Bone: Composition, Structure, Mechanical Properties, and Healing

Michael T. Gross, PT, PhD, FAPTA
Division of Physical Therapy
University of North Carolina at Chapel Hill

Properties of Bone
Bone Formation/Healing

Endochondral Ossification

- Mechanism of bone formation and healing for bone with reduced vascularity
- Formation of cartilaginous model
- Cartilage (callus) then becomes ossified as calcium salts are deposited within material
- Occurs more slowly than direct bone formation method
Properties of Bone
Bone Formation/Healing

**Endochondral Ossification**

- Primary ossification center of diaphysis
- Epiphyseal plate - adds bone to metaphysis for long bone increases in length
- Articular cartilage - increase in size of epiphysis and growth of bones that do not have epiphyses
- Cortical bone healing with immature callus
Properties of Bone
Bone Formation/Healing

**Intramembranous Ossification**

- Direct formation of bone without an intervening cartilaginous model
- Occurs beneath the periosteum of the diaphysis of long bones and periosteum of short bones
- Healing method for more vascular bone (i.e., cancellous bone)

- Healing occurs more quickly than with endochondral ossification
- See intramembranous ossification early on in bones that are needed for protection of soft tissues (e.g., cranium)
Properties of Bone
Factors Affecting Bone Strength & Healing

- Ca++ in diet and Vitamin D
- Dark sodas (Tucker et al, 2006)
- Caffeine greater than 300 mg leads to greater rate of bone loss in spine in post-menopause women (Rapuri et al, 2001). One 6 oz cup of coffee has 103 mg of caffeine. Increased risk of hip fracture in women (Cummings et al, 1995).

More on Caffeine

- Risk for fractures increases for women as consumption increases. Reverse is true for men. Meta-analysis of 15 studies that included 253,514 participants. (Lee et al, 2014)
- Negative effect on bone healing in rats (Bastos, 2014), stiffness of bone in pregnant rats (Olchowick, 2011), and ↓ BMD in a study of 61,433 Swedish women (Hallstrom, 2013)
Still More on Caffeine
Mechanisms of Action

• Caffeine may reduce BMD through enhancement of osteoclastogenesis. That is, the osteoclasts do more bone removal business. (Liu et al, 2011)
• Caffeine has negative impact on osteoblast cell viability (Zhou, 2010 and Lu, 2008). Therefore, less bone deposition business.
• Truly- A Double Whammy!

Some Good News

• Ladies- Beer, Wine, or Water?
• A study of 1697 ladies and their preferences for beer, wine, or no alcohol (Pedrera-Zamorano JD, 2009)
• Greater bone density on the beer drinkers compared with consumers of wine or no alcohol.
• Possibly the result of the phytoestrogenic content of beer.
Properties of Bone
Factors Affecting Bone Strength & Healing

- Prednisone
- Alcohol
- Some cancer meds
- Crack cocaine
- Estrogen
- Oral/injectable contraceptives (Pitts and Emans, 2008)

Properties of Bone
Factors Affecting Bone Strength & Healing

- Female endurance athlete
- Disordered eating
- Western diet with ↑ protein tends to make the body more acidic, resulting in greater Ca++ release from bone (Jajoo et al, 2006; Wynn et al, 2010)
- Nicotine
Osteoporosis Tx Recommendations

- Appropriate intake of calcium and vitamin D
- Increase weight-bearing exercise
- Limit alcohol and caffeine
- Avoid smoking
- Non-hormonal pharmacological options:
  - Biophosphonates
  - Calcitonin (Miacalcin)
  - Raloxifene (Evista)
  - Teriparatice (Forteo)
  - Denosumab (Prolia)


Properties of Bone
Epiphyseal Plate Structure

- Four zones of transition as bone is added to the metaphysis
- Interface between the last zone and metaphyseal bone is weakest structurally
- Suspect epiphyseal plate injury if excessive tension placed on tendon or ligament that might injure epiphyseal plate (e.g., MCL sprain in skeletally immature individual).
Organizational Structure of the Epiphyseal Plate

Properties of Epiphyseal Plate

- Compressive stress is the stimulus for activity that adds bone length
- Too little or too much pressure through the epiphyseal plate attenuates growth
- Skeletal malalignment, therefore, can be a major "feed forward" patient problem
Effect of Deformity on Growth Plate Function

Excessive pressures may inhibit endochondral ossification at growth plate and produce a feed forward scenario that may worsen the deformity, thereby increasing medial growth plate pressures.

\[ \sum M = 0 \]
\[ -(\text{GRF} \cdot \text{dGRF}) + (\text{W} \cdot \text{dW}) + (\text{STF} \cdot \text{dSTF}) = 0 \]
Effect of Deformity on Growth Plate Function

Excessive pressures may inhibit endochondral ossification on the medial sides of the growth plates at the distal femur and proximal tibia and produce a feed forward scenario that may worsen the deformity, thereby increasing medial growth plate pressures.


