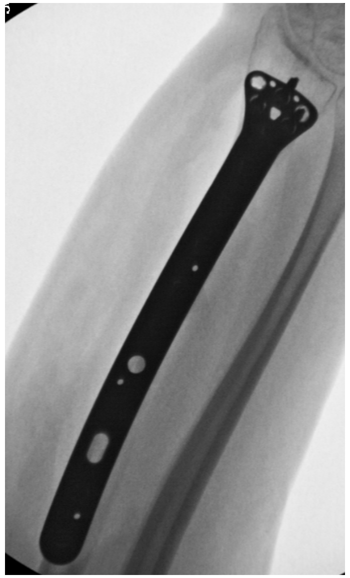
Biomechanics of Fractures and Fixation

Michael S. Kain MD
Assistant Professor
Boston University School of Medicine
Boston Medical Center

NOTE: all images are c/o Michael Kain MD unless otherwise specified

OVERVIEW

- **Basic Biomechanics**
- **Biomechanics of Fractures**
- **Bone Healing**
- **Fixation Strategies**
- **Constructs**



Introduction

- Fracture Fixation is a ***balance*** of **Biology** and **Mechanics**
- ***Race*** between **Bone Healing** and **Construct Failure**
- **Promote bone healing while considering the mechanical stability/durability of the fixation construct**
  - ***Example:*** **Cast is less stable than a LCDCP plate but does not disrupt the normal bone healing biology**
- **"Paradox of Internal Fixation"**
  - **The dichotomy of invasiveness of fixation vs normal bone healing**

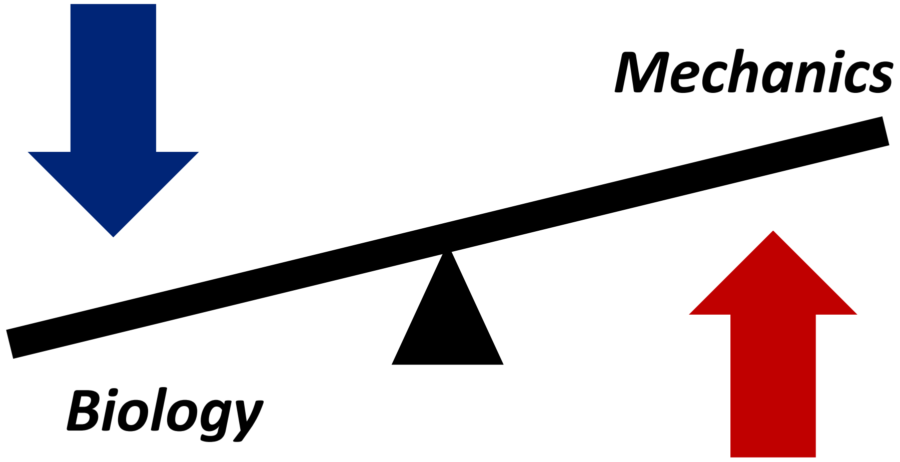
Introduction

- "Paradox of Internal Fixation"
  - The dichotomy of invasiveness of fixation vs normal bone healing

Carpentry vs Gardening

Introduction

- Balancing of principles:



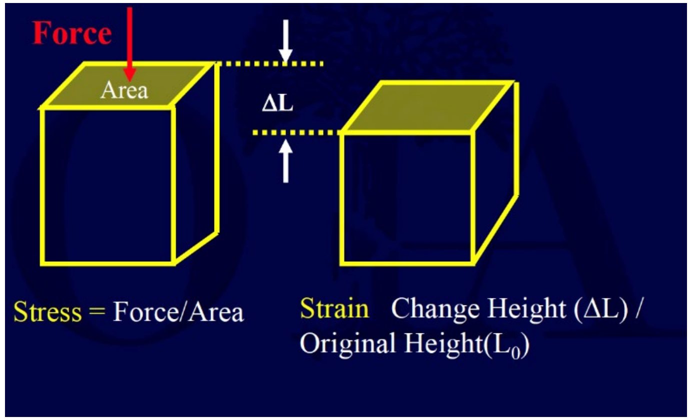
***Create enough rigidity to allow for function; yet have enough flexibility and a normal biologic environment to allow for and promote bone to return to its normal biomechanical state*.**

BASIC BIOMECHANICS

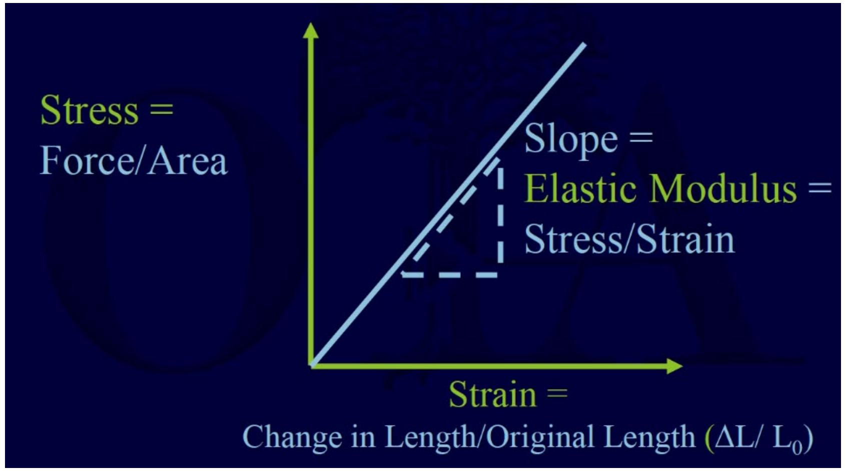
Mechanical Concepts

- **Mechanical Competence of Bone relies on**
  - **Material properties**
    - ***No consideration to geometry***
    - ***Independent of shape***
      - ***Elastic–Plastic, Yield Point, Brittle-ductile, Toughness***
  - **Structural properties**
    - **Considers geometry and material**
    - **Dependent on shape & material**
      - **Bending , Torsional, and Axial Stiffness**

MATERIAL PROPERTIES



- Stiffness regardless of specimen size
  - Stress (σ) = Force/Area
  - Strain (ε) = Change in Height (ΔL) / Original Height (L_0)
- Elasticity (Young's Modulus or E modulus)
  - E= (σ) / (ε)



- Strain expressed without units
- Stress and E modulus expressed as Gigapascals
  - Example stainless steel (E=200 GPA) 2x Titanium

