions tested in the stop, dwell and start phases of SDS motion. For each condition, $n=4$. 
For all conditions, the traction coefficients were nonzero, which was expected for the stop and start phases because the pin and disc system was in motion. However, a nonzero traction coefficient in the dwell condition was unexpected since the pin and disc system were at rest, and therefore the frictional forces were expected to be zero.

Table 4.2: Traction coefficients for the stop phase, n=4 for each condition.

<table>
<thead>
<tr>
<th>STOP</th>
<th>Dry</th>
<th>Water</th>
<th>Glycerin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AVG</td>
<td>SD</td>
<td>AVG</td>
</tr>
<tr>
<td>Untextured</td>
<td>0.362</td>
<td>0.080</td>
<td>0.104</td>
</tr>
<tr>
<td>Textured</td>
<td>0.217</td>
<td>0.039</td>
<td>0.103</td>
</tr>
<tr>
<td>Text – Untext</td>
<td>-0.145*</td>
<td></td>
<td>-0.001</td>
</tr>
</tbody>
</table>

Table 4.3: Traction coefficients for the dwell phase, n=4 for each condition

<table>
<thead>
<tr>
<th>DWELL</th>
<th>Dry</th>
<th>Water</th>
<th>Glycerin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AVG</td>
<td>SD</td>
<td>AVG</td>
</tr>
<tr>
<td>Untextured</td>
<td>0.297</td>
<td>0.736</td>
<td>0.108</td>
</tr>
<tr>
<td>Textured</td>
<td>0.177</td>
<td>0.032</td>
<td>0.138</td>
</tr>
<tr>
<td>Text – Untext</td>
<td>-0.120*</td>
<td></td>
<td>0.030†</td>
</tr>
</tbody>
</table>

Table 4.4: Traction coefficients for the start phase, n=4 for each condition

<table>
<thead>
<tr>
<th>START</th>
<th>Dry</th>
<th>Water</th>
<th>Glycerin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AVG</td>
<td>SD</td>
<td>AVG</td>
</tr>
<tr>
<td>Untextured</td>
<td>0.390</td>
<td>0.086</td>
<td>0.127</td>
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<td>Textured</td>
<td>0.233</td>
<td>0.039</td>
<td>0.132</td>
</tr>
<tr>
<td>Text – Untext</td>
<td>-0.157*</td>
<td></td>
<td>0.005</td>
</tr>
</tbody>
</table>

4.2.1 Effect of Lubricant

The traction coefficient for any given phase is dependent on the lubricant present and its viscosity. As the viscosity of the lubricant increased, the traction coefficient decreased in all phases for both untextured and textured specimens. The unlubricated condition, used as a worst-case scenario reference, had the highest coefficient of traction. Compared to the unlubricated condition, the introduction of water decreased the traction coefficient by 71.3%, 63.7% and
67.4% in the stop, dwell and start phases for untextured specimens, and by 52.4%, 22.0% and 43.3% in the stop, dwell and start phases for textured specimens. With glycerin as a lubricant, the traction coefficient decreased by 94.3%, 97.4% and 93.3% in the stop, dwell and start phases for untextured specimens, and by 93.1%, 93.5% and 87.8% in the stop, dwell and start phases for textured specimens. All of the traction coefficient reductions were significant in all phases and all conditions compared to unlubricated scenarios \((p=0.05, \text{ANOVA})\).

### 4.2.2 Effect of Texturing

The introduction of surface texturing did not produce consistent or reproducible results; however, some statistically significant patterns were observed.

In the stop phase (Table 4.2), a significant reduction in traction coefficient was observed in the unlubricated conditions \((p=0.05, \text{paired t-test})\) and glycerin conditions \((p=0.1, \text{unpaired t-test})\). In the dwell phase (Table 4.3), a significant decrease in traction coefficient was observed for the unlubricated conditions with the introduction of texturing \((p=0.05, \text{paired t-test})\), yet a significant increase in traction coefficient was observed in both the water \((p=0.1, \text{paired t-test})\) and glycerin \((p=0.1, \text{unpaired t-test})\) lubricated conditions.

In the start phase (Table 4.4), texturing did not reduce the traction coefficient as expected. In the unlubricated conditions, the traction coefficient was significantly reduced \((p=0.05, \text{paired t-test})\), but in the lubricated conditions no significant difference was observed. It must be noted that in the lubricated conditions, there were large variances between the differences in textured and untextured traction coefficients calculated; half of the station tests observed an increase in traction coefficient and half observed a decrease in traction coefficient.
4.3 Wear Patterns

A qualitative wear analysis was conducted by taking photographs of the surfaces of the worn specimens in the mixed-SDS region using an optical microscope (Olympus Canada Inc., Toronto, ON) at 50x magnification to observe the wear mechanisms present during the different lubricating and texturing conditions (Figure 4.8-Figure 4.14). Additionally, the diameters of the dimples in the textured specimens were measured in the worn mixed-SDS region and an unworn region on the specimen. The difference in diameter was calculated for each specimen and averaged to obtain an overall percent difference in dimple diameter for each condition (Table 4.5). Figure 4.7 is a schematic showing the locations of where the photos were taken on the worn specimens for both the qualitative and quantitative wear analyses.

Figure 4.7: Schematic of photo locations for both the qualitative and quantitative wear analyses.

For each tested specimen (n = 24), a photo was taken in the unworn region (Location 1) and the worn region (Location 2) at 50x magnification. For the quantitative analysis, the dimple diameters were measured using Motic Images 3.0 (Motic, Richmond, BC).
Figure 4.8: Photos of specimen surfaces in the mixed-SDS region after 6,000 cycles at 50x magnification.

For all photos, motion occurred from right to left. Unworn specimens provided for reference (a, b). In the unlubricated conditions, machining marks are absent and the surfaces appear to be worn smooth (c, d). Wear particles are present in the dimples of the textured unlubricated condition (d). In the water conditions, some machining marks are still present (e, f) and in the textured condition (f), there is a small amount of wear particulate in the dimples. In the glycerin conditions, the machining marks are still present but there is scratching in the direction of motion (g, h), and there no wear particles in the dimples in the textured condition (h).
4.3.1 Unlubricated Conditions

Severe wear was observed in the unlubricated conditions. In untextured specimens (Figure 4.9), burnishing was experienced. The entire surface was worn smooth and there were very few scratches.

In the textured specimens (Figure 4.10), the machining marks were also worn away and the surface was smooth. Wear particles were trapped in almost all of the dimples, and some of the dimples were distorted in the mixed-SDS region so they are no longer circular.

There was a significant reduction in traction coefficient for all phases when dimples were introduced into the surface of the UHMWPE, which may be related to the wear particulate trapping observed.

Figure 4.9: Untextured unlubricated specimen after 6,000 SDS cycles at 50x magnification.
4.3.2 Water Lubrication

Less wear was observed when water was used as a lubricant than in the worst case scenario condition (unlubricated). In the untextured specimens (Figure 4.11), some machining marks are still present and there is scratching in the direction of motion. Also, pitting is observed in some cases.

