Biomechanics & Biomaterials for the FRCS (Tr & Orth)

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A Few Rules...

• Langdown’s laws of teaching:
  – No taking notes – LISTEN!
  – Teaching is interactive
    • You retain the right to ask questions
    • I retain the right to be unable to answer
  – If you don’t understand, ASK
  – Knowledge of the basics will help you understand the rest
Topics to cover

• Biomechanics
  – Definitions
  – Laws
  – Forces
  – Moments
  – Equilibrium
  – Stress & strain
  – Geometric properties
Topics to cover

• Biomaterials
  – Mechanical properties
  – Material properties
    • Stress-strain curves
    • Fatigue
    • Viscoelasticity
    • Creep & stress-relaxation
  – Corrosion
Definitions

• Biomechanics:
  – The science of the effects of forces and energy on biologic systems

• Statics:
  – The description of the action of forces on objects at rest

• Kinematics
  – The description of motion of objects
    • Internal (joint motion) or external (gait & locomotion)
Newton’s Laws

• First law:
  – Objects at rest remain at rest until acted on by an outside force
  – Allows **STATIC** analysis

• Second Law
  – Acceleration of an object is proportional to the force applied to it
  – \( F = ma \)
  – Allows **DYNAMIC** analysis

• Third Law
  – For every action there is an equal and opposite reaction
  – Allows **FREE BODY ANALYSIS**
Forces

- Forces are vectors, having magnitude and direction
  - Can be resolved as per any other vector into normal and shear components
  - Normal = perpendicular to a given plane
  - Shear = parallel to a given plane
Moments

- The action of a force that tends to rotate an object about an axis
- Are vectors
  - Magnitude = force \times \text{perpendicular distance from axis of rotation}
Equilibrium

• Consider an object or structure….
  – If sum of all forces acting at a point = 0
  – And sum of all moments at same point = 0
• Then…
  – Linear acceleration = 0
  – Angular acceleration = 0
• The object is thus at Equilibrium
What is the magnitude of the force in the elbow flexors, B, and what is joint reaction force, J?

Assume equilibrium:

\[ B \times 0.05 + 20 \times 0.15 = 0 \]

\[ B = \frac{3}{0.05} = 60 \text{N} \]

And

\[ \text{Sum of forces} = 0 \]

\[ J + B - 20 = 0 \]

\[ J = -40 \text{N} \]
Equilibrium example 2: Hip

Assume A = 5cm, B = 12.5cm
C of G just anterior to S2
Single leg stance

\[ \sum MW = 0 \]
\[-5My + 12.5W = 0 \]
\[ My = 2.5W \]

\[ \sum F_y = 0 \]
\[-My - W + Ry = 0 \]
\[ Ry = 3.5W \]
\[ R = \frac{Ry}{\cos 30} \]
\[ R = 4W \text{ (approx)} \]
Equilibrium example 2: Hip contd

If we put a walking stick in the LEFT hand generating a force equal to 25% of W at 40cm away.....

\[ \Sigma M_{WC} = 0 \]
\[ -5My + 12.5W - 40C = 0 \]
\[ My + 2W = 2.5W \]
\[ My = 0.5W \]
\[ \text{i.e. 80\% reduction in abductor force!} \]

\[ Ry = W + My \]
\[ Ry = 1.5W \]
\[ R = \frac{1.5W}{\cos 30} \]
\[ R = 1.7W \]
\[ \text{i.e. 60\%↓ in R!} \]
Equilibrium 2: Hip

Practical applications:

- Shifting body weight over hip (reduces moment of W)
- Medialisation of acetabulum
- Lateralisiation of femur
- High offset femoral component
- Varus neck

• All reduce joint reaction force
Equilibrium 2: Hip

But:

– Varus neck increases shear
– PMMA resists shear poorly

And:

– Valgus neck increases R but reduces shear

So how do we solve the problem of implant longevity in THR?
Elasticity: Stress & Strain

• 3 assumptions;
  – Stress & strain are proportional to each other
  – Strain is reversible when stress is removed
  – Material is insensitive to rate of load application

