Tribology and Biotribology

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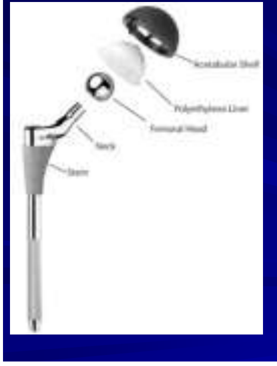
Overview of lecture



- 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

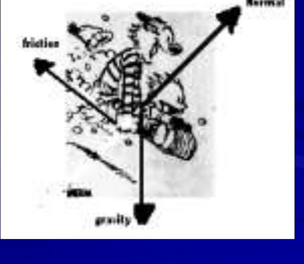
Tribology fundamentals

Jin et al, *Biotribology*, Current Orthopaedics, 2006, 20, 1, 32-40
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 (1)

- Friction force is a resistance to motion
- With no lubricant:
  - Friction force is proportional to normal force F = μN
  - 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)

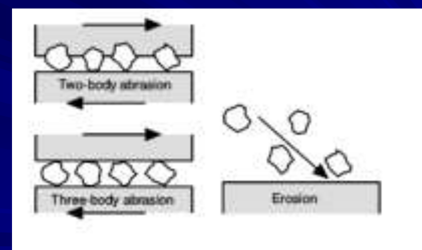
Friction (2)

- Friction force (F) = $F_{adhesion} + F_{ploughing}$

$F_{adhesion}$: Due to chemical bonding at the asperity contacts

$F_{ploughing}$: Due to breaking and deforming of one asperity by another

Wear



Wear (1)

- 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 (2)

- 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

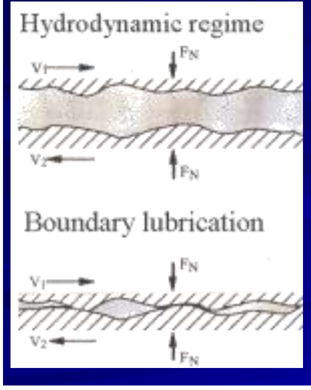
(Archard) Wear Equation

- Volume loss (mm^3) = Wear factor k (mm^3/Nm) x Load (N) x Sliding distance (m)
- Volume loss is proportional to load and sliding distance
- In a hip sliding distance given by
- Arc length = Radius x θ
- 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, λ
- Hydrodynamic lubrication (λ > 3)
- Mixed lubrication (1 < λ < 3)
- Boundary lubrication (λ < 1)
- Hydrodynamic lubrication (λ > 3) is to be preferred

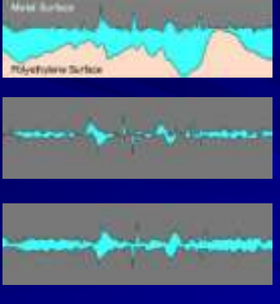
Calculation of lubrication regimes

$$\lambda = \frac{h_{min}}{\left[(R_{a1})^2 + (R_{a2})^2\right]^{1/2}}$$

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

- If roughness (R_a) increases, lambda decreases – lubrication gets worse
- R_{a1} and R_{a2} are the surface roughness values of each component, h_{min} is the minimum effective film thickness, R_x is the equivalent radius (m), η 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


The operation of the century: total hip replacement

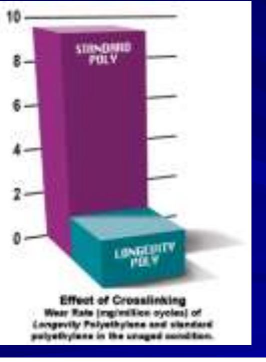
- '*Charnley LFA: a worldwide retrospective review at 15 to 20 years*' (Older, J Arthroplasty, 2002, 675-680). 83% survival rate at 20 years
- UK National Joint Registry (NJR) 2011 - 97% survival rate at 7 years (cemented hips)

THR failure due to osteolysis

- UHMWPE wear particles
- Volume: > 550mm^3 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

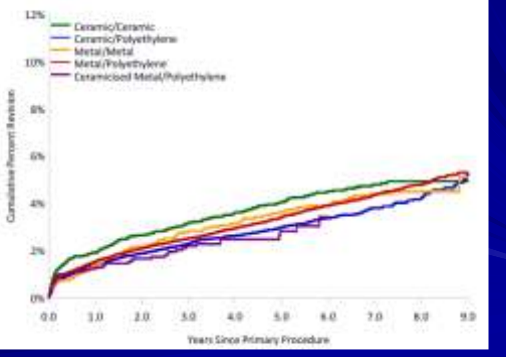


- Cross-linked polyethylene (XLPE)
- Clinical and in vitro trials suggest 50-80% reduction in wear
- 'Familiarity' for orthopaedic surgeons
- Polyethylenes are more 'forgiving' to malposition

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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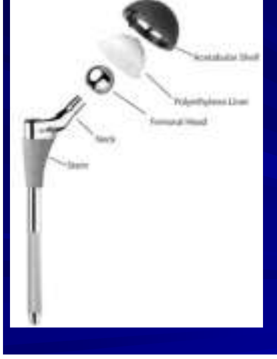

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