Maximizing lubricant film thickness in hard-on-soft bearings using patterns of axisymmetric texture features, with application in prosthetic hip implants

PhD Dissertation Defense
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Overview

• **Introduction**
  - Total hip replacement
  - Bearing surface materials
  - Limited longevity

• **Reducing polyethylene wear to increase longevity**
  - Conventional methods
  - Surface texturing
    - Physical mechanisms
    - Experiments
    - Simulations

• **Elasto-hydrodynamic lubrication (EHL) simulations**

• **Results**
  - Optimum texture design parameters as a function of bearing operating conditions
  - The effect of texture floor profile on the optimum texture design parameters
  - The effect of cavitation model on the optimum texture design parameters

• **Conclusions**
Add an accomplishments slide
Listing all journal and conference publications. This will set the tone before you start your defense.
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Introduction: Total hip replacement

- **Total hip replacement (THR)**
  - Replace the damaged natural hip joint with a prosthetic hip implant
  - Articulation between the femoral head and acetabular shell/liner replaces the hip joint motion
  - 370,000+ THR surgeries performed each year [1]
  - Increasingly younger patients are seeking THR each year [2]

Introduction: Bearing surface materials

• **Prosthetic hip implant bearing surface material pairs**

<table>
<thead>
<tr>
<th>Material Pair</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-on-polyethylene (MoP)</td>
<td>![MoP Image]</td>
</tr>
<tr>
<td>Metal-on-metal (MoM)</td>
<td>![MoM Image]</td>
</tr>
<tr>
<td>Ceramic-on-polyethylene (CoP)</td>
<td>![CoP Image]</td>
</tr>
<tr>
<td>Ceramic-on-ceramic (CoC)</td>
<td>![CoC Image]</td>
</tr>
</tbody>
</table>

- Bearing surface materials include:
  - Ultra-high molecular weight polyethylene (UHMWPE)
  - CoCrMo, titanium, or stainless steel
  - Alumina or zirconia
- Hard-on-soft configurations (MoP, CoP) are the most common [1]

Introduction: Limited longevity

- The statistical survivorship of prosthetic hip implants declines sharply after 15-20 years [3]
- Common causes for prosthetic hip implant failure [4]:
  - Mechanical complications
  - Mechanical loosening
  - Dislocation
- Osteolysis, loosening, and other complications are linked to polyethylene wear in hard-on-soft prosthetic hip implants [5]

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Reducing polyethylene wear

- **Conventional methods:** Improve material properties, change the bearing surface design
  - Highly cross-linked UHMWPE [6]
  - Vitamin-E infused/blended UHMWPE [7]
  - Ceramic materials
  - Surface coatings such as diamond-like carbon [8]

- **Proposed solution:** Texture features on the femoral head can reduce polyethylene wear by increasing the lubricant film pressure and thickness to reduce contact between the bearing surfaces

There are three main mechanisms whereby texture features reduce the friction coefficient and wear between sliding surfaces [9]:

- Lubricant reservoirs/trapping wear debris
- Micro-hydrodynamic bearings
- Reducing the nominal contact area

Surface texturing: Experiments

**Hip joint simulator:**
- 17% friction reduction, 60% wear reduction for textured CoCrMo femoral head and UHMWPE acetabular liner [10]

![Hip joint simulator diagram]

**Ball-on-disk:**
- 10% friction reduction for stainless steel ball and textured UHMWPE disk [12]

![Ball-on-disk diagram]

**Pin-on-disk:**
- 50% wear reduction for UHMWPE pins and textured CoCrMo disks [11]

![Pin-on-disk diagram]

**Ring-on-disk:**
- 75% friction reduction for stainless steel ring and textured UHMWPE disk [13]

![Ring-on-disk diagram]

Hydrodynamic lubrication (HL) models

Compute the hydrodynamic pressure generated between rigid surfaces

Solve Navier-Stokes equations with CFD, or use simplifying assumptions such as thin film, steady-state, laminar flow, incompressible fluid to arrive at the Reynolds equation:

\[ \frac{\partial}{\partial x} \left( h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( h^3 \frac{\partial p}{\partial y} \right) = 6\mu U \frac{\partial h}{\partial x} \]

Elasto-hydrodynamic lubrication (EHL) models

Also account for pressure-induced bearing surface deformations

Iterate between fluid pressure and mechanical deformation equations

Solve mechanical deformation with elasticity equations, using a Boussinesq approach or finite element analysis