In the textured specimens (Figure 4.12), there are some deep machine marks remaining, and there are wear particles observed in some of the dimples, but in smaller amounts than in the unlubricated conditions.

Figure 4.10: Textured unlubricated specimen after 6,000 SDS cycles at 50x magnification.
Figure 4.11: Untextured water lubricated specimen after 6,000 SDS cycles at 50x magnification.

Figure 4.12: Textured water lubricated specimen after 6,000 SDS cycles at 50x magnification.
4.3.3 Glycerin Lubrication

Using glycerin as a lubricant demonstrated minimal wear. In the untextured specimens (Figure 4.13), the machine marks are still present but there are deep scratches in the surface.

In the textured specimens (Figure 4.14), the machine marks are still present and the scratching is much less severe than in the untextured specimens. There are no wear particles in the dimples and they still have crisp edges.

Figure 4.13: Untextured glycerin specimen after 6,000 SDS cycles at 50x magnification.
4.4 Effect of Wear on Dimple Diameter

The reduction in dimple diameter was calculated for each lubricating condition as shown in Table 4.5: Dimple diameter data for worn and unworn specimens. Table 4.5. This is a relevant measure for wear because layers of the surface are worn away making the dimples’ diameter and volume smaller. When this occurs, the textured surface is not operating as expected.

The viscosity of the lubricant affects the amount of wear observed. While all of the reductions in dimple diameter are statistically significant (p<0.05, paired t-test), the least amount of wear was observed with glycerin as a lubricant, which is consistent with the qualitative wear observations and the traction coefficient magnitudes.

Figure 4.14: Textured glycerin specimen after 6,000 SDS cycles at 50x magnification.
Table 4.5: Dimple diameter data for worn and unworn specimens.

<table>
<thead>
<tr>
<th>Lubricant Condition</th>
<th>Average Dimple Diameter (μm)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unworn Region</td>
<td>Worn Region</td>
</tr>
<tr>
<td>Dry</td>
<td>448</td>
<td>401</td>
</tr>
<tr>
<td>Water</td>
<td>443</td>
<td>416</td>
</tr>
<tr>
<td>Glycerin</td>
<td>430</td>
<td>422</td>
</tr>
</tbody>
</table>

4.5 Summary of Findings

The traction coefficients for all phases and conditions were nonzero. This was not expected for the dwell phase, which was hypothesized to have a traction coefficient of zero since no motion was occurring. The effect of lubrication was dominant in reducing the traction coefficient in all phases regardless of the UHMWPE surface geometry. With glycerin as a lubricant, the traction coefficient was reduced by 87.8-94.3% during the stop and start phases. Additionally, surface wear was reduced when a lubricant was present compared to unlubricated conditions. As the viscosity of the lubricant increased, the amount of wear decreased in both the untextured and textured conditions. This was verified in the textured conditions as the dimple diameter with glycerin as a lubricant was reduced by 1.9% from the average unworn dimple diameter compared to a 10.5% decrease seen in the unlubricated conditions.

Texturing the surface of the UHMWPE also affected the traction coefficients. The traction coefficient was the same or significantly less with the introduction of dimples into the surface under unlubricated and glycerin conditions for the stop and start phases. In the dwell phase, the traction coefficient was significantly greater in the textured conditions for water and glycerin conditions compared to untextured conditions. The unlubricated condition was used as a worst-case scenario reference condition, however a 67.4% decrease in traction coefficient for textured samples compared to untextured samples was measured even though wear was high. This observation of the unlubricated textured conditions suggests that the ability to trap wear
particles in the dimples is a mechanism to reduce the traction coefficient in these systems.

Furthermore, surface wear of the polymer was observed to be similar for both the untextured and textured UHMWPE specimens.
Chapter 5

Discussion

In this study, the effects of lubrication and UHMWPE surface texturing in metal-polyethylene orthopaedic bearings on tribological conditions were investigated. The dominant factor affecting the traction coefficient and wear was the presence of a lubricant. The effect of texturing had a significant effect under specific conditions in both the lubricated and unlubricated conditions.

5.1 Effect of Lubrication

Lubrication between the sliding surfaces dominated both the coefficient of traction and wear of the UHMWPE surface. In both untextured and textured conditions, the introduction of a lubricant significantly reduced the traction coefficient regardless of its viscosity. As the viscosity of the lubricant increased, the traction coefficient and wear during SDS motion decreased.

Fam [82] conducted steady-state reciprocal pin-on-disc friction tests (semi-spherical pin on flat UHMWPE) with hyaluronic acid (HA) supplemented bovine calf serum (BCS) as the lubricant. The concentration of HA was varied in the solutions, and as the amount of HA added increased, so did the viscosity of the solution. The study concluded that the coefficient of friction decreased with increasing lubricant viscosity, which is consistent with the observations made in this study.

The observation of decreased traction coefficient and wear with increased lubricant viscosity agrees with previous quasi-static stress tests conducted on textured UHMWPE [75]. That is, when the dimples were sufficiently filled with fluid, there was less stress measured in the polymer contact regions as the viscosity of the fluid increased, because the entrained fluid in the dimples was assuming a portion of the load. These results suggest that a high viscosity fluid is required to retain the fluid in the dimples and to aid in reducing the start-up friction.
The two lubricants used in this friction and wear study (water and glycerin) were both newtonian fluids; however, synovial fluid is a non-newtonian, shear thinning fluid. Thus, it is unknown whether the results obtained in this study while motion is occurring would be the same *in vivo*. However, a hypothesis can be made for the success of the system *in vivo*. Because synovial fluid has a higher viscosity at lower shear rates, such as during the stopping and starting phases, it is expected that similar observations would be made to those as when glycerin was used as the lubricant.

Additionally, in textured conditions, even if the separation between the polymer contact regions is small, the gap size is larger between the dimples. As a result, the shear rate is greater between the contact regions than in the dimples. Therefore, the higher viscosity fluid in the dimples will contribute to separating the bearing surfaces and creating a film thickness large enough to enter into a mixed lubrication mode rather than a boundary lubrication mode. This should decrease traction coefficients and wear during any type of motion.

### 5.2 Effect of Texturing

#### 5.2.1 Unlubricated Condition

The unlubricated tests were used as a reference, worst-case scenario condition. Interestingly, a significant reduction in traction coefficient was observed with the introduction of the textured UHMWPE surface in all three SDS phases even though considerable wear was observed. It is hypothesized that in the untextured unlubricated condition, wear debris builds up between the articulating surfaces of the pin and UHMWPE, increasing the contact area between the two surfaces, thus increasing the traction coefficient. However, with the introduction of dimples, the wear debris becomes trapped in the dimples, reducing the amount of interaction of the asperities and the articulating surfaces. This exhibits itself as a lower traction coefficient compared to the untextured condition.
5.2.2 Lubricated Conditions

Texturing did not show the expected effects of reducing the traction coefficient under all lubricated conditions. In the water lubricated condition, an increase or no difference in traction coefficient was observed in all three SDS phases when the textured surface was introduced. However, there was less wear observed in both untextured and textured conditions compared to unlubricated conditions, which suggests some degree of lubrication between the two surfaces.

