Hip Prostheses Lifetime Prediction via Simulation-based Engineering

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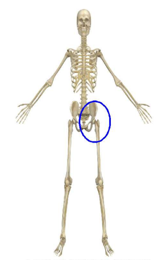
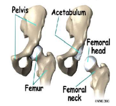
Introduction: Artificial Hip Joint 101



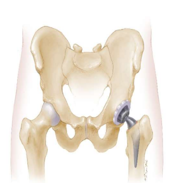
Human skeletal system

Healthy human hip joint



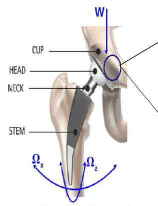
Osteoarthritic hip joint

Treatment of osteoarthritis

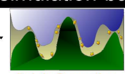


TOTAL HIP REPLACEMENT

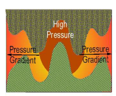
Motivation: What design improvements can be uncovered with simulation-based engineering?



Hip Joint Normal Articulation



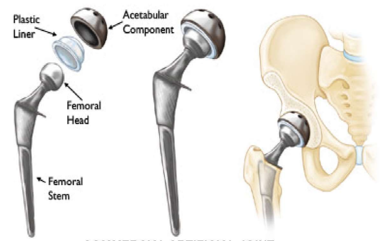
Debris Generation and Transport



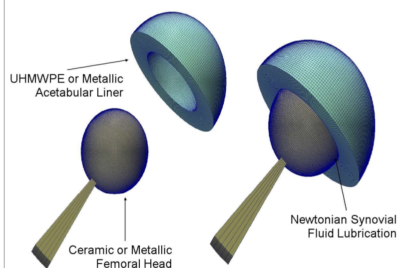
High Fluid Pressure

Osteolysis

Computational Model Setup

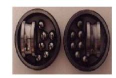


COMMERCIAL ARTIFICIAL JOINT



SIMULATED SETUP

Computational Modeling Approach: PAML

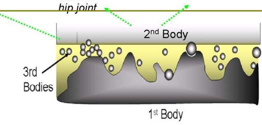


Bearing wear via lubricant debris

Wear in artificial hip joint

Teeth Wear

Head-crash due to contaminants in HDD



Particle Augmented Mixed Lubrication →Applied load is carried by both fluid pressure and contact stress, in presence of particles

PAML - lite

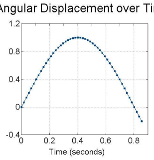
- **Fluid Mechanics**
  - Film thickness: $h = h(\theta,\varphi)$
  - Hydrodynamic Pressure: $p = p[h, \eta, \omega]$
- **Contact Mechanics**
  - Separation: $\Delta H = \Delta H(\theta,\varphi)$
  - Elastic Contact: $\sigma(\theta,\phi) = \frac{E(1-\nu)}{(1-2\nu)(1+\nu)r}\Delta H(\theta,\phi)$
- Fluid Mechanics + Contact Mechanics → Equilibrium
- **Particle Dynamics**
  - Particle generation: Uniform distribution from debris
  - Particle transport: Uniform Concentration
  - Particle deposition: Volume=f (G, v, D)
- **Wear**
  - Material Removal: $Volume(\theta,\phi) = K_{wear}\frac{(F * V_{rel})(\theta,\phi)}{H_{cup}}$

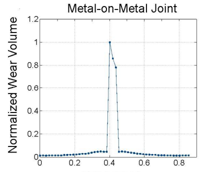
Results: Compare Component Wear

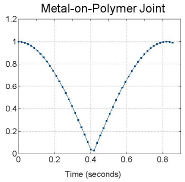
The model allows us to track several useful parameters over time. Spatial distribution of interfacial fluid pressure, solid-solid contact stress, instantaneous wear and net friction are some of the examples.

With these features, the model can be used to investigate the difference in operation of metal-on-metal and metal-on-polymer hip joint interfaces for a sinusoidal angular motion of the femur.