Soft EHL: one or both surfaces deform under low pressure

Mixed lubrication models: also account for (partial) solid-on-solid contact
State-of-the-art experiments and simulations:
- Do not account for a range of texture geometries and bearing operating conditions
- Do not compute the lubricant film thickness, but rather compute friction coefficient, wear, or lubricant load-carrying capacity
- Frequently use unidirectional or reciprocating sliding to arrive at non-axisymmetric texture shapes and floor profiles

This knowledge is crucial to design and manufacture textured prosthetic hip implants

Thus, the **research objective** is to characterize the lubricant film thickness in a textured hard-on-soft prosthetic hip implant bearing as a function of axisymmetric texture design parameters and bearing operating conditions, covering a range of in-vivo prosthetic hip implant operating conditions.
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Soft EHL simulations: Numerical model

- Rigid textured surface moves parallel to deformable UHMWPE surface
- Solve non-dimensional Reynolds equation (RE) with multi-grid finite difference method:
  \[ \frac{\partial}{\partial X} \left( H^3 \frac{\partial P}{\partial X} \right) + \frac{\partial}{\partial Y} \left( H^3 \frac{\partial P}{\partial Y} \right) = \frac{\lambda}{\delta^2} \frac{\partial H}{\partial X} \]
  - Flow factor: \( \lambda = 3\mu U/2r_p\rho_0 \)
  - Nominal separation: \( \delta = c/2r_p \)
- Linear elastic finite element analysis (FEA) for UHMWPE
  - \( E = 0.9 \) GPa, \( \nu = 0.46 \) [14]
  - Apply calculated lubricant film pressure to FEA model as a pressure load

Soft EHL simulations: Methodology

1. Set initial bearing spacing
2. Calculate lubricant film pressure
3. Calculate polyethylene deformation
4. Increase bearing spacing if necessary
5. Decrease bearing spacing if necessary
6. Check if converged
   - Yes: Desired load-carrying capacity? (End if yes)
   - No: Repeat steps 2-5
7. Check if lubricant pressure is too high or too low
   - Too high: Increase bearing spacing
   - Too low: Decrease bearing spacing
Soft EHL simulations: Numerical model

- **Texture design parameters:**
  - Texture aspect ratio: \( \varepsilon = h_p/2r_p \)
  - Texture density: \( S_p = \pi r_p^2/4r_1^2 \)

- **Bearing operating conditions:**
  - Flow factor: \( \lambda = 3\mu U/2r_p p_0 \)
  - Load-carrying capacity: \( W = \iint p(x,y) dxdy/p_0 = P_{avg} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load-carrying capacity, ( W )</td>
<td>2.467</td>
<td>19.738</td>
</tr>
<tr>
<td>Flow factor, ( \lambda )</td>
<td>0.003</td>
<td>0.300</td>
</tr>
<tr>
<td>Texture density, ( S_p )</td>
<td>0.100</td>
<td>0.700</td>
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<tr>
<td>Texture aspect ratio, ( \varepsilon )</td>
<td>0.010</td>
<td>0.100</td>
</tr>
<tr>
<td>Polyethylene stiffness, ( K )</td>
<td>1</td>
<td>1000</td>
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Optimum texture design parameters: Objectives

- **Simulate** lubricant film thickness in textured hard-on-soft bearings
- **Determine** optimum texture design parameters to maximize lubricant film thickness
- **Derive** empirical relationships between optimum texture design parameters, bearing operating conditions, and lubricant film thickness
Vary flow factor for constant load-carrying capacity

\[ \varepsilon_{\text{opt}} = 0.172\lambda^{0.492} \]

Vary load-carrying capacity for constant flow factor

\[ \varepsilon_{\text{opt}} = 0.214W^{-0.466} \]
Multiple regression analysis gives optimum texture aspect ratio as a function of both flow factor and load-carrying capacity:

\[ \varepsilon_{opt} = 0.380 \lambda^{0.511} W^{-0.445} \]

Optimum texture aspect ratio is proportional to lubricant film thickness:
- Constant flow factor (red):
  \[ \varepsilon_{opt} = 1.171 H + 0.019 \]
- Constant load-carrying capacity (black):
  \[ \varepsilon_{opt} = 1.377 H \]
Effect of UHMWPE stiffness