With glycerin as a lubricant, there was not a consistent reduction in traction coefficient with the introduction of a textured surface. The difference in traction coefficient between the textured conditions was highly varied between OrthoPod™ stations. However, the traction coefficient data for all glycerin tests were very small in magnitude and it is unknown whether the differences in traction coefficients could accurately be detected statistically. Furthermore, while the traction coefficient was not always lowered by texturing the surface of the UHMWPE, there was minimal visible wear after 6,000 SDS cycles. The machine marks were still visible, there were no wear particles in the dimples, and the dimples’ size and shape were relatively unaffected.

In the stop phase with glycerin as the lubricant, the reduction in traction coefficient was statistically significant \((p=0.1,\) unpaired t-test) and is suggested to be directly correlated to the area reduction with the introduction of dimples. According to Table 5.1, the reduction in plastic contact area and traction coefficient are both approximately 1/3, which supports the FEA results from previous studies [72], suggesting that as the \(c/d\) ratio of the textured geometry becomes smaller (less contact area), stress shielding increases. In this case \((c/d =1.5)\), 10% stress shielding was expected. The reduction in traction coefficient has surpassed this amount, which suggests texturing is more effective than predicted in the stop phase of SDS motion.
Table 5.1: Reduction in plastic area under pin and traction coefficient with the introduction of texturing for glycerin conditions.

<table>
<thead>
<tr>
<th>Plastic Area Under Pin (mm²)</th>
<th>Traction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untextured</td>
<td>28.3</td>
</tr>
<tr>
<td>Textured</td>
<td>16.9</td>
</tr>
<tr>
<td>% Reduction</td>
<td>40%</td>
</tr>
</tbody>
</table>

5.2.3 Effects on Material Properties

On several occasions, upon the initiation of the SDS waveform in the pin-on-disc testing machine, immediate delamination of the textured UHMWPE specimens occurred regardless of whether a lubricant was present, as shown in Figure 5.1. The top layer containing the dimples was removed. This brings into question whether the material properties of the surface are being affected during the texturing process. It has been reported that hot-pressed UHMWPE is more susceptible to delamination than machined UHMWPE [83]–[85].

A possible cause could have been sharp edges of the flat pin, but it was not consistent, and slight delamination was observed in some cases at the corners of the SDS waveform. The cause of the delamination is unknown at this point, so it is necessary to further examine the effects of the hot-embossing texturing process on the surface properties of the UHMWPE specimens.

Figure 5.1: Delaminated surface of textured UHMWPE specimen.
5.3 Conceptual Model for Intermittent Motion of Flat Cylindrical Pin on Flat UHMWPE

A conceptual model based on the traction coefficient and wear results is proposed to describe the motion of the pin during intermittent SDS motion and its effects on the plastic component during different events of interest. The model examines direct contact between the pin and polymer disc such as during unlubricated conditions, as well as with glycerin as a lubricant. Glycerin showed typical results expected in orthopaedic bearings, so the model intends to focus on this lubricant. A schematic of the model is depicted in Figure 5.2.

![Conceptual model of factors affecting intermittent sliding motion of a flat cylindrical pin.](image)

Figure 5.2: Conceptual model of factors affecting intermittent sliding motion of a flat cylindrical pin.

The top row shows the UHMWPE’s response to the punch and motion conditions, and the bottom row shows the FBD for that scenario. $F_d$ is a deformation force, $T$ is the traction force and $F_f$ is the friction force, $F_{app}$ is the applied force and $F_N$ is the measured normal force. $F_i$ is the sum of $F_d$, $T$ and $F_f$. 

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5.3.1 SDS Phases

Stop Phase. As the SDS sequence begins, the pin is already under an applied load so it is displaced below the original surface plane. Based on previous models [86]–[88], once the pin is in motion, the contact region is displaced in the direction of sliding and a deformation force \((F_d)\) develops at the leading edge of the pin (Figure 5.2A). In sliding with a flat pin, the build-up of plastic at the leading edge is also observed [87]. Furthermore, at the trailing edge of the pin, there is a traction force \((T)\), which is a tangential force that occurs because of the deformation caused by the leading edge of the pin that has yet to recover [86]. \(F_d\) is larger than \(T\) and acts in the same direction, opposite of the direction of motion.

Additionally, there is a friction force \((F_f)\), which opposes the sliding motion of the pin. It acts on the surface of the pin that is in contact with the UHMWPE and it varies with the speed of the pin.

Start Phase. As the pin resumes its motion, it must overcome the deformed plastic that has formed at the leading edge (Figure 5.2C). This is consistent with the sharp increase in \(F_t\) that is observed as the pin begins moving again (Figure 4.5). After this event, the system returns to the same mechanisms observed during the stop phase (Figure 5.2A).

Dwell Phase. When the pin is at rest in the dwell phase (Figure 5.2B), the traction coefficient is still nonzero. The cause of the nonzero traction coefficients is unknown, but misalignment of the pin and/or measurement error were suggested as causes.

First, pin misalignment was considered by relating measured traction and normal forces to the geometry shown Figure 5.3. If the pin is assumed vertical, no transverse force would be observed. If an offset angle, \(\theta\), is actually present, then a transverse force, \(F_t\), would occur, and produce an apparent traction coefficient: \(\mu = \sin(\theta)\). Offset angles were predicted based on the measured traction coefficients, indicating that angles greater than 17° would be required during the dwell phase to produce the measured coefficients. Angles of these magnitudes would be
observed visually. While it is likely pin misalignment contributes to the nonzero dwell traction coefficient, it is unlikely to be the main cause.

![Diagram of pin offset angle, θ, based on forces measured in the transverse (horizontal plane) and the normal force (vertical plane).](image)

**Figure 5.3:** Geometry of pin offset angle, θ, based on forces measured in the transverse (horizontal plane) and the normal force (vertical plane).

Measurement error as the cause of the nonzero traction coefficients was further investigated by adapting the SDS waveform in the OrthoPod™. The load was removed for a duration of the dwell phase to see if the measured friction forces went to zero with both flat and semi-spherical pins. With both pin geometries, $F_f$ went to zero when the pin was lifted and then returned to a nonzero value when the pin was loaded again. This suggests that other factors must be the cause of the nonzero traction coefficients because when a semi-spherical pin is used in static tests, it should be able to align itself. Further details can be found in Appendix D.

