Computational Assessments of THA Wear: Sliding-Distance-Coupled Finite Element Analysis

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Total Hip Replacement

Enabling Technology: 1960

2001: 250,000 cases / year

$22,000 / case
FDA-approved designs: 709
The Problem:

ACETABULAR SURVIVORSHIP

YEARS

95% C.I.

Charnleys
The Cause: Polyethylene Wear

The Mechanism: Osteolytic Aseptic Loosening
How to minimize failures?

• Interrupt osteolytic cascade
• Minimize wear

• Vehicles to evaluate wear
  – Patient LTFU
  – Laboratory simulators
Physical Testing
Computational Simulation

- Attractions of numerics
- Precedent surrogate: contact stress

- Abrasive/adhesive wear
  - Sandpaper analogy:
    
    Contact Stress x Sliding Distance x Abrasiveness

    (Archard, ca. 1950)
THA Archard Equation:

\[ w(\theta, \phi) = \int_{H.S.}^{T.O.} k \sigma(\theta, \phi) v(\theta, \phi) \, dt \]

Sliding-Distance-Coupled Finite Element Analysis:

\[ w(\theta, \phi) = \sum_{i=1}^{\text{# inc}} k \sigma_i(\theta, \phi) s_i(\theta, \phi) \]
Gait Analysis
Hip Load Discretization
Contact Stress Convergence

Number of Contact Nodes:

- 145
- 257
- 439
- 727

Contact Stress (MPa) vs. Normalized AP Distance
Sliding Velocity

100 mm/sec

ant. H-S+ 0.04 sec lat.

0.16 0.20 0.24 0.28 0.32

0.36 0.40 0.44 0.48 0.52

0.56 0.60 0.64 (T-O) 0.68 0.72

0.76 0.80 0.84 0.88 0.92
THA Archard Equation:

\[ w(\theta, \phi) = \int_{H.S.}^{T.O.} k \sigma(\theta, \phi) v(\theta, \phi) \, dt \]

Sliding-Distance-Coupled Finite Element Analysis:

\[ w(\theta, \phi) = \sum_{i=1}^{\# \, inc} k \sigma_i(\theta, \phi) s_i(\theta, \phi) \]
Archard Equation Solution
(Adaptive Meshing)
Adaptive Meshing

UHMWPE Removal:

\[ x_{\text{NEW}} = x_{\text{OLD}} + w(\theta, \phi) \hat{n}_x \]
\[ y_{\text{NEW}} = y_{\text{OLD}} + w(\theta, \phi) \hat{n}_y \]
\[ z_{\text{NEW}} = z_{\text{OLD}} + w(\theta, \phi) \hat{n}_z \]

Spatial Filter:

\[ w_{i,j} = \sum_{i=-1}^{1} \sum_{j=-1}^{1} w_{i+j, j} n_{i,j} \]
\[ n_{i,j} = \frac{1.0}{8.0 + \text{cwt}} \begin{bmatrix} 1.0 & 1.0 & 1.0 \\ 1.0 & \text{cwt} & 1.0 \\ 1.0 & 1.0 & 1.0 \end{bmatrix} \]
Per-Cycle Wear Distribution
Temporal Convergence

The graph illustrates the current volumetric wear rate over time (in months) for different update frequencies: 3-month updates, 6-month updates, and 9-month updates. The data shows a general increase in wear rate over time, with each update cycle converging towards a similar trend, indicating temporal convergence.
Corroboration from Retrievals
Physical Validation

Error: 4.1%
Design Changes

- Head Diameter
- Conformity
- Thickness
- Backing
- Materials
- Bearing Couples
Head Size Effect on Wear Evolution

![Graph showing the effect of head size on wear evolution. The graph plots linear wear rate against time (years). There are four lines representing different head sizes: 22 mm, 26 mm, 28 mm, and 32 mm. Over time, the wear rate decreases for all sizes, with the 22 mm size showing the highest initial wear rate and the 32 mm size showing the lowest.](image-url)
Head Size Effect on Cumulative Wear