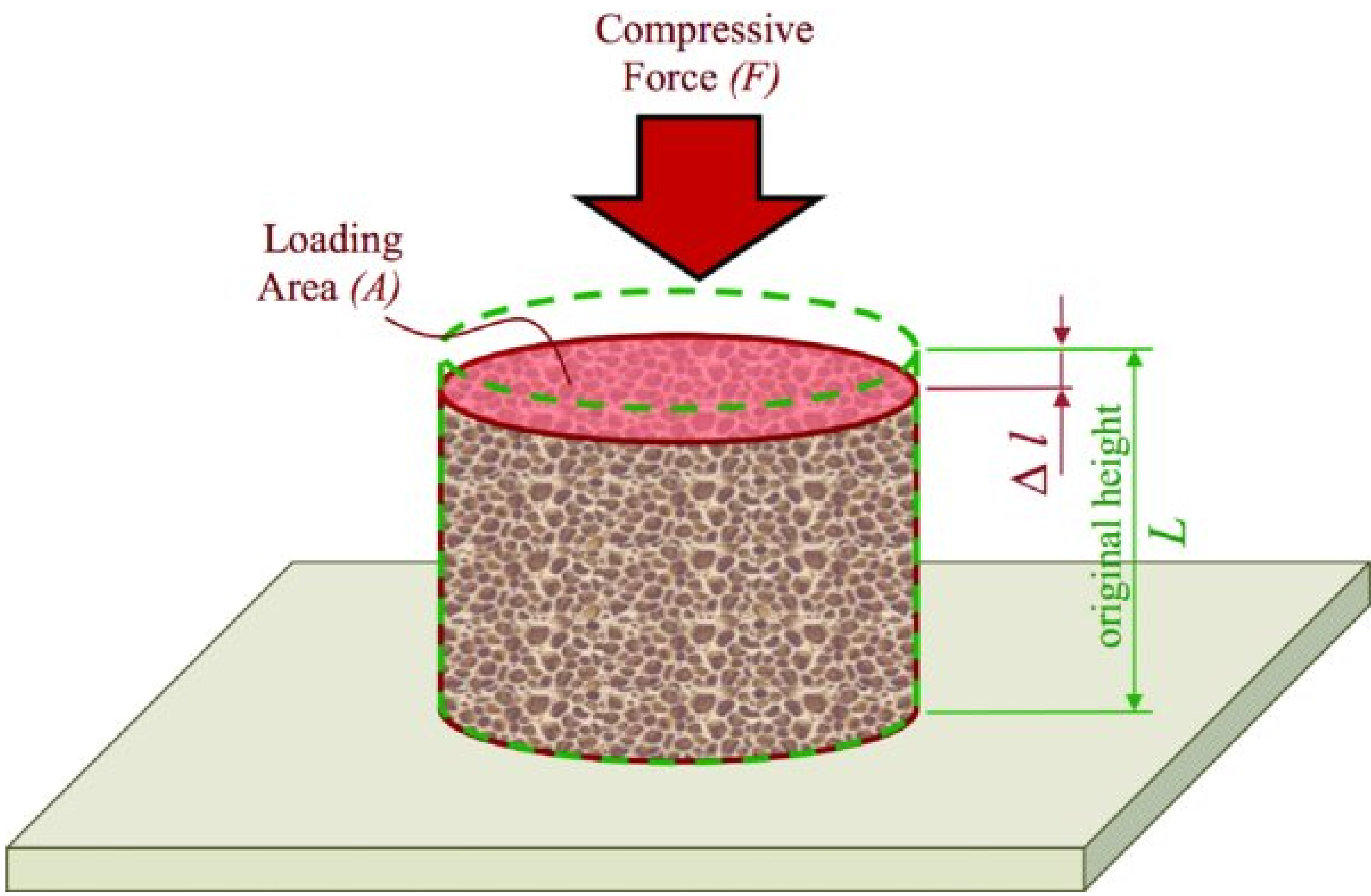
Compressive Strength

Strain (ε) =

$$\frac{\text{Change in Height } (\Delta L)}{\text{Orginal Height } (L_0)}$$

From: **1 Biomechanics of Fractures and Fracture Fixation**

Rockwood and Green's Fractures in Adults, 9e, 2019



Compression of a cylindrical specimen of trabecular bone.

Material Properties : Definitions

- **E- modulus**: defines the elasticity of the material, complete reversal of deformation is still possible

- ***Yield strength***: point where permanent elastic deformation occurs

- ***Ultimate Strength***: the point where material fractures

Material Properties : Definitions

- ***Ductile*** describes a material with lots of elasticity and the ability to deform
- ***Brittle*** describes a material with small amount of elasticity and has little ability to deform
- **Fatigue Failure** occurs from repetitive loading below ultimate strength limit and microfractures occur
- ***Fatigue Limit*** is the maximal load that will not cause a microfracture

Common Materials in Orthopaedics

- Elastic Modulus (Gpa)

Material	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Failure Strain (%)
UHMW polyethylene (arthroplasty)	0.9	25	40	5
Ligament (in tension)	1.5	60	100	15
PMMA (bone cement)	3	74	74	2
Cortical bone (in compression)	17	200	200	1
Titanium alloy	110	800	860	10
Stainless steel	200	700	820	12

Rockwood and Green table 1-1

From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

Common Materials in Orthopaedics

- Elastic Modulus (GPa)

Material	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Failure Strain (%)
UHMW polyethylene (arthroplasty)	0.9	25	40	5
Ligament (in tension)	1.5	60	100	15
PMMA (bone cement)	3	74	74	2
Cortical bone (in compression)	17	200	200	1
Titanium alloy	110	800	860	10
Stainless steel	200	700	820	12