Viscoelastic effects of the plastic causing asymmetrical deformation are suggested as a cause of the nonzero traction coefficients. It is suggested that while the pin is stopped, the plastic on both sides of the pin attempts to recover. The deformation of the plastic during the stop phase was asymmetrical and still is during the dwell phase. In Figure 5.4, the ideal symmetrical system expected to be observed is shown on the left where the pin is normal to the surface and equal traction forces are observed in the plastic at the edges. The actual asymmetrical system being...
observed is shown on the right. The pin is not normal to the surface due to the uneven deformation of the plastic. The traction coefficient on the left edge of the pin is small compared to the deformation force observed. There is a net imbalance in the left, so there are reaction forces at the right, making $F_d$ greater than $T$. This asymmetrical deformation in the plastic is likely a contributing factor to the nonzero traction coefficients observed in the dwell phase. Additionally, a friction force is present in the dwell phase even though there is no motion, making $F_f$ indeterminate (Figure 5.2C).

![Figure 5.4: Surface reactions for symmetrical (ideal) and asymmetrical (actual) pin loading scenarios.](image)

$F_{app}$ is the applied force, $F_N$ is the normal force measured in the vertical axis, $T$ is the traction force in the polymer, $F_t$ is the transverse force measured and $F_d$ is the deformation force of the plastic on the pin.

The cause of the nonzero dwell traction coefficient phenomenon is still relatively unknown, however it is expected that it would not be diminished in sliding semi-spherical pin conditions either based on the 0N dwell tests (Appendix D).
5.3.2 Addition of a Lubricant

The presence of a lubricant reduces $F_f$, which correspondingly reduces the traction coefficient. A fluid film is created separating the two articulating surfaces when they are in motion, allowing them to enter into a mixed lubrication mode instead of a boundary lubrication mode. However, in the dwell phase, even with a lubricant present, the system would be in a boundary lubrication mode because the fluid is squeezed out between the pin and UHMWPE. The pin and the UHMWPE surface would be in contact and a traction coefficient would be measured. Different lubricants of varying viscosities have different effects on the system.

5.3.2.1 Glycerin Lubrication

*Stop Phase.* While the pin is sliding in the stop phase, there is a boundary film present between the two articulating surfaces. As the pin stops, the boundary film diminishes, but the presence of dimples delays the loss of the boundary film because the dimples act as reservoirs for the fluid. The shear stresses at the surface are able to remove the entrained fluid from the dimples and extend the amount of time in which there is a fluid film between the sliding surfaces. This lowers the traction coefficient entering the dwell phase compared to untextured surfaces.

*Dwell Phase.* In the dwell phase, the traction coefficient was greater in the textured condition than the untextured condition. It is suggested that the system eventually enters a lubricant starved mode even when it is delayed due to the presence of dimples. In the untextured conditions, a crater-like reservoir forms from the pin deforming the plastic. The fluid remains within the deformed plastic region, which limits the surface-on-surface contact, reducing the traction coefficient. When the UHMWPE surface is textured and the fluid film breaks down, the fluid that would be in the deformed region is now in the dimples so there is more surface-on-surface contact, increasing the traction coefficient compared to the untextured condition. This was observed in the dwell phase traction coefficient results.
**Start Phase.** Even with fluid in the dimples when the surface is textured, the fluid film does not replenish quickly enough to consistently lower the traction coefficient during the start phase compared to the untextured condition. More specifically, comparing the results between the untextured and textured conditions at each station \((n=4)\), the traction coefficient decreased twice and increased twice with the introduction of texturing. Therefore, a conclusion cannot be made about the effect of glycerin in the start phase with the introduction of texturing.

These findings are consistent with the Jalali-Vahid model, which indicates that film thickness takes approximately 2-3 walking cycles to re-establish an elastohydrodynamic lubricant film in metal-on-metal hip implants [89]. It is difficult to immediately reduce friction between two surfaces at start-up, but even with some lubricant present in the dimples, improved wear performance could be observed; less opportunities for adhesive/abrasive wear or other forms of fatigue wear may be observed.

Later in the start phase, as speed increases, so does the traction coefficient which is consistent with the build-up of a fluid film and the Stribeck curve entering a mixed or hydrodynamic lubrication mode.

5.3.2.2 *Water Lubrication*

Water does not have a high enough viscosity to delay the breakdown of the fluid film as the pin stops, or accelerate the build-up of the fluid film during the start phase. This may be due to the dimples in the textured conditions not being in the orientation or having the necessary dimple diameter for optimal performance to delay the breakdown or accelerate the build-up of the fluid film. Additionally, due to the hydrophobicity of the UHMWPE, it is unknown whether water will be entrained in the dimples for the use of improving the tribological conditions during the transitions into and out of the dwell phase [75].
5.3.3 Effect of Texturing
If the cause of friction forces in the system is due to surface interactions, then the magnitude of the contact stress is less in the textured UHMWPE specimens because the contact regions are smaller than in untextured conditions. In fluid entrained dimples, the contact stress is lessened even more in the polymer contact regions because the fluid is presumed to be incompressible and assumes some of the load [17]. Additionally, the leading edge deformation force, \( F_d \), is most likely to be less in the textured conditions. This is due to less plastic at the leading edge of the pin to deform as there is no material to overcome whenever a dimple is being passed over.

When water was used as a lubricant, a reduction in traction coefficient was not observed with the introduction of texturing. There is evidence of less wear occurring than in the dry condition so it is expected that there is some degree of lubrication being provided by the water. There are still wear particulates in the dimples as in the textured unlubricated conditions, but much less. It is expected that there is still some wear debris floating in the water as third party wear particulates and increasing \( F_f \) due to increased surface contact.

With glycerin as a lubricant, minimal wear was observed and \( F_f \) was small, so more typical traction coefficients expected of metal-polyethylene systems were measured [90]. Since little wear is occurring, the drop in traction coefficient observed for textured UHMWPE specimens could be related to the reduction in deformation area compared to untextured conditions. Specifically, in the start phase, no difference in traction coefficient is detected because there is likely not enough recovery time for the deformed plastic during the dwell phase and the asymmetry dominates the effect of the lubricant and texturing.

5.4 Traction Coefficient versus Wear
Traction (or friction) coefficients and wear are complex mechanisms with many factors influencing them. High friction and high wear are typically observed together as are low friction and low wear, but there is no simple relationship between the two phenomena [49]. High traction
coefficients were observed in the unlubricated conditions coupled with a high degree of wear. Using glycerin as a lubricant produced low traction coefficients and minimal wear. However, tests conducted with water as the lubricant showed much greater traction coefficients than when glycerin was used, but still little wear.

Additionally, lower traction coefficients were not consistently measured with surface texturing, but wear was still observed to be minimal from the qualitative wear analysis conducted. In the unlubricated condition when wear was high, the dimples were an effective outlet for wear particulates which ultimately lowered the traction coefficients.

The two analysis methods do not necessarily agree with each other so it may be necessary to choose one type of analysis on which to base a success or failure. In the case of the long term durability of joint replacements, UHMWPE wear particulates are a main cause of osteolysis and ultimately implant failure.