Bone Composition

- Fiber Component- 90% of organic matrix is collagen, greatest concentration of all collagenous tissues
- Ground Substance- 
  -Glycosaminoglycans (GAGs)
  -Calcium salts and other mineral constituents (bone 45% inorganic)
  -Hyaluronic acid
- Cellular Component: osteoblasts and osteoclasts (collagen and GAGs)
Bone-General Properties

- Cortical bone: 5-30% porous and is relatively stiff with only 2% strain at failure.
- Cancellous bone: 30-70% porous with 7% strain at failure.
- Cancellous bone capable of absorbing appreciably more energy at failure because of its porous nature—implications for soft tissue injuries?

![Stress-Strain Diagram](image)

**FIG. 1—9**
Anisotropic behavior of cortical bone specimens from a human femoral shaft tested in tension (pulled) in four directions: longitudinal (L), tilted 30 degrees with respect to the neutral axis of the bone, tilted 60 degrees, and transverse (T). (Data from Frankel and Burstein, 1970.)
Adaptation of Architecture to Loading and Anisotropic Behavior that Will Result

Fig. 1-32. Alignment of collagen fibrils parallel to the pull of the patellar ligament.

General Behavior of Bone in Response to Different Stress Patterns

FIG. 1–22
Ultimate stress for human adult cortical bone specimens tested in compression, tension, and shear (average of data from Reilly and Burstein, 1975). Shaded area indicates ultimate stress for human adult cancellous bone with an apparent density of 35% tested in tension and compression (Carter, 1979).
Bone Stress Fracture Injuries

Unloading of Stress Via Truss Support

Bone Stress Fractures

Unloading of Stress Via Truss Support
Bone Stress Fractures

Truss Support Structures

- Plantar fascia
- Plantar ligaments
- Plantar intrinsic muscles
- Plantar tendons from extrinsic muscles

Unloading of Stress Via Off-the-Shelf or Custom Fitting “Bump”
Unloading Stress from Bending Loads

Dynamic Truss Support From Plantar Intrinsics and Extrinsics

Unloading Stress from Bending Loads – Role of Plantar Fascia

- Gefen (2002) – 204% increase in tensile stress within deep plantar ligaments and 65% increase in metatarsal bending with total pf release.
Cantilever Bending

Effects of Gluteus Medius on Decreasing Tensile Stress on the Femoral Neck

Sinaki and Mikkelsen (1984) – studied 59 post-menopausal women assigned to one of four groups: extension ex. (E), flexion ex. (F), combined F & E, and no (N) exercise. Additional fractures over 6 year follow-up were: E 16%, F 89%, E & F 53%, N 67%.

The abdominals are not powerful force producing muscles based on their physiological cross-sectional area. The name of the game, however, is bending moment for this injury, and the abdominals may have the largest moment arm of any muscle group as they act on the spine.

The iPosture® can be used to remind the older woman to maintain a good posture:
http://www.iposture.com/
Bone Stress Fractures
Implications for Intervention

- Unload stress via support
- Gradual progression of intensity, duration, and frequency to allow adaptation of bone and truss supporting structures
- Endurance strengthening of muscle-tendon units that might provide truss support
- Address malalignment issues that might increase bending loads (e.g., forefoot varus)

Bone Stress Fractures
Implications for Intervention

- Shock absorption/attenuate the GRF via ground surface selection, shoewear, inserts within the shoe, decreasing body weight, and avoiding hills
- Strengthen muscles to make them more effective as shock absorbers
- Redirect activities to those with lesser magnitude, duration, frequency bending loads- change movement strategies
Properties of Bone

Torsional Loading

- Imposed by moments at each end of a long bone acting in opposite directions
- Creates oblique lines of tensile and compressive stress
- Creates longitudinal lines of shear stress

Stress Patterns from Torsional Loading and Spiral Fracture that May Result

FIG. 1—28
Schematic representation of a small segment of bone loaded in torsion. Maximal shear stresses act on planes parallel and perpendicular to the neutral axis. Maximal tensile and compressive stresses act on planes diagonal to the axis.