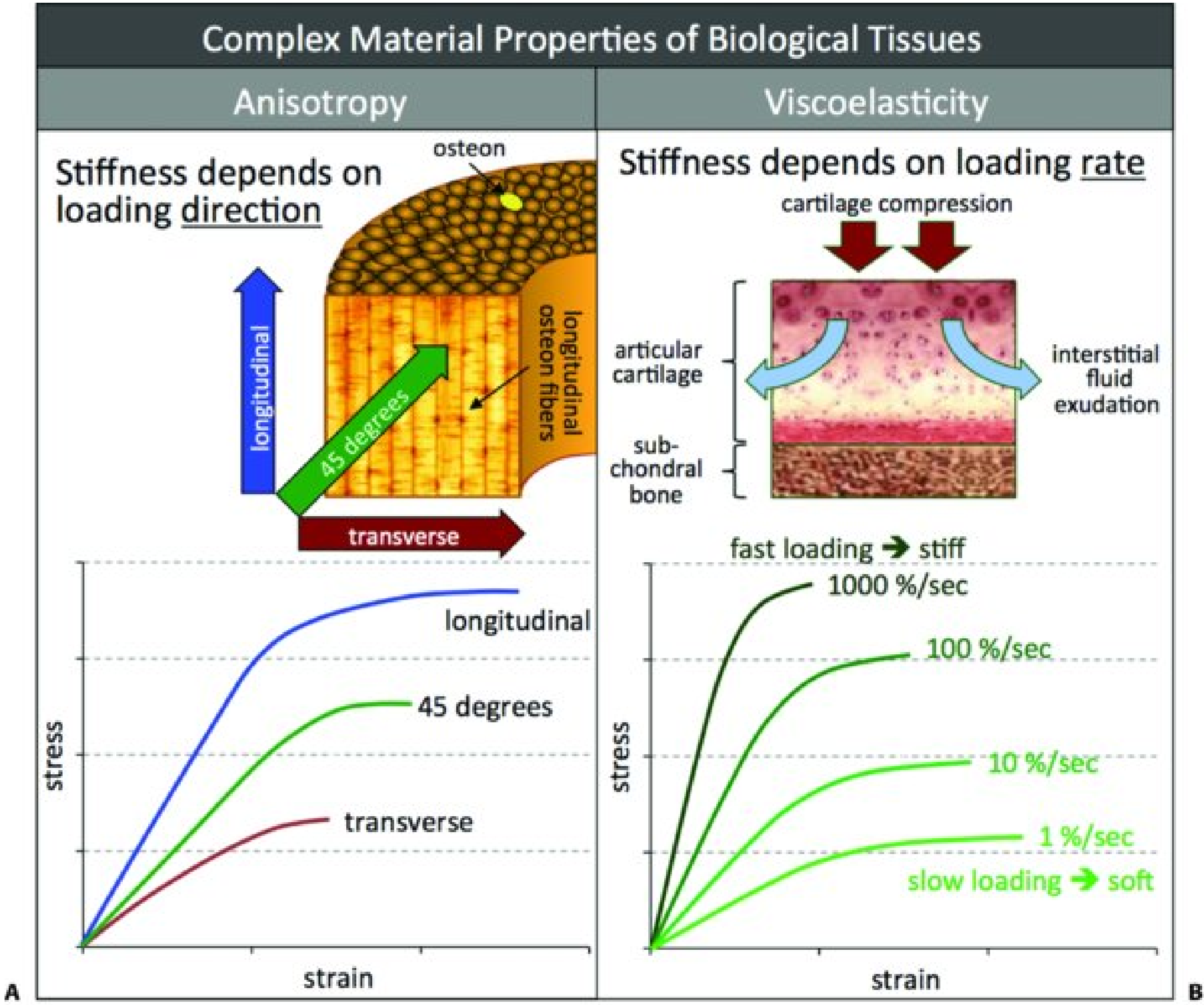
Rockwood and green table 1-1

Material Properties

- **Anisotropic**: direction-dependent mechanical properties of a material
  - Bone: a transversely anisotropic material
- **Isotropic:** no change in properties regardless of load direction
  - Stainless Steel and Titanium
- **Viscoelastic:** is time dependent deformation, and stiffness increases with faster loading
  - Gradual deformation is ***creep***

Material Properties

Anisotropy
vs
Viscoelasticity



Most biologic tissues are composed of multiple components, organized in a structurally optimized microstructure.

Figure From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

Structural Properties

- Material Properties and the shape and size of the object

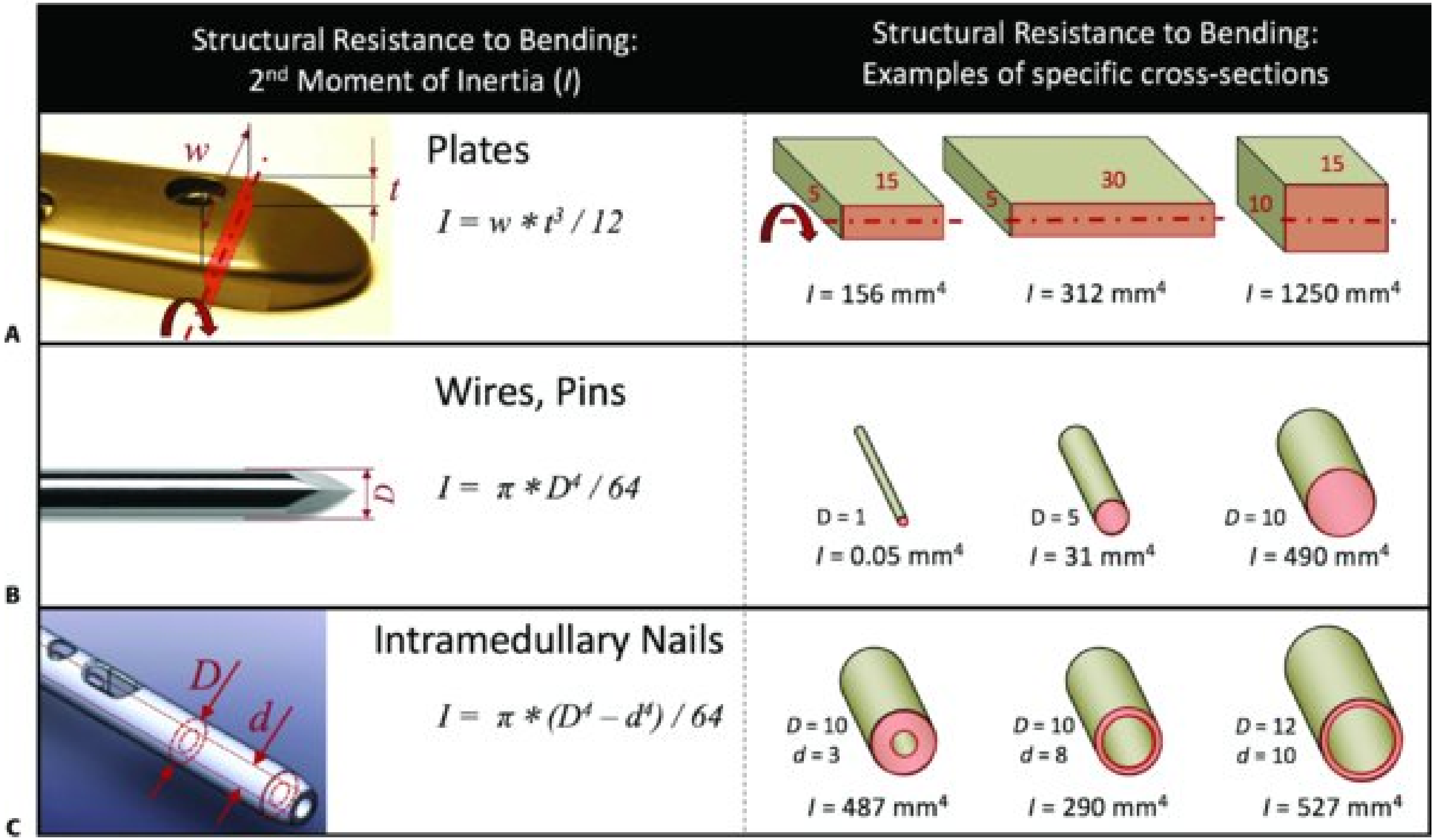
- In Fracture Management think about both size and shape of 2 objects:
    1. Bone
    2. Fixation Device

- Bending Stiffness of Plate: collinear with width but 1/3 thickness
- Bending of K-wire: increases by the 4^{th} power so doubling is 16 fold increase

Orthopaedic Implants

- **Plates:** think about width, thickness, and length
- **Wires/Pins:** diameter, solid
- **Nails:** Hollow so they are lighter but maintain strength, ideal weightbearing

Influence of cross-sectional geometry on bending stiffness for basic implant shapes.