5.5 Clinical Relevance
In this study, a simplified SDS test to investigate the factors affecting traction coefficients in SDS motion was conducted. The intent of this study was to improve the tribological characteristics in joint replacements. To develop this test, it was necessary to simplify the loading conditions of the hip in attempt to achieve the worst-case wear conditions.

To compare this test to expected clinical observations, it was necessary to examine the load and motion conditions. Maximum stresses in the hip during normal walking range from 4-6MPa [80]. In this test, the contact stress was 5.3MPa, which is within this range.

There are relatively few studies that report the expected surface speeds under SDS motion. However, based on typical walking kinematics, surface speeds for hip replacements range from 112-144mm/s (28-36mm diameter heads) [91]. The maximum speed in the SDS waveform is 41.3mm/s. While the sliding speeds in this study are slower than in typical walking, there was no need to achieve maximum speeds because only those experienced during the start
and stop phases of SDS motion were of interest. Additionally, it was expected that low speeds would maximize contact area to be more consistent with pure sliding and the congruent geometry of the hip joint.

While steady-state walking is the most common simulation method for THA, 74.6% of the daily activities executed by a THA patient are in static positions such as sitting, standing and lying. Walking and stair climbing make up 10.6% of daily activities and the remaining 14.8% are unknown [8]. Damaging effects to implanted joints are experienced during pauses as resting periods are known to initiate adhesive binding. The results of the unlubricated conditions in this study support this finding; high traction coefficients in the start phase and a high degree of wear were observed. Resting periods most frequently last 2-5s (99.4 times per hour) with an average resting period between activities of 11s, which is reported to have a 50-60% increase in static friction compared to reciprocating dynamic friction. If resting durations of 60s are experienced, friction is suggested to increase by 75% at start-up [92].

The temporal effects and duration of the dwell phase are important considerations because of the viscoelastic properties of the polymer. Stress relaxation tests by Waldman et al. [79] report that regardless of the strain rate, it takes UHMWPE approximately 10s to begin to relax and 100s to fully relax. Thus, the long dwells are influenced by the viscoelastic properties of the polymer. The short dwell of 0.8s in this study was chosen to limit these effects. Long dwells are common and damaging to a joint’s ability to lubricate itself, but short dwells do also occur. An example of this is stumbling, which has a response time of approximately 0.6s [93].

Morlock suggests that longer and more frequent pauses could cause damaging effects due to frictional effects and adhesive wear [78]. However, Hadley observed no significant increase in wear rates when the dwell duration was increased [10].
5.6 Limitations

Pin-on-disc testing machines are a simple and affordable way of screening candidate materials for the development of orthopaedic bearings, and only the promising material pairs would be tested in a joint simulator [94]. Pin-on-disc tests with multidirectional sliding motion have been found to be capable of ranking formulations of UHMWPE with respect to their predicted \textit{in vivo} wear rates. However, there is concern about the capability of pin-on-disc testers to realistically simulate clinically relevant wear mechanisms with repeatability across different laboratories to help define standardized test parameters [95].

In previous modelling of start-up conditions, while the lubricant film does deteriorate during the dwell phase, the lubricant film is restored in 2-3 steps after motion resumes [89]. Even in intermittent walking, optimal lubrication conditions resume quickly so over the 10 steps Morlock and colleagues [8] have reported that the average THA patient takes between pauses or activity changes, wear rates would average out to normal. However, this cannot be recreated in the pin-on-disc wear tester so the SDS waveforms are not necessarily realistic compared to what is observed clinically.

Additionally, with respect to the pin-on-disc tester, it is unlikely that full alignment could be achieved and maintained for consistent contact area with a flat metal pin according to Haider and Baykal [96]. Even with chamfered edges as the pins in this study had, the contact area could not be controlled to remain constant. This problem was known to be observed because of the nonzero dwell traction coefficients. In these tests it is common to use semi-spherical pins, however the choice of a flat pin was justified in order to cover the greatest number of dimples. Regardless of the justification of the decision made about the pin shape, the use of the flat indenter likely affected the traction coefficient results.

Due to the size constraints of the UHMWPE specimens, the SDS sequence could not be entered into at a constant sliding speed as would occur \textit{in vivo} and as done in Hadley’s SDS
waveforms. The SDS sequence began at approximately zero speed because it stopped at the corner of the rectangle the SDS waveform created (Figure 3.8). Therefore, between the first and second pin location, start-up effects were observed when they were not desired.

Another limitation of this study compared to in vivo or even in vitro hip simulator tests is the choice of lubricants. Two newtonian fluid lubricants were used in water and glycerin. Since synovial fluid is a non-newtonian, shear thinning fluid, the effects of texturing the UHMWPE component of TJA under typical lubricating conditions can only be speculated.
Chapter 6

Conclusions and Recommendations

This thesis examines the performance of a novel UHMWPE surface texturing method developed by Kamil [17] as an approach to improve tribological conditions and reduce the traction coefficient under intermittent SDS motion in orthopaedic bearings. A simplified SDS test was created and executed, a method to extract meaningful traction coefficient data was developed and an analysis of the wear mechanisms present were carried out to observe the factors influencing tribological conditions when the surface of UHMWPE was textured.

Firstly, a simplified SDS profile in a pin-on-disc tester was developed analytically based on the flexion angle inputs from an SDS hip simulator protocol produced by Hadley [10]. A waveform was created where the pin and disc system decelerates over 0.48s, dwells for 0.8s, and accelerates over 0.4s before returning to the origin on a separate path over 0.32s. This waveform in conjunction with a flat pin and flat UHMWPE sample represent a worst-case kinematic condition. The mixed-SDS region was a region of interest and is defined as the area under the pin during the dwell phase that also contains a portion of the stop and start phases.

Secondly, a method to obtain a representative traction coefficient for the stop, dwell and start phases was developed. To capture the effects of SDS motion, the stop and start traction coefficients were calculated as the average of the data points where the surface area of the pin was more than 50% within the mixed-SDS region. The dwell phase traction coefficient was calculated based on the results of a convergence test.

Lastly, the factors affecting the tribological conditions under SDS conditions were explored. The main factors affecting the traction coefficients and wear were the rheology of the lubricant and the introduction of the textured surface. The results indicate that regardless of the surface geometry, lubrication dominated in reducing the coefficient of traction and wear in metal-
UHMWPE systems. While the presence of any lubricant reduced the traction coefficient, the higher viscosity lubricant (glycerin) reduced the traction coefficient up to 97.4% whereas the lower viscosity fluid (water) reduced the traction coefficient up to 71.3%.

The introduction of a textured surface resulted in a significant reduction in traction coefficient in the unlubricated and glycerin conditions during the stop phase. In the start phase, a significant reduction in traction coefficient was observed in the unlubricated conditions and no change was observed in the glycerin conditions. Also, wear observed in the textured specimens was comparable to that of the untextured specimens. These results were consistent with the mechanism proposed in Section 2.6.2 that lowering the stresses in the polymer would lead to decreased traction coefficients in the stop and start phases.