Stress = Elastic modulus x strain
Definitions

• Stress:
  – Internal reaction to an externally applied force distributed over cross section of the material
  \[
  \text{Stress} = \frac{\text{Force}}{\text{area}} \text{ (N/m}^2\text{)}
  \]

• Strain:
  – Internal deformations of material in response to an applied stress
  \[
  \text{Strain} = \frac{\text{change in dimension}}{\text{original dimension}} \text{ (\%)}
  \]
Geometric properties of objects

- Moment of inertia (I)
  - Important in describing resistance to bending
  - \( I = \frac{1}{12}wd^3 \)
  - Cross sectional area is important
  - \( \uparrow \) thickness \( \uparrow \) bending resistance by factor of 8
Geometric properties of objects

- Polar moment of inertia (J)
  - Important in describing resistance to torsion
  - \[ J = \frac{1}{2} \pi r^4 \]
  - i.e. doubling radius \( r \) by factor of 16
Biomaterials

• A term used to refer to synthetic materials used to augment or replace body tissues & functions
• Most important biomaterials are body’s own
Mechanical properties

• Hooke’s Law:
  – Stress is proportional to strain
    • In a given particular direction
    • Assumes no deformation
    • Experimental extrapolation to real life is of limited accuracy
Stress-strain curve

- **Stress**
- **Strain**

- **Elastic zone**
- **Yield point**
- **Ultimate strength**
- **Breaking point**
Definitions

• Elastic/Young’s modulus
  – Slope of linear part of curve
• Yield point
  – Elastic to plastic deformation point (0.2% strain for most metals)
• Ductility
  – Measure of plastic deformability
• Toughness
  – Amount of energy absorbed before failure
    – = area under curve
• Brittle
  – A substance with little or no plastic deformability
# Relative Modulus of Elasticity

<table>
<thead>
<tr>
<th>Material</th>
<th>M of E/GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancellous Bone</td>
<td>0.5-1</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>1</td>
</tr>
<tr>
<td>PMMA Cement</td>
<td>2</td>
</tr>
<tr>
<td>Cortical Bone</td>
<td>15-20</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>100</td>
</tr>
<tr>
<td>316 Stainless Steel</td>
<td>200</td>
</tr>
<tr>
<td>Co-Cr</td>
<td>220</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>220</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>300</td>
</tr>
</tbody>
</table>
Fatigue

• The property of a material that causes it to fail at a relatively low load applied many times
  – Endurance limit is the theoretic upper limit of stress below which a material will not fatigue
  – Can be described by the S-N curve
  – Enhanced by corrosion
S-N curve

Stress

No of cycles

Endurance limit
Viscoelasticity

• Material’s property varies according to rate of loading
  – Loading & unloading curves not identical
  – Not all of energy applied is recovered
  – Loss of strain energy (heat) is HYSTERESIS
Creep & Stress Relaxation

- **Creep:**
  - Progressive deformation over time when exposed to a constant load

- **Stress-relaxation:**
  - Time-dependent reduction in stress when constant load applied

Describe similar characteristic: a material that exhibits one will usually exhibit the other

E.g. bone, poly, skin, IV disc, wood
Corrosion

• Gradual degradation of a material by electrochemical attack
  – All metals corrode
  – Polymers undergo chemical degradation
  – Ceramics are inert
  – Passivation:
    • The spontaneous formation of a corrosion resistant surface layer
    • Titanium & some stainless steels
    • Implants manufactured with passivation layer by acid treatment
Types of Corrosion

• Uniform
  – Continuous: not suitable for implant

• Galvanic
  – 2 electrochemically dissimilar metals
    • i.e. do not mix (esp CoCr & SS; Ti & SS)

• Crevice
  – Local concentration of M+ and Cl- ions in crevices enhances corrosion

• Pitting
  – Similar to crevice. E.g. in break of passivation layer

• Intergranular
  – Corrosion within the metal as a result of local galvanic cell between metal grains. Reduced by lowering carbon content in SS

• Stress Corrosion Cracking
  – Cracking in a corrosive environment. Cracks accelerate corrosion: cyclic loading may interfere with re-formation of passivation layer