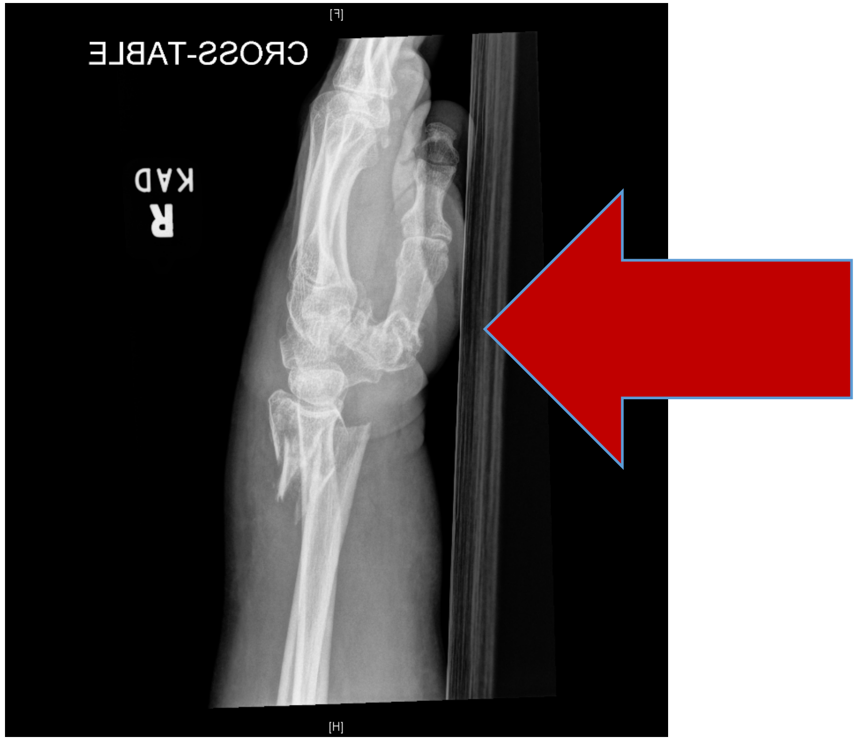
From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

Load Transfers

- **Vectors:** Force and Direction
- **Rotational Moments (M):**
    - Created by the Force (F) and distance (d)
- **Lever arms:** example of Seesaw

Load Transfers

- **Vectors:** Force and Direction



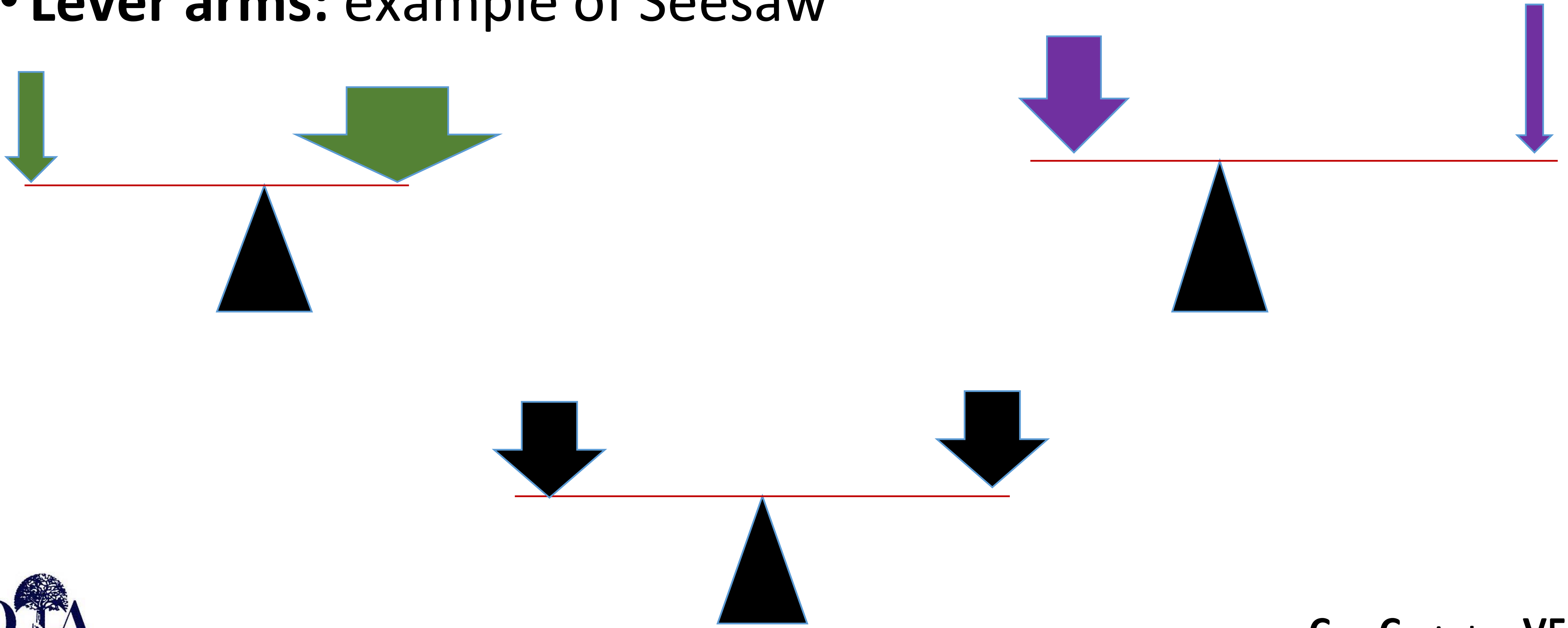
Load Transfers

- **Rotational Moments (M):**

  Created by the Force (F) and distance (d)