A conceptual model was proposed to describe the deformation and lubricant mechanisms occurring during SDS motion in textured UHMWPE. It is suggested that in the stop and start phases, the dominant force contributing to the traction coefficient is the deformation force at the leading edge of the pin due to a buildup of polymer. In textured UHMWPE however, there is less material at the leading edge of the pin due to the presence of the dimples causing lower deformation forces at the leading edge of the pin, and therefore lower traction coefficients. Additionally, in textured lubricated specimens with a high viscosity lubricant, the breakdown of the fluid film entering the dwell phase is delayed due to the dimples acting as a reservoir for fluid. Once in the dwell phase, the model focuses on the cause of the nonzero traction coefficients. It is suggested that the misalignment of the pin is the main cause in conjunction with asymmetrical deformation of the plastic.

6.1 Recommendations for Future Work

To gain a better understanding of the mechanisms affecting the tribological characteristics in the metal-textured UHMWPE pairing, further pin-on-disc tests should be developed and conducted:
I. Pin-on-disc tests should be conducted with CoCr spherical pins on flat UHMWPE specimens to remove the detrimental asymmetry effects of the flat pin, as well as have the desired material pair of CoCr and UHMWPE, which is most commonly seen in TKA. Achieving the necessary contact area to observe the effects of texturing as well as achieving the desired sliding and rolling kinematic conditions observed in TKA are challenges that would be encountered.

   a. Another possibility in limiting the effects of pin misalignment is to articulate an UHMWPE pin on a metal disc. The UHMWPE texturing process could be adjusted to texture pins instead of discs. While an optimized process would need to be redeveloped, it is possible. An UHMWPE pin could be used because, with reasonable alignment and some expected deformation at the edges, predictable contact area could be maintained with reversing and crossing motions [97].

II. Pin-on-disc tests continuing to examine the effects of lubricants, surface motion and stress on friction and wear should be conducted by varying the speed of the SDS waveform, the load and lubricant viscosity.

III. The current study examined friction quantitatively and wear qualitatively. In the future, more sophisticate quantitative techniques should be conducted.

   a. Gravimetric wear analysis should be introduced for pin-on-disc tests to quantify the amount of wear in the system.

   b. The dimple diameter of the worn and unworn regions of textured UHMWPE specimens should continue to be measured. With this information, the change in thickness of the UHMWPE specimens could be determined from the change in dimple diameter and a map of the amount of surface wear could be created.

   c. Additionally, surface wear can be observed quantitatively by measuring the surface roughness of the UHMWPE specimens before and after the SDS tests.
Surface roughness would provide insight into the material’s potential for friction and wear. A rough surface would suggest greater interaction and potential interlocking of surface asperities, increasing friction and wear.

IV. Pin-on-disc tests should be conducted using synovial fluid analogues simulating synovial fluid of varying health levels developed in previous studies [98], [99] to see the effects on traction coefficient and wear when the solution is non-newtonian. Additionally, alterations to the viscosity of the synthetic synovial fluid should be investigated to observe the effects on tribological conditions.

In addition, further investigation into the clinical applications of the textured UHMWPE should be made:

V. FTIR tests on the textured UHMWPE surfaces should be conducted to detect the oxidation index to determine if the hot-embossing manufacturing process affects the material properties of the UHMWPE. If the effects of hot-embossing the UHMWPE are negative, an alternative texturing processes, such as laser texturing should be considered.

VI. Adding synthetic wear debris that would be expected in vivo, such as metal fragments or bone chips, could be added to SDS tests in the pin-on-disc tester to obtain conditions more similar to those observed clinically.

VII. An investigation into improving the textured system’s ability to scavenge wear particles as a way to limit the effects of the debris rather than limiting wear itself should be conducted.

VIII. In the long-term, the polymeric component of a TJA (hip and/or knee) should be textured using the hot-embossing process and tested in a joint simulator. Wear will be assessed, and textured and untextured specimens will be compared.
References


I. Etsion, Y. Kligerman, and G. Halperin, “Analytical and Experimental Investigation of Laser- Textured Mechanical Seal Faces Analytical and Experimental Investigation of


102 S. Yu and T. Bryant, “Stress-shielding Effect of UHMWPE Texturing during Stop-Dwell-Start (SDS) Motion in Total Joint Arthroplasty.”


# Appendix A

**UHMWPE Specification Sheet**

<table>
<thead>
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<th>Material</th>
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Commonly used as machine guards and as liners in chutes and hoppers. These sheets, bars, and strips have a slippery surface and excellent abrasion, wear, and impact resistance.
Appendix B

Journal Article Contribution

3rd CIRP Conference on BioManufacturing

Process parameter optimization for hot embossing uniformly textured UHMWPE surfaces for orthopedic bearings

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Abstract

To improve wear properties and reduce friction in orthopedic bearings, UHMWPE surface texturing is a proposed approach to retain fluid, reduce stress in the polymer and promote lubrication in the joint. The objective of this study was to establish a preliminary procedure to texture UHMWPE specimens using a custom die in a hot embosser. Four parameters were varied in subsequent stages: hold pressure, chamber temperature, hold duration and specimen cooling. Each stage was based upon the successful results of the previous stage. A dimple diameter of 96\% of the desired diameter was achieved. These parameters will be used to commence a formal procedure to optimize the process using a formal DOE method.

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Keywords: Total joint replacement; polyethylene; UHMWPE; embossing; texturing

1. Introduction

In cases of major cartilage deformation in a joint, a total joint arthroplasty (TJA) is the primary solution. The most common bearing design for TJA is a metal CoCr component on an ultra-high molecular weight polyethylene (UHMWPE) counterface [100]. Wear of UHMWPE in TJA is a concern as it can lead to the generation of debris and consequently the deterioration of bearing performance. Debris produced by wear of UHMWPE can cause implant loosening and osteolysis, which may lead to the need for revision surgeries [2].

Factors affecting wear in TJA include lubrication between bearing surfaces and it is believed that intermittent stop-dwell start (SDS) motion accelerates wear. During SDS motion, the speed of the articulating surfaces decreases to zero, dwells for a period of time under a constant compressive force and then increases again to a non-zero value [65]. Clinical studies have reported that an average total hip replacement patient typically walks in bursts of 10 steps before pausing or changing to another activity such as stair climbing or sitting, with a typical pause duration of 2 – 5 seconds between activities [8]. This finding is consistent with the assumption of SDS motion and recent studies suggest that these loading conditions increase wear rates by up to 490\% [9]. Furthermore, Hadley \textit{et al.} [101] suggest that this increased wear is attributed to deterioration of the lubricant films between the
surfaces during the dwell phase when entraining motion tends towards zero. When motion resumes, the surfaces are assumed to be operating at a less effective lubrication regime than normal, leading to increased surface wear.