- Vary UHMWPE stiffness, $K$

- UHMWPE deformation and nominal bearing spacing combine for nearly identical lubricant film thickness, independent of UHMWPE stiffness
Optimum texture design parameters: Summary

• We simulate hard-on-soft textured bearings

• We determine that:
  - Optimum texture density: 0.10 - 0.40
  - Optimum texture aspect ratio: 0.01 - 0.14
    o Increases with increasing flow factor and decreasing load-carrying capacity
    o Proportional to the lubricant film thickness
  - Polyethylene stiffness does not affect lubricant film thickness

• We derive best-fit equations to predict optimum texture aspect ratio for given bearing operating conditions

Results published in: Q. Allen, B. Raeymaekers “Maximizing the lubricant film thickness between a rigid microtextured and a smooth deformable surface in relative motion, using a soft elasto-hydrodynamic lubrication model” *Journal of Tribology* 142(7) p. 071802 (2020)

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Texture floor profile: Objectives

- **Simulate** lubricant film thickness for spherical, cylindrical, and conical texture floor profiles

- **Determine** optimum texture design parameters to maximize lubricant film thickness

- **Derive** empirical relationships between texture floor profile, texture design parameters, bearing operating conditions, and lubricant film thickness

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<td>0.700</td>
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<tr>
<td>Texture aspect ratio, $\varepsilon$</td>
<td>0.010</td>
<td>0.100</td>
</tr>
</tbody>
</table>
Texture floor profile: Results

- Vary flow factor for constant load-carrying capacity
- Vary load-carrying capacity for constant flow factor
Texture floor profile: Results

- Optimum texture aspect ratio increases with flow factor, decreases with load-carrying capacity

- Optimum texture density has opposite trend
Texture floor profile: Results

• Multiple regression analysis gives optimum texture aspect ratio as a function of flow factor and load-carrying capacity

<table>
<thead>
<tr>
<th>Shape</th>
<th>$\varepsilon_{opt}$</th>
<th>$\lambda$</th>
<th>$W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>0.3799 $\lambda^{0.5114} W^{0.4449}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylinder</td>
<td>0.2193 $\lambda^{0.4970} W^{0.3952}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cone</td>
<td>0.4914 $\lambda^{0.4405} W^{0.4827}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Texture feature volume is proportional to texture aspect ratio
Each texture floor profile has different proportionality constant between optimum texture aspect ratio and lubricant film thickness:

<table>
<thead>
<tr>
<th>Texture</th>
<th>( \varepsilon_{opt} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>( 1.3441H_{opt} + 0.0061 )</td>
</tr>
<tr>
<td>Cylinder</td>
<td>( 0.6826H_{opt} + 0.0104 )</td>
</tr>
<tr>
<td>Cone</td>
<td>( 1.9126H_{opt} + 0.0092 )</td>
</tr>
</tbody>
</table>

All texture floor profiles show same proportional relationship between texture feature volume and optimum lubricant film thickness:

\[ V_{opt} = 1.4073H_{opt} + 0.0073 \]
Texture floor profile: Results

- “Inverse cone” texture floor profile shows predictive power of relation between lubricant film thickness and texture feature volume:

  - Computation 1:
    o **Given:** $H_{opt} = 0.050$
    o **Predict:** $V_{opt} = 0.078$, $\varepsilon_{opt} = 0.058$
    o **Simulate:** $\varepsilon_{opt} = 0.60$, $H_{opt} = 0.050$

  - Computation 2:
    o **Given:** $\varepsilon_{opt} = 0.050$
    o **Predict:** $V_{opt} = 0.067$, $H_{opt} = 0.042$
    o **Simulate:** $\varepsilon_{opt} = 0.050$, $H_{opt} = 0.044$
Texture floor profile: Summary

• We **simulate** spherical, cylindrical, and conical texture floor profiles

• We **determine** that:
  - Cylindrical floor profiles create thickest lubricant film
  - All texture floor profiles have a different proportional relationship between optimum texture aspect ratio and lubricant film thickness
  - Texture feature volume is proportional to lubricant film thickness for all axisymmetric texture floor profiles

• We **derive** equations between optimum texture design parameters, bearing operating conditions, lubricant film thickness, and texture feature volume for all texture floor profiles


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Cavitation model: Objectives

