Bone Biomechanics
1. A review of some anatomical concepts that relate to mechanics
2. Some mechanical concepts
   – Anisotropy and viscoelasticity
3. What causes and prevents increased bone mineral content & corresponding fractures?

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, long bones are levers and joints are axes

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

矿物: 约50%的骨重量, 提供刚性和压缩强度（主要为钙化合物）
胶原: 约25%的骨重量, 提供拉伸强度和刚性
水: 约25%的骨重量, 提供压缩强度并有助于维持骨健康
骨基质: 约1%的骨重量, 增加弹性能力
**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 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

**Two 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.

**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</td>
<td>133 MPa</td>
</tr>
<tr>
<td>Tension</td>
<td>193 MPa</td>
</tr>
<tr>
<td>Compression</td>
<td>68 MPa</td>
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<tr>
<td>Shear</td>
<td></td>
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</tbody>
</table>

**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

**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
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

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 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

Decreased loading results in decreases in bone mineral density

- Physical activity levels...
- Certain athletes: swimmers, cyclists...

Anything else?

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
- Osteoperosis – 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

Fracture Types

- **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