20 Years
<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Linear Wear (mm/year)</th>
<th>Volumetric Wear (mm³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0</td>
<td>0.0433</td>
<td>14.3</td>
</tr>
<tr>
<td>6.0</td>
<td>0.0438</td>
<td>14.4</td>
</tr>
<tr>
<td>3.0</td>
<td>0.0441</td>
<td>14.5</td>
</tr>
</tbody>
</table>
Effects of Initial Bearing Surface Congruity

<table>
<thead>
<tr>
<th>Head Diam. (mm)</th>
<th>Cup Diam: 28.20 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.02</td>
<td>0.0478</td>
</tr>
<tr>
<td>27.99</td>
<td>0.0502</td>
</tr>
<tr>
<td>27.97</td>
<td>0.0523</td>
</tr>
<tr>
<td>27.94</td>
<td>0.0544</td>
</tr>
<tr>
<td>27.84</td>
<td>0.0615</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Linear (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td>28.02</td>
<td>0.0478</td>
</tr>
<tr>
<td>27.99</td>
<td>0.0502</td>
</tr>
<tr>
<td>27.97</td>
<td>0.0523</td>
</tr>
<tr>
<td>27.94</td>
<td>0.0544</td>
</tr>
<tr>
<td>27.84</td>
<td>0.0615</td>
</tr>
</tbody>
</table>

20 years
Effect of Backing & Fixation

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Support Condition</th>
<th>Linear (mm/year)</th>
<th>Volumetric (mm³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All polyethylene</td>
<td>Bony bed</td>
<td>0.2430</td>
<td>115</td>
</tr>
<tr>
<td>Cemented, metal backed</td>
<td>Bony bed</td>
<td>0.2441</td>
<td>116</td>
</tr>
<tr>
<td>Noncemented, metal backed</td>
<td>Bony bed</td>
<td>0.2441</td>
<td>115</td>
</tr>
<tr>
<td>Cemented, metal backed</td>
<td>Rigid</td>
<td>0.2446</td>
<td>115</td>
</tr>
<tr>
<td>Noncemented, metal backed</td>
<td>Rigid</td>
<td>0.2446</td>
<td>115</td>
</tr>
</tbody>
</table>

5 Years
THA Backside Wear

Kurtz et al.,
J. Biomech 32, 1999
TKA Fatigue/Delamination Wear

Sathasivam & Walker
Inter-Patient Variability of Wear

Years post-surgery

Wear Rate (mm/yr)
Head Abrasiveness (3rd body)
Mechanism:

3rd Body Debris
Debris Convection during Subluxation
Local Roughening FEA

Non-Roughened

\[ w(\theta, \phi) = k \int_{\text{cycle}} \sigma(\theta, \phi, t) \, v(\theta, \phi, t) \, dt \]

Roughened

\[ w(\theta, \phi) = \int_{\text{cycle}} k(\theta, \phi, t) \sigma(\theta, \phi, t) \, v(\theta, \phi, t) \, dt \]
Look-up Table for $k (\theta, \phi, t)$

Cup Reference Frame

Head Reference Frame
Wear Front Changes

Baseline

Local Roughening
Local Head Roughening

- X
- Y
- Z
- θ
- φ
- 95 mm³/year
- 62 mm³/year
- 76 mm³/year

Femoral Neck Axis
## Effects of Wear Coefficient

<table>
<thead>
<tr>
<th>Case (k,mm$^3$N$^{-1}$m$^{-1}$)</th>
<th>Volumetric Wear Rate (mm$^3$/year)*</th>
<th>Linear Wear Rate (mm/year)*</th>
<th>Direction ($\theta$, degrees)</th>
<th>Direction ($\phi$, degrees)</th>
<th>Departure (b, degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.065 x 10$^{-6}$</td>
<td>19.8</td>
<td>0.08</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>2 x</td>
<td>21.2</td>
<td>0.08</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>5 x</td>
<td>25.2</td>
<td>0.10</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>10 x</td>
<td>31.0</td>
<td>0.11</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>50 x</td>
<td>62.0</td>
<td>0.18</td>
<td>68.9</td>
<td>21.3</td>
<td>9.88</td>
</tr>
<tr>
<td>100 x</td>
<td>83.0</td>
<td>0.22</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>250 x</td>
<td>107</td>
<td>0.27</td>
<td>61.8</td>
<td>33.2</td>
<td>7.48</td>
</tr>
<tr>
<td>500 x</td>
<td>120</td>
<td>0.31</td>
<td>61.8</td>
<td>33.2</td>
<td>7.48</td>
</tr>
<tr>
<td>1000 x</td>
<td>139</td>
<td>0.33</td>
<td>67.4</td>
<td>42.3</td>
<td>12.4</td>
</tr>
</tbody>
</table>
Effect of Roughened Area Size