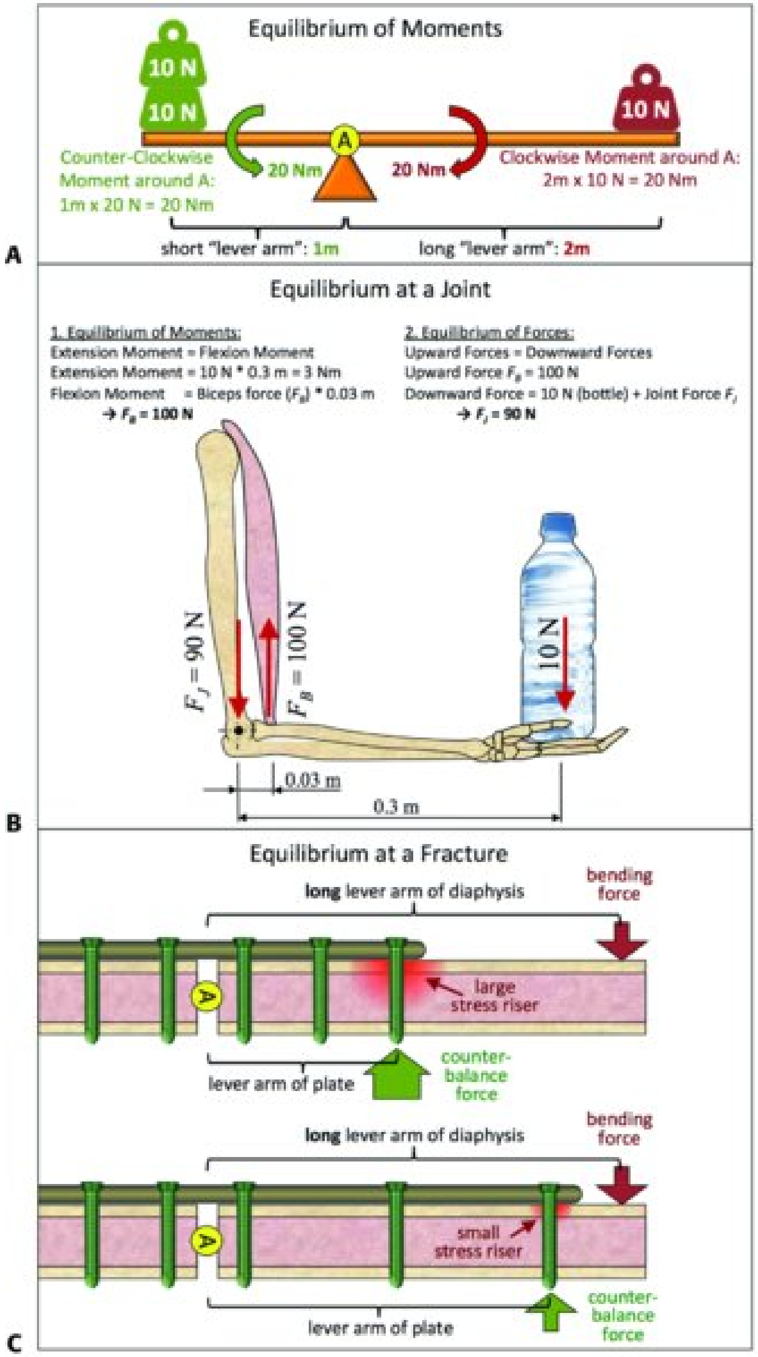
Load Transfers

- **Lever arms:** example of Seesaw



Lever Arms

- Examples of Lever Arms
  - ➢Seesaw
  - ➢Arm
  - ➢Plate length



From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

BIOMECHANICS of FRACTURES

Bone Biomechanics

- Bone is ***anisotropic*** material: direction of load matters
- Bone is **viscoelastic**: Trabecular bone becomes stiffer with compression
- Bone Properties: ***weakest in Shear***

BONE Properties

Strength **Weak**

Compression > >>>Tension >>>>Shear

Bone Biomechanics

- Diaphyseal Bone: has hollow cylinder properties

- Density of Bone
- Cortical = Trabecular Bone
  - Cortical Bone is less porous
  - Trabecular Bone is more porous
  - Porosity affects the stiffness and strength of trabecular bone