To reduce friction and wear in the polymeric component of TJA, UHMWPE surface texturing has been proposed as a potential approach to retain fluid and promote lubrication within the joint. It is expected that surface texturing influences tribological performance in sliding bearings due to the ability to control surface contact area thereby increasing hydrodynamic pressure, entraining fluid and isolating wear particles [102]. Studies on textured metal and ceramic bearings have developed models that include the effect of material properties, dimple shape and texture geometry on enhancing fluid lubrication [18]. Studies have also indicated that non-circular feature shapes are more likely to enhance lubrication between articulating surfaces of orthopedic bearings and that optimum geometries exist for given material pairs [9,10]. Sawano et al. [19] found a significant reduction in friction and wear when 1 μm diameter dimples were textured onto the surface of metal hip replacements in simulator testing, mainly due to the containment of wear particles. Kustandi et al. [71] textured UHMWPE using nano-implant lithography to produce parallel line gratings with 1 μm spacing and observed an 8 – 35% reduction in the coefficient of friction under dry conditions with a ceramic counterface. Zhang et al. [105] replicated natural cartilage surface morphology described by Clarke [70] onto the surface of UHMWPE. The textured UHMWPE samples articulated against a metal counterface showed a reduction in the coefficient of friction of 67 – 86% using water lubrication. While these studies considered performance under steady state and dynamic conditions, the effect of UHMWPE texturing under SDS conditions is not known.

A textured UHMWPE surface area has been designed and the approach has been theoretically demonstrated to:

- Reduce the coefficient of friction during the dwell phase of SDS motion,
- Improve the tribological conditions in the transition between the stop-dwell and dwell-start phases of SDS loading conditions, and
- Reduce stress in the polymer [102].

![Fig. 1. Model for textured polymer-metal contact with entrained fluid. (a) Undefomed state showing the entrained fluid in dimples. The surface deflects the amount, δ, due to the motion of the metal upper surface under the applied load; (b) Resulting contact stress in a dimple and its adjacent area due to the normal load application.](image)

It is hypothesized that under quasi-static conditions, dimples in the polymer surface will entrain fluid and develop locally pressurized regions under loading normal to the polymer surface (Figure 1a). The stress distribution in the polymer contact areas (B, B’) depends on the viscoelastic properties of the bulk, entrained materials and the geometry of the dimples. It is expected that the stress in the fluid ($\sigma_1$) will be higher than the contact stress in the polymer ($\sigma_2$) due to a higher structural stiffness in the region under the indentation, which reduces contact stress in the polymer (Figure 1b). This phenomenon is referred to as stress shielding. Furthermore, during the stop-dwell or dwell-start phases of SDS motion, the thicker fluid layer in the dimple will have a lower shear than at the polymeric contacts. Due to the non-Newtonian behavior of synovial fluid, there will be a higher viscosity in the indentations and lower viscosity at the polymeric contacts. As a result, fluid should be retained in the polymer contact regions producing a continuous fluid film under a large range of stress and motion conditions. Improved lubrication between the articulating surfaces of orthopedic bearings should reduce friction and wear.

The proposed surface texture geometry includes spherical dimples with diameter, $d$, and center-to-center spacing, $c$, over the range $1 < c/d < 2$ as seen in Figure 2 [102]. From FEA analysis of the dimple configuration in Figure 2 with $c/d$ ratios ranging from 1 to 2, stress shielding as high as 75% was observed for $c/d = 1.09$, however this represents an unrealistic configuration in practice since the size of the contact region between the dimples would be small. Practical configurations were suggested in the range of $1.2 <
c/d < 1.6 which corresponds with stress shielding from 10 – 45\% [102].

To evaluate the stress shielding theory, textured UHMWPE samples with c/d ratios of 1.3 (d = 500 μm, c = 650 μm) and 1.7 (d = 1000 μm, c = 1700 μm) were to be tested experimentally. The long-term aim of this project was to produce an optimized procedure to manufacture textured UHMWPE surfaces. The specific aim of this study was to identify the relative effect of process variables in order to design future studies using formal design of experiment (DOE) techniques.

2. Methods

Textured UHMWPE was manufactured by imprinting the surface of blank UHMWPE specimens with a novel die design in a heated vacuum under an applied load, using a micro-embossing process. While surface texturing of UHMWPE is a well researched area, the novelty of the proposed approach is associated with the die design and fabrication method.

2.1. Die

To prepare the die, holes of diameter, d, were drilled into an aluminum plate with a depth of d/2 using a micro-milling machine with programmable hole drilling capabilities (Microlution 363-S, Chicago, IL) as seen in Figure 3. The micro-milling machine was programmed to produce the hexagonal pattern shown in Figure 2.

The die fabrication was completed by press fitting precision 316-stainless steel micro-balls with diameter, d, (Abbott Ball Company, West Hartford, CT) into the holes in the aluminum plate as seen in Figure 4a. The aluminum plate was fixed between two steel blocks and pressed to ensure the micro-balls were fixed into the holes and would not be affected during use. The aluminum plate was then attached to a polished steel block (die base, Figure 3) using Loctite A234 adhesive with Loctite 075 adhesive activator (Henkel Corporation, Düsseldorf, Germany) to produce the completed die (Figure 4b). The manufacturer reports that the adhesive is at 15\% strength at 100 °C compared to room temperature, which is believed to be sufficient for adhering the aluminum plate to the steel base due to the system being under compression [15].

2.2. Specimen Preparation

An EVG® 510HE hot embosser (EV Group, Austria) was used to prepare the textured UHMWPE surface. The hot embosser consists of an upper and lower stage with the top stage being able to move in the vertical direction via a piston mechanism (Figure 5a). The die was placed on the lower stage and a commercial grade UHMWPE specimen (32 x 20 x 7 mm) was placed on top of the die (Figure 5b).
The hot embosser chamber (top and bottom plates) was heated to a specified temperature above the glass transition temperature (-160°C) and below the melting temperature (137°C) of UHMWPE in a vacuum [33]. The upper stage was lowered to press the die into the UHMWPE specimen to the desired load above the yield strength of the polymer which is approximately 5 MPa at 100°C, corresponding to a load 1440 N over the area to be textured [77]. The top stage held the desired pressure for a duration of time. The chamber was then cooled to below as specified temperature by lowering the temperature of the upper and lower plates at a desired rate, the upper stage was raised and the vacuum was removed in subsequent order. Dimple diameter and center-to-center distance were measured on the samples by taking photographs using a photo-microscope and Motic Images Plus 2.0 (Motic, British Columbia) at 2x magnification.

2.2.1. Parameters

Because the manufacturing process was unknown, several parameters were varied in stages based on the results of the previous stage. The effect on dimple diameter was investigated for the following parameters in specific stages as indicated in Figure 6.

Stage 1. Hold pressure.
Stage 2. Chamber temperature.
Stage 3. Hold duration.
Stage 4. Specimen cooling.