- Volumetric Wear (mm$^3$/year)
- Area (mm$^2$)
- Direction Change (deg)

5% of Hemisphere
## Effects of Roughening Location

<table>
<thead>
<tr>
<th>Case (α, degrees)</th>
<th>Volumetric Wear rate (mm³/year)*</th>
<th>Linear Wear Rate (mm/year)*</th>
<th>Direction (θ, deg)</th>
<th>Direction (φ, deg)</th>
<th>Departure (b, deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unroughened</td>
<td>19.8</td>
<td>0.08</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>0</td>
<td>62.0</td>
<td>0.18</td>
<td>68.9</td>
<td>21.3</td>
<td>9.88</td>
</tr>
<tr>
<td>45</td>
<td>95.1</td>
<td>0.24</td>
<td>90.0</td>
<td>30.0</td>
<td>7.51</td>
</tr>
<tr>
<td>135</td>
<td>22.0</td>
<td>0.09</td>
<td>104</td>
<td>30.8</td>
<td>15.0</td>
</tr>
<tr>
<td>180</td>
<td>19.8</td>
<td>0.08</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>225</td>
<td>19.8</td>
<td>0.08</td>
<td>75.2</td>
<td>30.8</td>
<td>0.00</td>
</tr>
<tr>
<td>315</td>
<td>76.2</td>
<td>0.20</td>
<td>111</td>
<td>21.3</td>
<td>18.0</td>
</tr>
</tbody>
</table>
Wear Front Non-Sphericity

Arc Length (mm)

Wear Depth (mm)

Roughened FEA

Test Tube
Wear Rate Evolution

\[ \text{Wear Rate (mm}^3\text{/yr)} \]

\[ k_B = 1.06 \times 10^{-6} \text{ mm}^3\text{N}^{-1}\text{m}^{-1} \]

Time (years)
Shoulder Effect
Summary

• Sliding-distance-coupled FEA
  – Experimentally grounded
  – Physically validated

• Complements clinical & laboratory data

• Applications
  – Design, manufacturing, fixation
  – Inter-patient variability: Minimize 3rd body!
LTFU Wear (Penetration) Assessment

O (0.1-0.2 mm / yr)
Roentgen Stereophotogrammetry (RSA)

Baldursson et al.
Manual Wear Measurement  (Livermore et al., 1990)
Digital Edge Detection

Shaver et al.
JBJS 79A, 1997
Physical Validation

CNC mill, ± 0.0001 “
Depths: 0.262 to 1.98 mm

<table>
<thead>
<tr>
<th>Method</th>
<th>Avg. Error (%)</th>
<th>C.O.V. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular Templating</td>
<td>28.1</td>
<td>25.2</td>
</tr>
<tr>
<td>Digital Edge Detection</td>
<td>3.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Digital Edge Detection

Martell & Berdia
JBJS 79A: 1997
Early Wear Rate Projection

Shaver et al. JBJS 79A, 1997

2 → 10 years
r = 0.683
3-D Technique

Devane et al.,
CORR 319, 1995
In-Plane vs. 3-D?

Sychterz et al.,
CORR 365, 1999
Cohort Comparisons

Linear (mm/yr):
- Wire: 0.079
- Cable: 0.120

Volumetric (mm³/yr):
- Wire: 24.5
- Cable: 37.5

Early measurements: error => 0.02 mm
Acknowledgements

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NIH: AR-35788
  AR-43314
  AR-46601
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DePuy, Inc.