Tribology and Biotribology

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Overview of lecture
- Tribology and biotribology
- Fundamentals of friction, wear and lubrication
- Focus on total hip replacement (THR)
- Metal-on-Polyethylene THR
- Metal-on-Metal THR
- Ceramic-on-Ceramic THR
- Compliant layer THR
- Research at Newcastle

Tribology fundamentals

Joyce, *Biopolymer Tribology*, in *Polymer Tribology*, Imperial College Press, 2009, 227-266

Definition of tribology
- Tribology, from the Greek *tribos* ‘to rub’
- The science of interacting surfaces in relative motion, including friction, lubrication and wear
- Biotribology is this science related to the body
- Primarily synovial joints and replacement joints

Friction

- Friction force is a resistance to motion
- With no lubricant:
  - Friction force is proportional to normal force $F = \mu N$
  - Friction is independent of velocity
  - Friction is independent of apparent contact area
  - Friction is dependent on real contact area (1 to 0.0001% of apparent contact area)
Friction (2)

Friction force \( (F) = F_{\text{adhesion}} + F_{\text{ploughing}} \)

Due to chemical bonding at the asperity contacts
Due to breaking and deforming of one asperity by another

Wear

Wear is the progressive loss of material from a surface. Various wear regimes:
- Adhesive – due to bonding
- Abrasive – due to hard asperities
- Fatigue – due to cyclic stresses
- Erosive – due to relative motion with a fluid containing hard particles
- Corrosive – due to chemical reactions

May occur singly or in combination

Wear (1)

Wear can be measured as a depth, but volume is much better

Generally wear volumes:
- Increase with load
- Increase with sliding distance
- Increase with surface roughness
- Decrease with surface hardness

However, many other factors can be involved in the wear process

Wear (2)

(Archard) Wear Equation

Volume loss \( (\text{mm}^3) = \text{Wear factor } k \times \left( \frac{\text{mm}^3}{\text{Nm}} \right) \times \text{Load } (N) \times \text{Sliding distance } (m) \)

Volume loss is proportional to load and sliding distance

In a hip sliding distance given by

\[ \text{Arc length} = \text{Radius} \times \theta \]

So if we compare an implanted 22mm diameter Charnley THR with a 54mm diameter Birmingham Hip Resurfacing, what might we expect?

Lubrication

Adds a fluid film to separate surfaces
Lubrication regimes

- Indicated by lambda ratio, $\lambda$
- Hydrodynamic lubrication ($\lambda > 3$)
- Mixed lubrication ($1 < \lambda < 3$)
- Boundary lubrication ($\lambda < 1$)
- Hydrodynamic lubrication ($\lambda > 3$) is to be preferred

Calculation of lubrication regimes

$$\lambda = \frac{h_{\text{min}}}{\left(\frac{R_a}{R_x}\right)^2 + \left(\frac{R_a}{R_x}\right)^2}$$

$$h_{\text{min}} = 2.80 \left( \frac{\eta}{E^* R_x} \right)^{0.65} \left( \frac{w}{E^* R_x^2} \right)^{-0.21}$$

- If roughness ($R_a$) increases, lambda decreases – lubrication gets worse
- $R_{a1}$ and $R_{a2}$ are the surface roughness values of each component, $h_{\text{min}}$ is the minimum effective film thickness, $R_x$ is the equivalent radius (m), $\eta$ is the viscosity of the lubricant (Pa s), $u$ is the entraining velocity (m/s), $E^*$ is the equivalent elastic modulus (Pa), and $w$ is the load (N)

Surface roughness and lubrication

- Typical metal-on-polymer joint, polymer relatively rough
- Metal-on-metal joint under typical mixed lubrication
- Resurfacing metal-on-metal joint. Fluid film lubrication possible during gait

Different types of hip prostheses

- 22mm diameter stainless steel head: polished to better than 0.050μm Ra
- Initially a low friction PTFE cup which wore quickly
- UHMWPE acetabular cup: roughness of 1.29μm Ra, radial clearance 0.2mm

Lancet 2007

- ‘Charnley LFA: a worldwide retrospective review at 15 to 20 years’ (Older, J Arthroplasty, 2002, 675-680). 83% survival rate at 20 years
- UK National Joint Registry (NJR) 2011 - 97% survival rate at 7 years (cemented hips)
THR failure due to osteolysis
- UHMWPE wear particles
- Volume: > 550mm³ joint comes loose
- Size: majority in a range of 0.1-0.5µm
- Numbers: half a million particles at each step
- Provoke negative cascade of responses
- Loose prosthesis, radiolucent zones on X-ray, pain for the patient

Therefore minimise the wear

Improved polyethylenes
- Cross-linked polyethylene (XLPE)
- Clinical and in vitro trials suggest 50-80% reduction in wear
- ‘Familiarity’ for orthopaedic surgeons
- Polyethylenes are more ‘forgiving’ to malposition

Metal-on-Metal (MoM) THR
- 100 fold reduction in wear claimed compared with Metal-on-Poly
- Volumetric wear was reduced
- But particle size was smaller, typically 1nm rather than 1µm for UHMWPE
- Actual numbers of CoCrMo particles higher than UHMWPE
- Potential danger from metal particles?
- In US, 35% of THR were MoM (Bozic, 2009, JBJS)

Australian Joint Registry 2010 ≤28mm femoral head size

MoM resurfacing THR
- 46% patients under 55 years of age had a resurfacing implant (Steffen, JBJS, 2008)
- But since then the number of resurfacing operations has declined
- ‘Pseudotumours’ (Pandit et al JBJS 2008)
- Different resurfacing designs give different results

Ceramic-on-ceramic THR
- Femoral head and acetabular cup made of hard ceramic material
- Potential benefits – low wear
- Brittleness was a concern
- Fracture rates now less than 0.1%
- Squeaking?
- Expensive
Summary of key biotribological factors in THR

- Wear of PE leads to osteolysis and revision operations
- So reduce the wear
- Increase hardness: metal-on-metal, ceramic-on-ceramic
- Reduce surface roughness and maintain it
- Move from boundary to fluid film lubrication – increase head diameter, reduce surface roughness and radial clearance between head and cup

Compliant layer THR

- Based on a concept of mimicking the superb natural joint with its compliant articular cartilage
- Polyurethane as the ‘cartilage’
- Low friction and wear during motion
- But at ‘start up’?
- Now in human trials

A provocative slide?

- “I only implant Delta Motions and BHRs, everything else is rubbish”
- “Implanting 100 Exeters well won’t get me in JBJS”
- “Smith and Nephew won’t fly me to the academy for putting in Charnleys”
- Cemented MoP 97% survival at 7 years (NJR 2011)

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