Fretting Fatigue in Modular Orthopaedic Implants

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Introduction

• Modular orthopaedic devices are a feature of total joint replacements today

• Benefits:
  • Allow surgeons to choose from a variety of available implant sizes, designs & material options for the procedure & patient specific requirements

• Drawbacks:
  • Can lead to fretting fatigue & corrosion, due to the resulting micro-motion & contact stresses
  • Found at mismatched surfaces during cyclical loading, resulting in interface wear
  • Can lead to implant rejection, due to wear debris induced osteolysis
Example Modular Implants

- **Components**
  - Acetabular Cups (Liners & Shells)
  - Femur Stems
  - Femur Heads
  - Knee
  - Total System (Knee, Femur, Head & Cup)

- **Materials**
  - Cobalt Chromium Alloys
  - Technical Ceramics
  - Titanium Alloys
  - Steel Alloys
  - Polymers (UHMWPE & PEEK)

METS Modular Total Femur (Stanmore Implants, UK)

Trinity™ Cup & MiniHip™ Stem (Corin, UK)
OVERVIEW & AIM
Overview

Assessment of Femur Head & Stem

→ Variation in interface design
  1. Tolerances
  2. Geometric parameters
  3. Materials

→ Study look at variation in interface angle ($\theta$):
  1. $\theta_{\text{stem}}$
  2. $\theta_{\text{head}}$
Aim

- Quantify & compare fretting fatigue for three specific fits between the femur stem & head

1. $\theta_{\text{stem}} = \theta_{\text{head}}$
2. $\theta_{\text{stem}} > \theta_{\text{head}}$
3. $\theta_{\text{stem}} < \theta_{\text{head}}$

<table>
<thead>
<tr>
<th>Ideal fit</th>
<th>Positive mismatch</th>
<th>Negative mismatch</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{stem}} = \theta_{\text{head}}$</td>
<td>$\theta_{\text{stem}} &gt; \theta_{\text{head}}$</td>
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</table>
Geometry Generation, Materials & Loads
Geometry Generation from CT Scans

CT scan (Patient Specific)

Geometry Generation

Bone Property Mappings (Density)

Implant Femur Stem & Head Design
Bone Properties (Density, Modulus & nu Relationships)

Density

\[ \rho = f(HU) \]

Young's Modulus

\[ E = 6.4 \rho_{app}^{1.54} \]

Poisson's Ratio

\[ \nu = \begin{cases} 
0.12 \frac{0.2}{500} \rho_{app} - 0.04 & \text{if } \rho < 1000 \\
0.32 & \text{if } 1000 \leq \rho \leq 1500 \\
 & \text{if } \rho > 1500 
\end{cases} \]

Helgason [2008]
### Material Properties (Validation: Patient Specific)

<table>
<thead>
<tr>
<th>Femur</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>0.1</td>
<td>8.3</td>
<td>23.3</td>
</tr>
<tr>
<td>Validated Femur [Helgason 2008]</td>
<td>0.5</td>
<td>6.6</td>
<td>22.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E (GPa)</th>
</tr>
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<tbody>
<tr>
<td>Fraction</td>
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</table>
Density Refinement (Femur Cortical Surface)

Bone density mapping was refined around cortical surface to capture high variation in density which may be missed out by using standard grid method.
Density (kg/m³)

Surface Plot

Sectional Slice Plot
Young's Modulus (GPa)

Surface Plot

Sectional Slice Plot
Implant Materials (SN Curves & Fatigue Properties)

Graphs showing the fatigue strength model (stress range) vs. number of cycles for different materials.

- **TI-6Al-4V**: Stem
- **Nickel-Co-Cr**: Head
FE Model Load Validation

- Kinematic load data obtained from Bergmann et al.[6], based on average physical data from 4 patient data sets

- Loads muscle force boundary conditions to FEA model

Cyclic loading applied on femur head & abductor muscle

Kinematic model data for different activities (typical patient) [6]
THEORY
General Material Fatigue

- General Material fatigue described by relating:
  - Oscillating mean stress & stress amplitude
- Using either the Goodman, Gerber or Soderberg relationships, an equivalent stress amplitude with no mean stress can then be found from the mean stress & stress amplitude
  - Soderberg’s relationship is utilised as conservative compared to Goodman or Gerber relationships.
- This equivalent stress amplitude with no mean stress, can then be read off physical SN curves ($R=-1$) to obtain the predicted number of cycles to failure for the fatigued part due to cyclic loading.