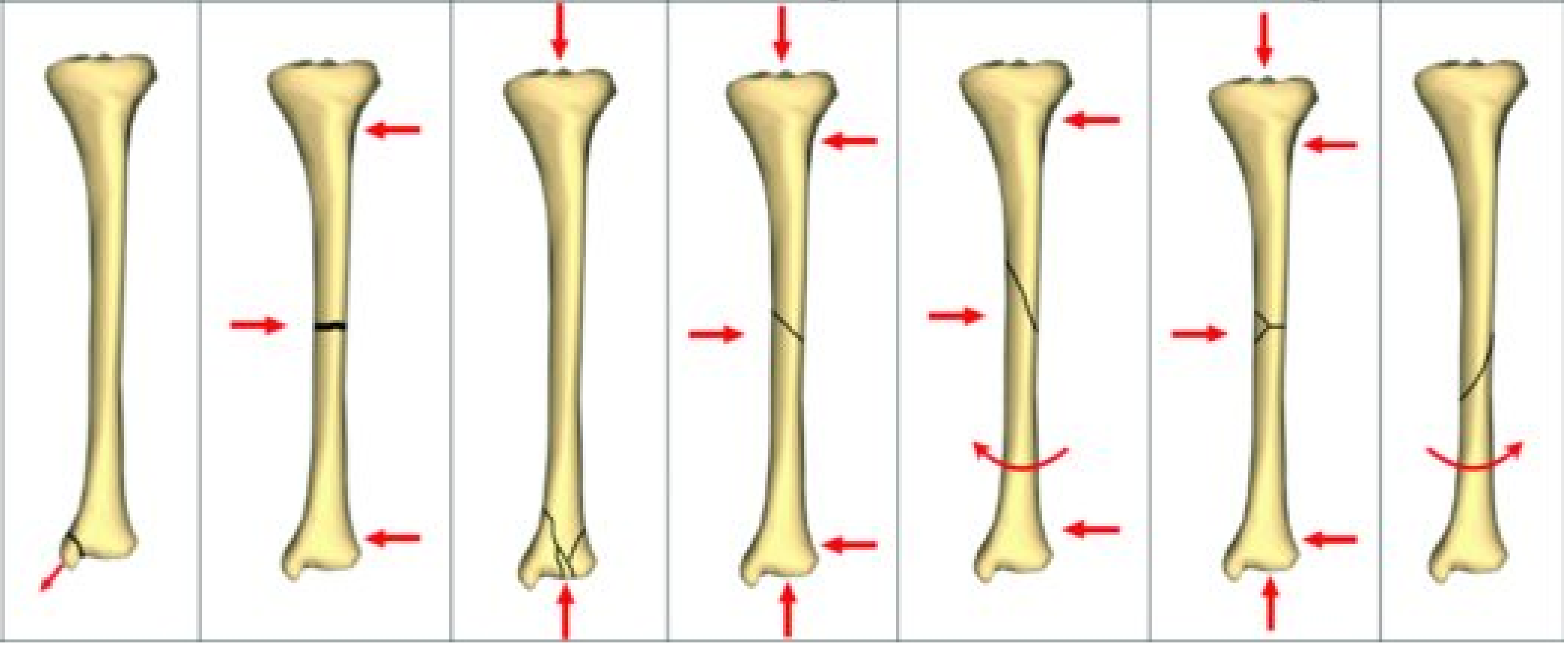
Traumatic Loading of Bone

- **Fracture** is a result of the *bone being loaded to failure*
  - Magnitude and Direction of the Force vary
  - Different Patterns associated with different Magnitudes and Directions: different bones fail differently
  - Examples:
    - Transverse Patella fx = Tension failure
    - Vertebral body= Compression failure
    - Tibia= Torsional Failure

Types of Fractures

- Transverse: Force is ***Perpendicular*** to long axis of bone
- Spiral Fractures: ***Torsional*** Forces
- Oblique: Force is ***Diagonal*** to axis of bone
  - 3 types: Axial, Bending & Axial, Torsional & Bending
- Butterfly: combination of ***Bending Force*** and ***Compression Force***
-
- Comminuted: Force ***High Energy***

Types of Fractures

Fracture Type	Transverse	Oblique			Butterfly	Spiral
Load	Tension	Pure compression	Compression + Bending	Bending + Torsion	Compression + Bending	Torsion
Morphology						

From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

Osteoporosis- Biomechanical Considerations

- Trabecular Bone more Porous
- Density of bone affects Trabecular Bone
- A Small Decrease in Density weakens Trabecular Bone

- **2 Biomechanical Challenges**
    - Risk of fracture from daily activities
    - Poor/Limited ability to obtain fixation in weakened bone

Osteoporosis:

- Definition of Osteoporosis: bones become brittle and fragile from loss of tissue, typically as a result of hormonal changes, or deficiency of calcium or vitamin D

- Fracture resistance of osteoporotic bone is a function of the 3rd power of the Bone Mineral Density (**BMD**)

- See Cortical Bone thinning becomes trabecular bone

Stress Risers:

- A defect in bone or sudden change in STIFFNESS results in a STRESS riser
  - Periprosthetic Fractures
  - Interprosthetic Fractures
  - Peri-implant Fractures
  - Bone Defects

Periprosthetic Fractures

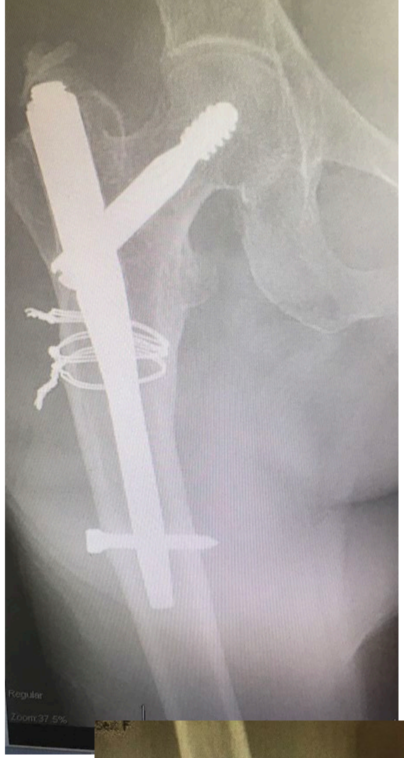
- Low energy
- Vancouver A = torsional forces
- Vancouver B & C = bending forces

The presence of a hip prosthesis (THA) decreases the strength of the femur by 32%

A loose implant increases risk of PPFx, particularly in torsion

Interprosthetic Fractures

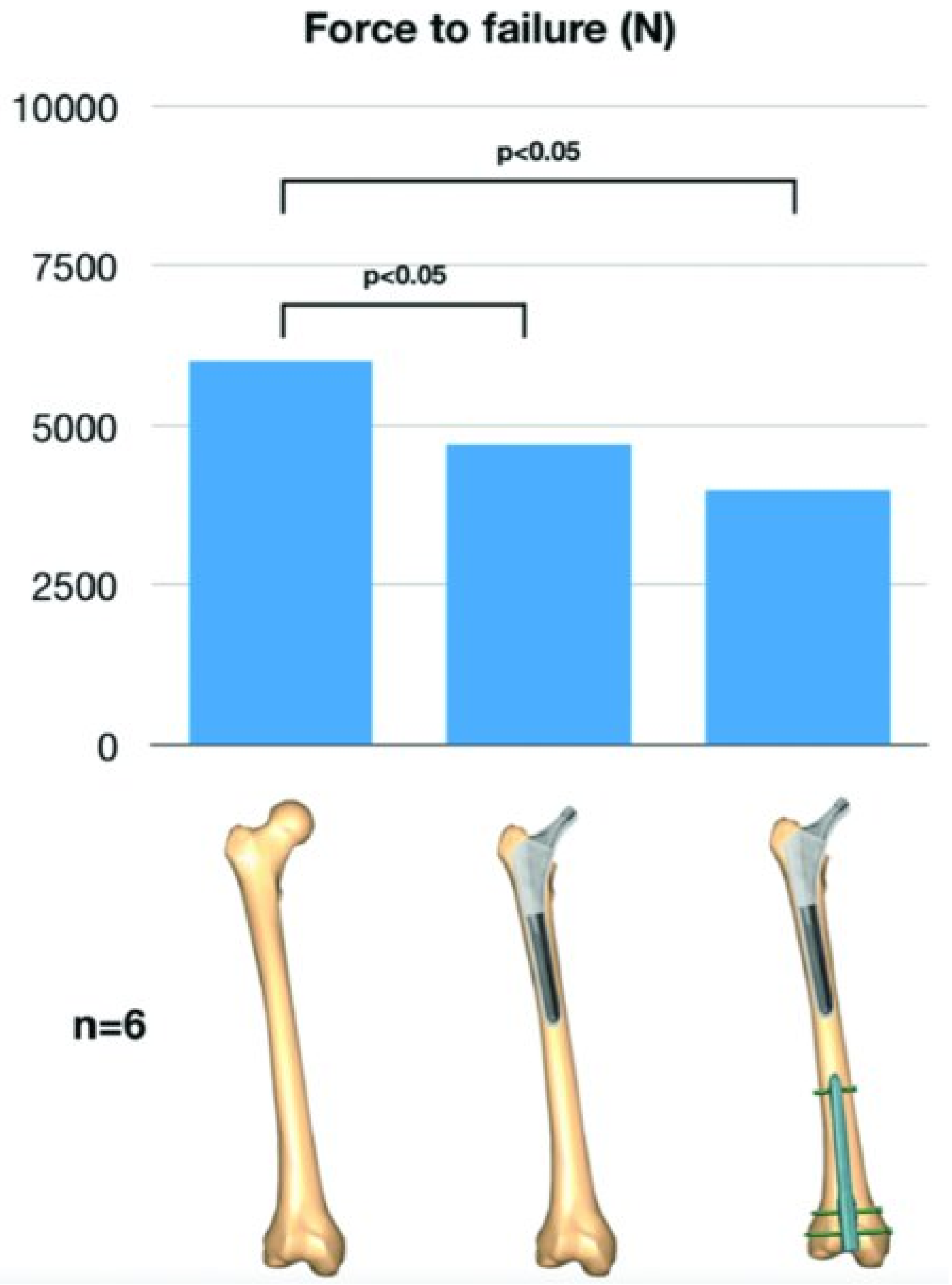
- Factors and Risk of Fracture
  - Distance between Implants (? 110mm)
  - Cortical Thickness
  - Loose Prothesis or Implant