When a new stage was commenced, the parameters that produced the maximum dimple diameter in previous stage were used as a starting point.
3. Results and Discussion

For each textured UHMWPE produced (Figure 7), 15 measurements (3 measurements on 5 photos) were taken for both the dimple diameter and center-to-center distance values. Analysis will be limited to the dimple diameters because the average experimental center-to-center distance for all samples was 98% of the desired distance so it was assumed that this measurement did not vary and could be excluded. Dimple diameter results will be discussed as a percentage of the desired diameter.

The first stage of the preliminary parameter optimization involved varying the holding pressure. Figure 8 shows the effects of increasing the hold pressure while maintaining the chamber temperature and hold duration at 100°C and 30 minutes, respectively. At smaller loads, increasing the hold pressure had a greater effect on increasing the size of the dimple diameters than at larger loads. The dimple diameters increased 11.3% between 400 and 700 N, and 6.2% between 700 and 1400 N. As the load approached the yield strength of the specimens (1440 N), the effects of increasing the load became less apparent. An increasing decaying exponential function was fitted to the percent of desired dimple diameter ($D_p$) as a function of holding pressure ($P$):

$$D_p = a(1 - \exp(-bP))$$

(1)

where $a > 0$ and $b > 0$. An asymptote at approximately 83% of the desired dimple diameter was indicated. Interestingly, the asymptote corresponded to the yield strength of the UHMWPE specimens at the testing temperature.

The response to hold pressure variation becomes saturated at approximately 1500 N (approximately 5.5/b); however, this only accounts for 83% of the desired dimple diameter. Therefore, other processing parameters must contribute to achieve the desired dimple diameter.

For stages 2 – 4, only one specimen was prepared for each set of parameters. The second parameter investigated was the chamber temperature. Due to only preliminary results being available, the percent change in dimple diameter between stages is reported (Table 1). A 10°C increase in temperature resulted in a -1.6% change in dimple diameter when compared to the maximum average dimple diameter measured in stage 1 which was 85.6% the desired dimple diameter at 1800 N. This percent change is very small and therefore it is unknown whether the effects were caused by the increase in temperature. Continuing to increase the chamber temperature
though is not desirable because the melting temperature of UHMWPE is being approached. Because UHMWPE is a semi-crystalline polymer with a high molecular weight, the polymer does not flow above the melt temperature [33]. However, most of the amorphous regions recrystallize during cooling and shrinkage or warpage can occur when cooling does not happen uniformly [33]. This phenomenon could likely have contributed towards the smaller dimple diameter as UHMWPE has low thermal conductivity and did not cool evenly [33].

Increasing the hold duration from 30 to 60 minutes resulted in a 3.9% increase in dimple diameter (Table 1). While these are promising results, the length of time to produce textured specimens is approaching being unpractical. In addition to the hold duration, the chamber must also heat up, produce a vacuum, cool down and return to atmospheric pressure. Therefore, once production costs are considered, the process may not be economically feasible.

Because shrinkage of the dimples on the polymer surface is a concern, controlling recrystallization during cooling was attempted. This was the fourth stage of parameter optimization. Cooling after the hold duration was changed from 35°C at the hot embosser’s maximum cooling rate to 20°C at 1°C/min. The best results were observed in this stage at 96% of the desired dimple diameter (Table 1). These results suggest that the amorphous polymer chains present during heating of the UHMWPE were able to recrystallize while the die was still pressing on the surface and not allowing shrinkage to occur.

Therefore, to begin a formal manufacturing optimization procedure, the parameters in stage 4 should be the starting point.

**4. Conclusions**

A preliminary optimized procedure to texture UHMWPE specimens with dimples in a hexagonal pattern using a die in a hot embosser was developed. Four parameters—hold pressure, chamber temperature, hold duration and cooling—were varied to achieve the desired dimple diameter. It was concluded that these four parameters affect the resultant dimple diameters, however there is a saturation point in a parameter’s ability to contribute to the production of the desired dimple diameter.

Based on the process shown in Figure 6, the initial parameter settings in which a formal manufacturing procedure optimization will be developed are as follows:

- Hold pressure: 1800 N
- Hold temperature: 100°C
- Hold duration: 60 minutes
- Specimen cooling: 20°C at 1°C/min

While the parameters listed above have produced a dimple diameter of 96% of the desired dimple diameter, further optimization must be done that accounts for manufacturing factors such as overall production time and cost.

**Acknowledgements**

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**References**


geometry for improvement in wear resistance. Precis Eng 2009;33:-492.


Appendix C

Hot Embosser Protocol

Figure C.1 depicts the custom hot embosser protocol used to manufacture the textured UHMWPE specimens.

![Diagram of hot embosser manufacturing process]

Figure C.6.1: Hot embosser manufacturing process.
Appendix D

Effect of Loading on Traction Forces in the Dwell Phase

This appendix describes a supplementary test to examine the effect of normal forces on measured traction forces in the dwell phase.

**Objective.** The cause of the nonzero traction coefficients during the dwell phase was further investigated by conducting an adapted version of the study’s SDS waveform in the pin-on-disc tester. During the dwell phase, the pin was lifted until the normal force was 0N and then was returned to 150N. This test was to determine whether measurement error was the cause of the nonzero traction coefficients.

**Methodology.** The SDS waveform was adjusted in the dwell phase only, which consists of 10 out of the 25 segments (Figure 3.8). During the dwell phase, the pin was raised for the middle six segments (0.48s) using both flat and semi-spherical pins under unlubricated conditions. The semi-spherical pins were manufactured from CoCr and had a diameter of 25mm. A semi-spherical pin was used in this test because the stress gradient produced across its face can accommodate some degree of misalignment, thus minimizing the effect of misalignment as a possible cause for the nonzero dwell traction coefficients.

The transverse force, or traction force ($F_t$), in the horizontal plane was measured. It was expected to be zero when the normal force ($F_n$) was zero.

**Results and Discussion.** The results of the test can be seen in Figure D.1. The top plot is the programmed applied force and the bottom plots depict the transverse plots for the flat and semi-spherical pins during the dwell phase. When $F_n$ goes to zero, $F_t$ also goes to zero, which suggests that machine error is not the cause of the nonzero traction coefficients.

When a flat pin was used, $F_t$ was approximately 40N when a load was applied and when a semi-spherical pin was used, $F_t$ was approximately 10N. This suggests that with a flat pin, misalignment affects the magnitude of $F_t$. Furthermore, when the semi-spherical pin was used and
the issue of misalignment was lessened, there was still a transverse force present outside the ±4N accuracy in the horizontal plane.

**Conclusions.** Therefore, machine error is not the cause of the nonzero dwell traction coefficients. It is expected that misalignment is affecting the traction coefficient in conjunction with other factors such as the viscoelastic properties of the UHMWPE.

![Figure D.1: Transverse force plots for the dwell phase of flat and semi-spherical pins during 0N dwell tests.](image)

All the plots show forces versus time during the dwell phase. The top plot is the normal force measured, the middle plot is the traction force measured with a flat pin and the bottom plot is the traction force measured with a semi-spherical pin.