Musculoskeletal Biomechanics

Greg Wohl Ph.D., P.Eng.
Department of Mechanical Engineering
McMaster School of Biomedical Engineering

Suggested Reading
[including McMaster Health Sciences Library call numbers]


I. Joint Mechanics

- Mechanical “advantage” (levers, moments)
- Joint structures and dynamics
- Determination of joint loading
- Example of novel measurement techniques

Musculoskeletal Biomechanics

I. Joint Mechanics

II. Material Properties and Behaviours

- stress, strain, elastic modulus
- wear and fatigue
- directional properties (anisotropy)
- viscoelasticity

III. Examples of Bone Adaptation in Aging and Repair

- Aging – bone geometry and structural properties
- Repair – the effect of implant modulus on bone adaptation

Mechanical Advantage

Levers — Moments (Torque)

Diarthrodial Joint Moments

Muscle – Joint Loads
Limbs and Diarthrodial Joints

A compromise

Joint loads > body weight

Kinematic Advantage

Mechanical Disadvantage

Example: Hip Joint Forces

JRF = 500 N + 1500 N
JRF = 2000 N

Joint Structures and Dynamics

• Kinematics constrained by:
  • bone geometry, ligaments, tendon/muscles

• Load transfer:
  • Compressive:
    – cartilage, meniscus, bone
  • Tensile:
    – ligament, tendon/muscle

Example: Hip Joint Forces

JRF = 500 N + 1500 N
JRF = 2000 N

JRF = 500 N + 1000 N
JRF = 1500 N

Knee Kinematics

cruciate ligaments

Cruciate 4-Bar Linkage

femur

anterior

posterior

tibia

C

D

A

B

C

D

A

B

JRF = ?

JRF = ?

Single-link stance with tibia

Single-link stance
Knee Kinematics

Cartilage and Meniscus

Divergence of femoral condyles

Joint Structures

- Kinematics constrained by:
  - bone geometry, ligaments, tendon/muscles

- Load transfer:
  - Compressive:
    - cartilage, meniscus, bone
  - Tensile:
    - ligament, tendon/muscle

Determination of Joint Loading

- Significant number of variables
- Timing of load application
e.g. muscle activation
- Indeterminate system
  (too many unknowns)
- Difficulties measuring tissue loads in situ or in vivo

Knee Walking Curves

Ethier and Simmons
Why is it important to measure / determine joint loads?

- Natural loading environment of joint tissues.
- Effect of altered mechanics, injury or disease on joint loading.
- Predict need for repair / replacement
- Understand effect of repair / replacement
- Engineer suitable implants or biological alternatives.
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II. Material Properties & Behaviour

1. Material properties (e.g., stress, strain)
2. Wear and Fatigue
3. Directional properties (anisotropy)
4. Viscoelasticity

1) Material Properties
Mechanical Tests: Tensile Test — Bone

2) Material Properties
Load and Deformation are Structural Properties
- they depend on both geometric and material properties
2) Material Properties

Stress \( (\sigma) \) – Normalization of Load

\[ \sigma = \frac{F}{A} \]

MPa = N / mm\(^2\)

Strain \( (\varepsilon) \) – Normalization of Deformation

\[ \varepsilon = \frac{\Delta L}{L} \]

\( \varepsilon = \text{mm} / \text{mm} \) (dimensionless)

Material Properties

Stress–Strain Curve

Independent of the size of the sample

LOAD

DEFORMATION

A

B

C

ULTIMATE

STRESS

YIELD

STRESS

Elastic Modulus ("Young’s" Modulus) (normalized stiffness)

\[ E = \frac{\Delta \sigma}{\Delta \varepsilon} \]

MPa = [MPa] / [mm/mm]

Material Properties – Examples

Examples of Geometric and Material Changes (Bone)

Osteoporosis – loss of bone mass (geometric)

Also altered material properties?

Representative stress-strain curves of common materials

\[ E \text{ [GPa]} \]

- cobalt chromium 210
- titanium 110
- stainless steel 190
- bone 17

* values from Wright and Maher, in Einhorn et al. 2007

Charles Turner
www.engr.iupui.edu
II. Material Properties & Behaviour

1. Material properties (e.g., stress, strain)

2. Wear and Fatigue

3. Directional properties (anisotropy)

4. Viscoelasticity

2) Wear and Fatigue

Failure Mechanisms

- Wear Failure
  - A structure loaded repetitively in shear will sustain cumulative damage resulting in attrition and loss of the surface.