Peri-Implant or End Screw Fractures

- Risk lower in nonlocked screws (1-3%)
- <u>Increased for locked screws (2.6%) – increased stiffness</u>
- Unicortical screws lower the strength of bone compared to bicortical
- Angled screws at the end may decrease pullout and fracture risk
- End Dual plating constructs at different levels (create overlap)

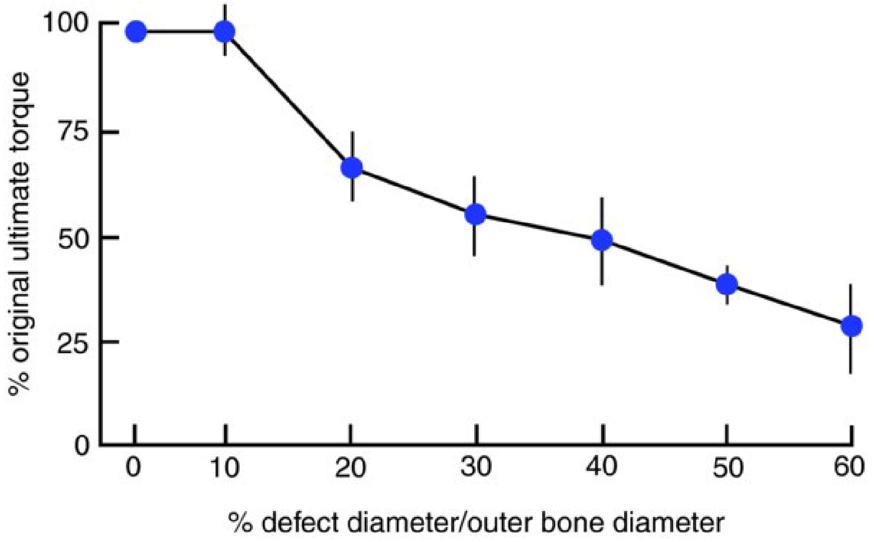
Loads required to cause a femur fracture



From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

Bone Defects

- When plates and screws removed, risk of fracture increases
- Bending and torsional forces cause risk
- No increased risk with defect less than 10% diameter
- 10%-20% defect: 34% decrease in bone strength
- 20%-60% defect: linear decrease in relation to the size