Angular Displacement over Time





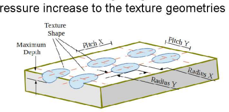


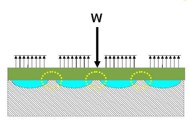
The metal-on-metal joint operates in the Elasto-Hydrodynamic Lubrication (EHL) regime and hence observes almost no wear in regular operation. Only when the velocity becomes very low, near the extrema, the two solids contact and cause wear. The metal-on-polymer joint operates in the boundary or mixed lubrication regime and hence generates large wear volumes throughout its operation, until when velocity becomes low enough and relative sliding distance decreases, thus reducing the instantaneous wear rate.

Results and Discussion

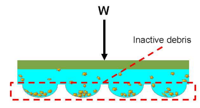
Texturing can enhance the lifetime of artificial joints by following mechanisms:

i. Reducing friction and wear of acetabular cup
ii. Preventing generated debris from getting out of the interface
iii. Limiting the pressure increase to the texture geometries

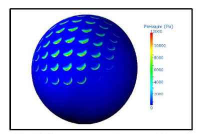




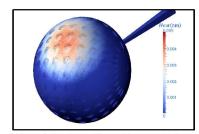
Reduce debris generation



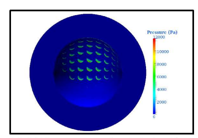
Trap generated debris



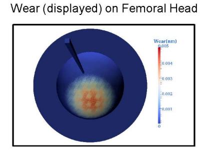
Fluid Pressure on Femoral Head



Wear (displayed) on Femoral Head



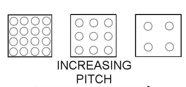
Fluid Pressure on Acetabular Cup



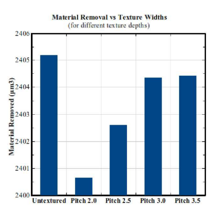
Wear on Acetabular Cup

Parametric studies can be conducted to study the effect of texture parameters on lubrication, deposition and final debris concentration.

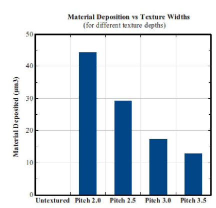
The effect of changing the separation between textures (pitch) has been shown here as an illustration.



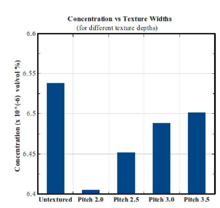
INCREASING PITCH



Total material removed from the surface of the cup



Total material trapped in the textures



Final concentration for different pitch values

Conclusions

- The multi-physics framework, PAML-lite, that models fluid mechanics, contact mechanics and wear, is presented
- The framework can be used to gain insight into the operation of different types of artificial joints
- Extended lifetime hip candidates from multiphysics simulations can be 3D printed
- High-fidelity deterministic modeling is critical to fully leverage patient-specific prosthesis design

References

1. Jhurani, S. M., and Higgs, C. F., "An elastohydrodynamic lubrication (EHL) model of wear particle migration in an artificial hip joint," Tribology International, 43 (8), 1326–1338, Aug. 2010.
2. Wang, F. and Jin, Z. "Lubrication modelling of artificial hip joints: From fluid film to boundary lubrication regimes", 2004, American Society of Mechanical Engineers, New York, NY 10016-5990
3. Ito, H., Kaneda, K, Yuhta, T,, Nishimura, I., Yasuda, K., Matsuno T., "Reduction of polyethylene wear by concave dimples on the frictional surface in artificial hip joints.", J Arthroplasty;15(3):332-8, Apr. 2000
4. Gao,L., Yang, P., Dymond, I., Fisher, J., and Jin, Z., "Effect of surface texturing on the elastohydrodynamic lubrication analysis of metal-on-metal hip implants," Tribology International, vol. 43, no. 10, pp. 1851–1860, Oct. 2010.

Acknowledgements

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