- **Simulate** lubricant film thickness for different cavitation models, including Reynolds, half-Sommerfeld (HS), and Jakobsson-Floberg-Olsson (JFO).
- **Determine** optimum texture design parameters to maximize lubricant film thickness for each cavitation model and quantify the differences.
- **Derive** empirical relationships between the texture design parameters, bearing operating conditions, and lubricant film thickness for each cavitation model.
Cavitation model: Methods

- **Half-Sommerfeld (HS)**
  - Cavitation enforced at end

- **Reynolds**
  - Cavitation enforced every iteration

- **Jakobson-Floberg-Olsson (JFO)**
  - Mass conservation in cavitation region
  - Film content parameter, $\theta$

\[
\frac{\partial}{\partial X} \left( H^3 \frac{\partial P}{\partial X} \right) + \frac{\partial}{\partial Y} \left( H^3 \frac{\partial P}{\partial Y} \right) = \frac{\lambda}{\delta^2} \frac{\partial}{\partial X} (\theta H)
\]

<table>
<thead>
<tr>
<th>Cavitation algorithm</th>
<th>Cavitation boundary conditions</th>
<th>Cross-sectional view of pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bearing geometry</strong></td>
<td></td>
<td><img src="image" alt="Cross-sectional view" /></td>
</tr>
<tr>
<td>None</td>
<td>N/A</td>
<td><img src="image" alt="Cross-sectional view" /></td>
</tr>
<tr>
<td><strong>Half-Sommerfeld</strong></td>
<td>$P = P_{cav}$</td>
<td><img src="image" alt="Cross-sectional view" /></td>
</tr>
<tr>
<td><strong>Reynolds</strong></td>
<td>$P = P_{cav}$, $dP/dX = 0$</td>
<td><img src="image" alt="Cross-sectional view" /></td>
</tr>
<tr>
<td><strong>JFO</strong></td>
<td>$P = P_{cav}$, $dP/dX = 0$</td>
<td><img src="image" alt="Cross-sectional view" /></td>
</tr>
</tbody>
</table>

mass conservation
Cavitation model: Results

- HL simulations lead to more uniform-sized cavitation regions in each texture feature.

- EHL simulations allow cavitation size to change because of surface deformation.
Cavitation model: Results

- Vary flow factor for constant load-carrying capacity
- Vary load-carrying capacity for constant flow factor
Cavitation model: Results

- Optimum texture aspect ratio:
  - Increases with increasing flow factor
  - Decreases with increasing load-carrying capacity
  - Is proportional to the lubricant film thickness

\[ \varepsilon_{opt} = 1.661H_{opt} - 0.023 \]
Cavitation model: Results

- Percent difference between the Reynolds and JFO cavitation models:
  - Increases with increasing texture aspect ratio and texture density
  - Increases with decreasing flow factor and increasing load-carrying capacity

<table>
<thead>
<tr>
<th>Cavitation model</th>
<th>Mean runtime [hr]</th>
<th>Standard deviation of runtime [hr]</th>
<th>Mean function calls</th>
<th>Standard deviation of function calls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds</td>
<td>0.596</td>
<td>0.613</td>
<td>12.010</td>
<td>4.378</td>
</tr>
<tr>
<td>JFO</td>
<td>7.788</td>
<td>13.460</td>
<td>29.135</td>
<td>52.606</td>
</tr>
</tbody>
</table>
Texture floor profile: Summary

• We simulate textured hard-on-soft bearings with the Reynolds and JFO cavitation models

• We determine that:
  - The Reynolds cavitation model predicts thicker lubricant films and greater optimum texture design parameters than the JFO cavitation model
  - The difference between the Reynolds and JFO cavitation models increases with increasing texture aspect ratio and decreasing flow factor

• We derive relations between the optimum texture design parameters, bearing operating conditions, and lubricant film thickness for both cavitation models

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**Conclusions**

- Optimum texture design parameters maximize the lubricant film thickness at a range of bearing operating conditions
  - The optimum texture aspect ratio is proportional to the lubricant film thickness because the texture feature volume is proportional to the lubricant film thickness
    - Cylindrical texture floor profiles lead to thicker lubricant films and smaller optimum texture aspect ratios than spherical or conical texture floor profiles
    - The JFO cavitation model predicts thinner lubricant films and smaller optimum texture aspect ratios than the Reynolds cavitation model, but both predict the same linear relationship between optimum texture aspect ratio and lubricant film thickness

- This knowledge may help inspire patient-specific prosthetic hip implants, tailored to each patient based on factors such as age, weight, and activity level
Questions?