Bone Biomechanics—overview

1. Review of some anatomical concepts that relate to mechanics
2. Some mechanical concepts that relate to anatomy
   - Strength and stiffness
   - Load/deformation and stress/strain
   - Anisotropy and viscoelasticity
3. Discuss some mechanical factors that relate to altered bone mineral.

Primary Mechanical Functions of the Skeletal System

1. Leverage and attachment sites for muscle
2. Support
3. Protection

Skeletal System: Mechanical Functions

Leverage: provides levers (simple machines that magnify force or speed of movement) and axes of rotation about which the muscles generates movement

Within this context, your long bones are the levers and your joints are the axes

Skeletal System: Mechanical Functions

Support: provides a support structure to which the muscular system attaches; facilitates upright posture and movement

Protection: provides protection for numerous internal vital organs

Bone Tissue

Bone function dictate bone makeup
Bone has to be very strong and stiff
Bone is one of the body’s hardest structures
What makes bone so hard?

Bone Tissue

Mineral: ~50% of bone weight; provides stiffness and compressive strength (primarily calcium compounds)
Collagen: ~25% of bone weight; provides tensile strength and stiffness
Water: ~25% of bone weight; provides compressive strength and helps maintains bone health
Ground Substance: ~1% of bone weight; provides some elastic capabilities
Bone Architecture

Two architectures (classified by porosity) also relate to function:

1. Cortical (compact) bone is 5-30% porous
2. Cancellous (trabecular or spongy) bone is 30-90% porous

Bone strength and stiffness are influenced by bone architecture

Bone Cells

Osteocyte: a bone cell

Osteoblasts: specialized bone cells that form new bone tissue

Osteoclasts: specialized bone cells that resorb existing bone tissue

Under normal circumstances, activity of these cells is balanced

Mechanical Properties of Biological Tissue

Mechanical properties of biological tissue can be described using strength and stiffness:

- These two properties are shown graphically in this load × deformation curve:
  - Strength is related to the load, while stiffness (k) is the slope of the load × deformation curve.

The elastic region of the curve is between points A and B. With initial loading, bone can change shape (up to ~3% deformation). When deformation is < 3%, bone is more likely to return to its original shape after the load is removed (elastic deformation).

The plastic region of the curve is between points B and C. If loading continues beyond the yield point, plastic deformation is likely to occur. The transition from the elastic to the plastic region is called the yield point.

Joint stiffness
The stress × strain curve

**Stress (σ):** Internal force (N), normalized by cross sectional area (m²); units are Pascals

**Strain (ε):** \( (\ell - \ell_o)/\ell_o \); \( \ell \) = new length; \( \ell_o \) = original length; strain is dimensionless

Young's Modulus (E) describes the intrinsic stiffness of a tissue; it equals the slope of the stress × strain curve.

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

**Principal Mechanical Stresses (σ)**

How might your bones be stressed in these ways?
Bones respond differently to different stress
What stress do you think your bone most effectively bears?

Resistance to Stress
Bone bears compressive stress most effectively and shear stress least effectively.

How do you suppose we know this?

![Graph showing stress to failure for compression, tension, and shear](image)

**Mechanical Testing Device**

Note the various measures of strength

**Sample Problem**
A bone sample is subjected to a stress of 80 KN. The cross sectional area is 1 cm² (0.0001 m²) and Young's Modulus is 70 GPa. What strain might be expected as a result of this stress?

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

**Solution**

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\begin{align*}
F &= 80,000 \text{ N} \\
A &= 1 \text{cm}^2 = 0.0001 \text{m}^2 \\
E &= 70 \text{ GPa} \\
E &= \frac{\sigma}{\varepsilon} \\
70 \text{ GPa} &= \frac{80,000 \text{ N}}{\varepsilon} \\
\varepsilon &= \frac{800 \text{ MPa}}{70 \text{ GPa}} = 0.0114, \text{ or } 1.14\%
\end{align*}
\]
Two Additional Unique Mechanical Characteristics of Bone

**Anisotropic**: bone responds differently depending on the direction of applied load. Stress × strain curves differ, depending on load direction.