- Fatigue (Cyclic) Failure
  - A structure loaded repetitively below its monotonic failure force, will accumulate microscopic damage leading to crack formation, loss of strength and eventual fracture

2) Wear and Fatigue

In bone, cracks are repaired by osteonal remodeling

2) Wear and Fatigue

In implants, fatigue and wear are the most common failure mechanisms

E.g., UHMWPE implant wear rapidly compared to metal-on-metal (MoM) implants

2) Wear and Fatigue

In implants, fatigue and wear are the most common failure mechanisms

E.g., UHMWPE implant wear rapidly compared to metal-on-metal (MoM) implants
2) **Directional Properties**

**Poisson’s Effect** — lateral deflection due to axial load

E.g., elastic band

E.g., balloon

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2) **Poisson’s Effect**

— Loading of the Intervertebral Disc

- Nucleus pulposus is always under compression and carries the majority of compressive load
- Annulus fibrosus carries load through hoop stress

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3) **Directional Properties**

- **Isotropic:**
  Material properties are the same regardless of direction (do not depend on direction of load)
  - e.g., metals, glass, plastics
- **Anisotropic:**
  Material properties depend on loading direction
  - e.g., wood, bone, ligament, meniscus, cartilage
  - anisotropy governed by microstructure (e.g., fibril structures, lamellar growth)

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3) **Directional Properties**

**Anisotropic Behaviour**

Tensile loading — cortical bone

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3) **Directional Properties**

**Anisotropy of Cortical Bone**

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II. **Material Properties & Behaviour**

1. Material properties (e.g., stress, strain)
2. Wear and Fatigue
3. Directional properties (anisotropy)
4. Viscoelasticity
4) Viscoelasticity

- Mechanical properties sensitive to:
  - strain rate
  - load duration

- Time dependent behaviours:
  - creep
  - stress-relaxation

4) Viscoelasticity

- Strain rate dependence — (e.g., cortical bone)

4) Viscoelasticity

- Creep, stress relaxation — (e.g., cartilage, ligaments, tendons)

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Effect of Bone Geometry on Bone Mechanics in Aging

- Exercise, Aging and Bone Mass

- Adapted from Modlesky and Lewis 2002
Effect of Bone Geometry on Bone Mechanics in Aging

Seeman, NEJM 2003

Effect of Geometry and Structural Properties

Bending:

\[ \sigma = \frac{M y}{I} \]

- \( y \) = distance from n.a.
- \( I \) = moment of inertia
- \( c \) = max radius of section

\[ \sigma_{\text{max}} = \frac{4 M c}{\pi I c^4} \]

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\[ I = \pi c^4 \]

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\( \sigma_{\text{max}} = \frac{4 M c}{\pi I c^4} \)

Effect of Geometry and Structural Properties

Moment of Inertia (second moment of area):

- a measure of the distribution of material in a section

\[ A_1 = \pi c_1^2 \]

\[ I_1 = \frac{\pi c_1^4}{4} \]

\[ A_2 = \pi (c_2^2 - c_1^2) \]

\[ I_2 = \frac{\pi (c_2^4 - c_1^4)}{4} \]

\[ I = \sum d^2 \Delta A \]

Bone distribution (hollow tubes)

optimization of Strength:Weight ratio

better load resistance

Effect of Geometry and Structural Properties

Peak bone strains are similar across species (and bone sizes) for various physiological activities

- 1982 – Rubin and Lanyon

<table>
<thead>
<tr>
<th>Animal</th>
<th>Activity</th>
<th>Peak strain [µε]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horse radius</td>
<td>Trotting</td>
<td>-2800 (-0.28% ε)</td>
</tr>
<tr>
<td>Dog radius</td>
<td>Trotting</td>
<td>-2400</td>
</tr>
<tr>
<td>Goose humerus</td>
<td>Flying</td>
<td>-2800</td>
</tr>
<tr>
<td>Sheep femur</td>
<td>Trotting</td>
<td>-2200</td>
</tr>
<tr>
<td>Pig radius</td>
<td>Trotting</td>
<td>-2400</td>
</tr>
<tr>
<td>Fish hypural</td>
<td>Swimming</td>
<td>-3000</td>
</tr>
<tr>
<td>Monkey mandible</td>
<td>Biting</td>
<td>-2200</td>
</tr>
</tbody>
</table>

from Martin et al., 1998
1) Material Properties - Examples

At a given stress ($\sigma$), a material with a greater modulus of elasticity ($E$) will experience less strain ($\varepsilon$).

Stress [MPa] | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_3$
---|---|---|---
$E_1$ | $E_2$ | $E_3$
Strain [mm/mm]

1) Material Properties - Examples

Selected Material Properties - tensile tests

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (GPa)</th>
<th>$\sigma_u$ (MPa)</th>
<th>$\sigma_y$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>190</td>
<td>930</td>
<td>790</td>
</tr>
<tr>
<td>Cobalt Chromium</td>
<td>210</td>
<td>1896</td>
<td>1606</td>
</tr>
<tr>
<td>Titanium</td>
<td>110</td>
<td>965</td>
<td>896</td>
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<tr>
<td>PMMA</td>
<td>2.1</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cortical Bone</td>
<td>17.0</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Trabecular Bone</td>
<td>0.1</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

2) Material Properties - Examples

Stress Shielding Examples

Nordin 2001

QUESTIONS?