![Combined Cyclic & Mean Stress Schematic](image1)

![Soderberg's Amplitude & Mean Stress Relationship](image2)
Equivalent $\sigma_{\text{amplitude}}$ & Cycles to Failure

- For each material domain, mean stresses & stress amplitudes are calculated over single walking gait load cycle.
- Using Goodman diagram & Soderberg relationship
  - Equivalent stress amplitude with zero mean stress are obtained
  - Stress Ratio ($R$) = -1
- Equivalent stress amplitudes are then read off SN curves (function) to predict number of cycles to failure for the fatigued part due to cyclic loading.

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**Stress Amplitude**

- Stress Amplitude ($\sigma_a$)
- Equivalent Stress Amplitude with no Mean Stress ($\sigma_{a\text{Equiv}}$)
- Mean Stress from Model ($\sigma_m^{\text{Model}}$)

**Model Predicted Number of cycles to Failure**

- Number of Cycles ($N_{\text{Model}}$)

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a) Obtaining Equivalent Stress Amplitude with no Mean Stress from Soderberg's Amplitude & Mean Stress Relationship

b) Predicted of Number of Cycles to Failure from SN Curves using Equivalent Stress Amplitude with no Mean Stress
For Fretting Fatigue, the SN curves were adjusted by the following equation for fretting strength \( S_{fr} \) to take account of early prediction to failure due to fretting:

\[
S_{fr} = S_0 - 2 \times \mu \times p_o \times [1 - e^{-l/k}]
\]

Where,
- \( S_{fr} \) = Fretting fatigue strength [MPa]
- \( S_0 \) = Fatigue strength in the absence of fretting [MPa]
- \( \mu \) = Coefficient of friction
- \( p_o \) = Contact pressure [MPa]
- \( l \) = Fretting amplitude [µm]
- \( k \) = Constant (3.8 [µm])

Relation between Plain Fatigue vs. Fretting Fatigue

Plain Fatigue SN Semi-log Curve \( (S_0) \)

Fretting Fatigue SN Semi-log Curve \( (S_{fr}) \)
(Only applicable on contact surfaces)
RESULTS
Implant Stress & Load (Walking Gait Cycle)

Load at 20% gait cycle  Load at 60% gait cycle

Load vectors during gait cycle  von Mises stress on the stem
Results: von Mises Stress

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## Results: Contact Pressure

<table>
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<tr>
<th>Condition</th>
<th>Anterior Side</th>
<th>Posterior Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal fit</td>
<td><img src="image1" alt="Ideal fit Anterior" /></td>
<td><img src="image2" alt="Ideal fit Posterior" /></td>
</tr>
<tr>
<td>Positive mismatch</td>
<td><img src="image3" alt="Positive mismatch Anterior" /></td>
<td><img src="image4" alt="Positive mismatch Posterior" /></td>
</tr>
<tr>
<td>Negative mismatch</td>
<td><img src="image5" alt="Negative mismatch Anterior" /></td>
<td><img src="image6" alt="Negative mismatch Posterior" /></td>
</tr>
</tbody>
</table>

| Condition          |  |  |
|--------------------|  |  |
| \( \theta_{\text{stem}} = \theta_{\text{head}} \) | Ideal fit | \( \theta_{\text{stem}} > \theta_{\text{head}} \) | Positive mismatch | \( \theta_{\text{stem}} < \theta_{\text{head}} \) | Negative mismatch |
Results: Areas of Fretting Fatigue

<table>
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<th>Area of evident fretting fatigue (% of total contact area):</th>
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<tbody>
<tr>
<td>Ideal fit</td>
</tr>
<tr>
<td>0.29%</td>
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Results (Summary)

- Under walking load (gait cycle) conditions for particular modular implant configuration:
  - The ‘ideal fit’ is not actually the best design to minimise fretting fatigue as would have been thought
  - Negative misalignments give rise to larger observed fretting fatigue

- A slight positive misalignment minimises fretting fatigue, for this particular modular implant configuration
- Only 3 variations in stem misalignment assessed
  - No sensitivity analysis was performed on magnitude of misalignment

- Only assessed one a particular modular implant configuration & design
  - Additional design & or geometric parameters may play a larger role in determining magnitude of fretting fatigue

- Only assessed two specific materials, CoCr (head) against Titanium Alloy (Stem)
  - The results may change with material change
  - Softer head vs. harder stem
  - Harder stem vs. softer head
Conclusion

- A Fretting fatigue model has been implemented in COMSOL
- Validation of fretting fatigue models vs. physical tests is ongoing
- More work needs to be done to fully describe the fretting fatigue characteristics of misaligned implants, in terms of
  - Misalignment sensitivity
  - Material variation (Soft on hard vs. hard on soft)
  - Additional designs & or geometric characteristics
  - Surface finishes, roughness & coatings may change results
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THANK YOU!

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