**Viscoelastic**: bone responds differently depending on rate of load application. Stress × strain curves differ, depending on rate of load application.

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Anisotropic Behavior of Bone

**Anisotropic behavior of cortical bone from a human femoral shaft**

(Frankel & Burstein, 1970)

<table>
<thead>
<tr>
<th>Loading Mode</th>
<th>Ultimate Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Tension</td>
<td>138 MPa</td>
</tr>
<tr>
<td>Compressive Stress</td>
<td>192 MPa</td>
</tr>
<tr>
<td>Shear</td>
<td>65 MPa</td>
</tr>
</tbody>
</table>

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Viscoelastic Behavior of Bone

Three stress × strain curves for cortical bone (tension) at three different loading rates

As loading rate increases, the modulus of elasticity and strength increases

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Wolff’s Law (1892)

*Bone elements place or displace themselves in the direction of functional forces, and increase or decrease their mass to reflect the magnitude of those functional forces...*  

In other words, bone adapts to increased use (physical activity) or disuse (bed rest)

Mechanical properties of bone (strength and stiffness) that depend upon form (size, shape) can be altered in response to load

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Increased Bone Mineral Content

**Osteoblast Activity > Osteoclast Activity**

Degree of increase in bone density directly proportional to the magnitude of force application

Bones with increased density are stronger and more resistant to fractures

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Increased Bone Mineral Content

External loads, especially high-magnitude loads, increase bone density:

- Weight bearing loads...
- Obesity...
- Certain athletes: tennis

A tibia that was a fibula (Adrian and Cooper, 1989)

A construction worker (Ross, 1997)
**Decreased Bone Mineral Content**

**Osteoclast Activity > Osteoblast Activity**

Reduced loading on bone can lead to substantial demineralization: 17 weeks of bedrest has been shown to lead to 10.5% reduction in bone density.

Bone that is less dense is not as strong or resistant to fracture.

**Decreased Bone Mineral Content**

Space related bone loss:

Amount of bone loss is proportional to time spent away from gravitational field (~1% per month)

Countermeasures are now being developed to delay rate of bone loss.

**Decreased Bone Mineral Content**

Age related bone loss:

- **Osteopenia** – reduced bone mineral density (1.0 - 2.5 SD), predisposing individual to fractures
- **Osteoporosis** – disorder involving decreased bone mass (+2.5 SD) and strength commonly resulting in fracture

Vertebral compression fractures most common, followed by femoral neck and wrist fractures.

**Osteopenia & Osteoporosis**

Bone mineral density peaks in late adolescence and starts to decrease as early as the 20’s; trabecular bone is affected most.

Women most severely affected:

- Lose 0.5 to 1.0% of bone mass each year until age 50
- Lose as much as 6.5% of bone mass per year after age 50

**Bone Fractures**

The most common injury to bone

Derived from the Latin *fractura*, meaning to break

A disruption in the structural continuity of bony tissue

Occurs when an applied load exceeds the bone's ability to withstand the force.
Fracture Types

- **Spiral or Oblique**: bending or torsional loads fracture bone at oblique angle to long axis
- **Avulsion**: a tendon or ligament pulls the bone away (e.g., tensile loading during explosive jumping or throwing)
- **Greenstick**: incomplete fracture common in children due to larger proportion of collagen; bending loads

- **Comminuted**: fragmented into many pieces (most common during increased loading rates and force magnitudes)
- **Simple**: One break, bone remains within the skin
- **Compound**: One break, bone protrudes through the skin

Stress Fractures

*Stress Fractures*: repetitive low-level loading, with inadequate time for bone remodeling

Common sites: tibia, metatarsals, femoral neck, pubic bone

Often due to abrupt changes in training duration or intensity, or a lack of proper nutrition