FIG. 1—29
Experimentally produced torsional fracture of a canine femur. The short crack (arrow) parallel to the neutral axis represents shear failure; the fracture line at a 30-degree angle to the neutral axis represents the plane of maximal tensile stress.
Properties of Bone
Effects of Speed of Loading
(Strain Rate)

- Increase in ultimate strength
- Increase in stiffness
- Increase in energy release at failure - more potential for soft tissue damage

Properties of Bone
Effects of Bone Shape and Size
Bending Loads

3-Point Bending
Base
Cross-sectional Area
Perpendicular to Plane in which Bending Occurs
Properties of Bone
Effects of Bone Shape and Size
Bending Loads

Area Moment of Inertia = Resistance to Stress From
Bending Loads

AMI = \( \frac{B \cdot H^3}{12} \)

Implications for Intervention

- Splint/brace with larger dimensions of material oriented along the height in the plane of 3-point bending stress
- Modify activities to decrease bending loads
- Modify equipment to decrease bending loads (e.g., orthotics, shoewear, etc)
Properties of Bone
Effects of Bone Shape and Size
Torsional Loads

Polar Moment of Inertia
Resistance to Stress from Torsional Loading

Fig. 1-29
Distribution of shear stress in two cross sections of a tibia subjected to torsional loading. The proximal section (A) has a higher moment of inertia than does the distal section (B), because more bony material is distributed away from the neutral axis. (Adapted from Frankel and Burstone, 1978.)

Polar Moment of Inertia (J)

\[ J = \frac{\pi (r_0^4 - r_1^4)}{2} \]

Intramedullary Cavity
Polar Moment of Inertia (J)

Diaphysis

Metaphysis

Bone X-Sectional Area = 25.13
PMI (J) = 40\pi

Bone X-Sectional Area = 21.99
PMI (J) = 87.5\pi

Properties of Bone
Effects of Bone Shape and Size
Torsional Loads
Implications for Intervention

- Splint/brace with rigid material positioned farther away from the longitudinal axis (e.g., hinged braces with rigid shells control moment better than hinge and strap configurations)
- Modify activities to decrease torsional loads
- Modify equipment to decrease bending loads (e.g., orthotics, shoewear, etc)
Properties of Bone

Fracture Healing

Large Mass of Immature Callus
Increases AMI and PMI

Properties of Bone

Effect of Bone Defect

FIG. 1-43
Stress pattern in an open and closed section under torsional loading. A. In the closed section, all the shear stress resists the applied torque. B. In the open section, only the shear stress at the periphery of the bone resists the applied torque. (Adapted from Frankel and Burstein, 1970.)
Bone Defect With Hardware Removal

- Kukla C et al. Studied 37 patients who had standard gamma interlocking nails (SGN) for fixation of trochanteric femoral fractures. Three individuals sustained second fractures once they resumed full WBing following removal of hardware.
- Studied cadavers and force required for fracture following removal of SGN versus smaller dynamic hip screw. Force to fracture significantly less following removal of larger fixation device.
- Either leave larger implants in unless there is infection, or exercise caution upon removal. J Biomech. 2001;34(12):1519-26

Properties of Bone

Effect of Bone Defect

Decrease in AMI and PMI as well as Stress Concentration from Redirection of Stress Lines

FIG. 1-44: Load-deformation curves for human adult tibiae tested in vitro under torsional loading. The control curve represents a tibia with no defect; the open section curve represents a tibia with an open section defect. (Adapted from Frankel and Burstein, 1970.)
Properties of Bone
Effect of Bone Defect
Implications for Intervention

- Tendency to leave hardware in place often
- Caution if hardware is removed for any reason
  1. Structural weakness until bone fills in and adapts to gradual progress of stress imposition
  2. Need to modify intensity, duration, and frequency of loading until this occurs

Properties of Bone
Effect of Rigid Fixation

Stress Concentration at Interface between Materials with Dissimilar Mechanical Properties
Properties of Bone
Epiphyseal Plate Fractures

Shearing Injury - Closed
Reduction & Good Prognosis

Shearing & Bending - Closed
Reduction & Good Prognosis

Type I Injury

Greene KA, Ross MD. Slipped capital femoral epiphysis in a patient referred to physical therapy for knee pain. JOSPT 38((1):26
Type I Injury

Properties of Bone

Epiphyseal Plate Fractures

Rare Distal Tibia Fracture in Teenagers- One Part of Plate is Closed and the Other is Not-Closed Reduction with Good Prognosis

Figure 16.14. Type III epiphyseal plate injury. Fracture of part of the epiphysis.
Properties of Bone
Epiphyseal Plate Fractures

Occurs Commonly at Lateral Condyle of Humerus- Requires Open Reduction and Perfect Alignment of Plate so that Growth will Continue without Fracture Healing Across the Plate

Severe Crush Injury, Usually at Knee or Ankle- Difficult to Diagnose and Prognosis is Usually Poor- Treated with NWB for 3 Weeks