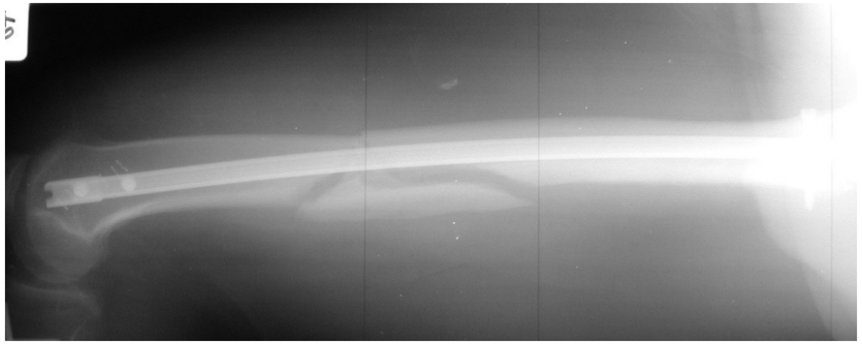


From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

BONE HEALING AND BIOMECHANICS

Bone Healing and Biomechanics

- Biology and Mechanics
- 2 Types of healing for bone

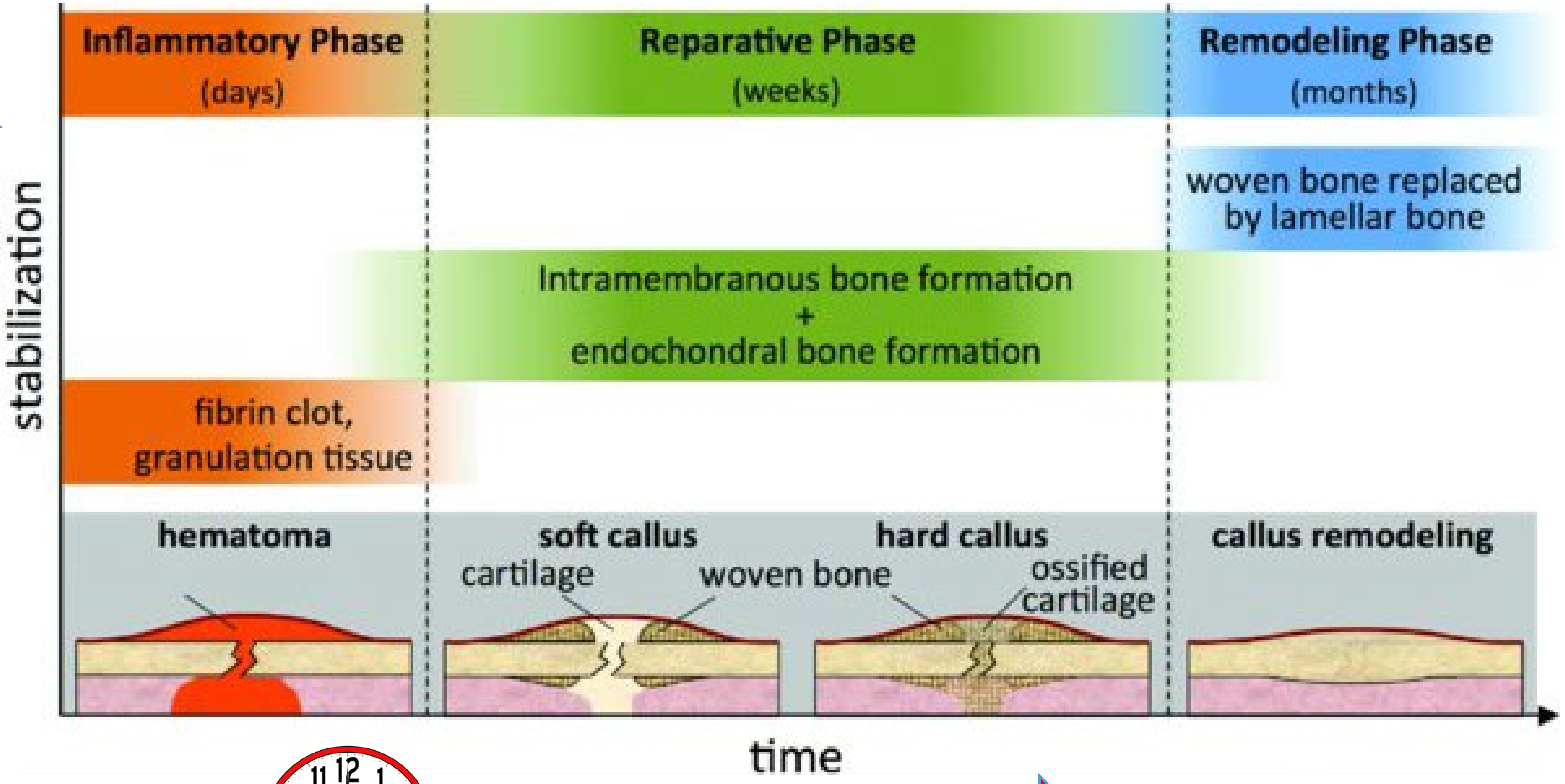


  - **Natural Bone Healing**
  - Secondary or Endochondral Bone formation
    - 4 stages (Hematoma / Soft Callus / Hard callus / Remodeling)
    - Relative Stablility
    - EX: Intramedullary nailing

  - **Primary Bone Healing**
    - Cutting Cones
    - No Callus
    - Absolute Stability
    - Ex: Compression plating

Natural Bone Healing

- Ultimate Tensile Strength Increases with time



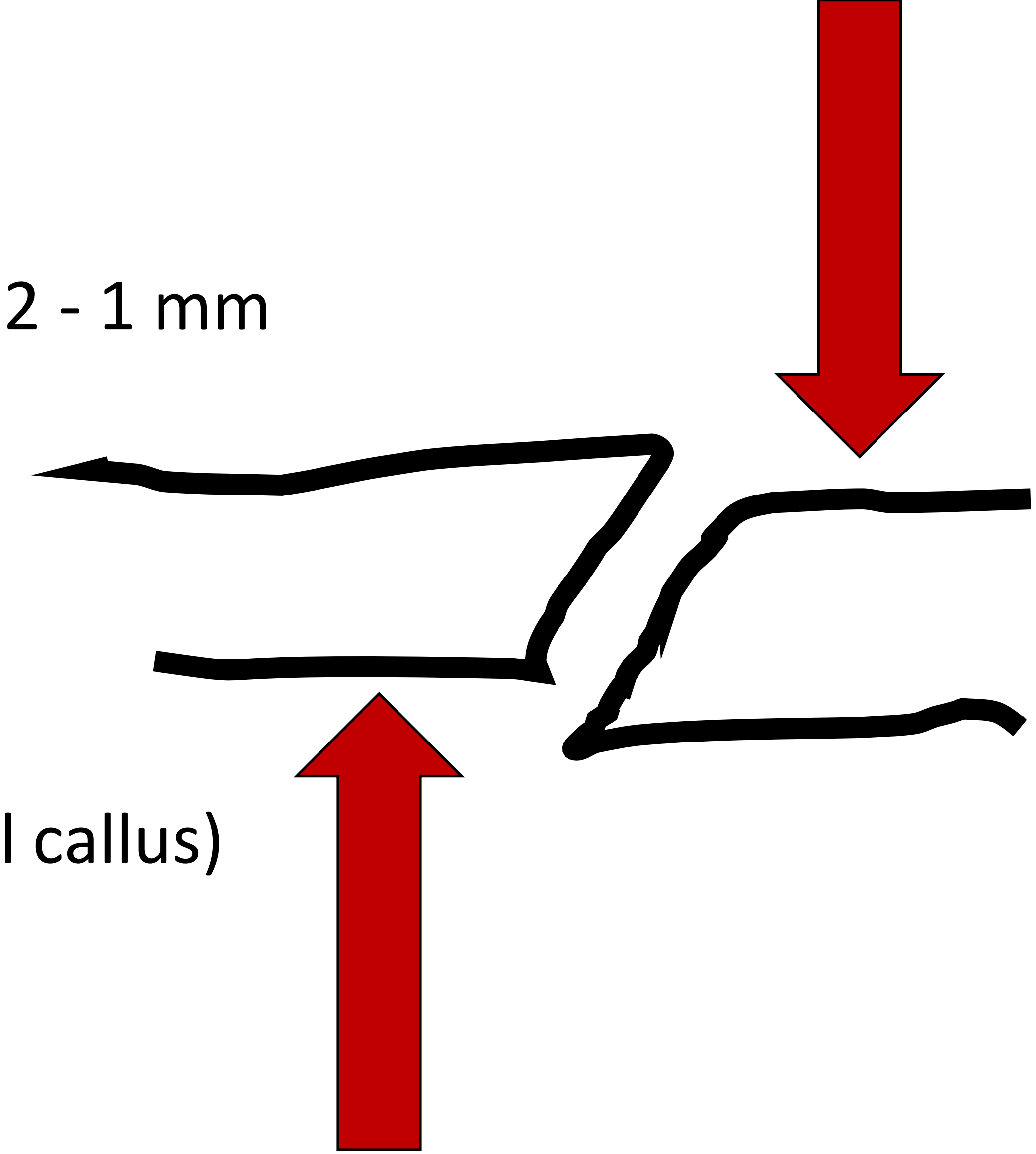
From: **1 Biomechanics of Fractures and Fracture Fixation**
Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA. Wolters Kluwer Health, Inc; 2019.

Stages of Natural Healing

- **Hematoma**: fibrin clot
- **Soft Callus**: granulation tissue to stabilize and allow cartilage
  - Volume of tissue creates stability
- **Hard Callus**: calcification of cartilage
  - The end of healing when hard callus forms
- **Remodeling:** decreased motion = more mature lamellar bone
  - Volume of material decreases

Natural Bone Healing

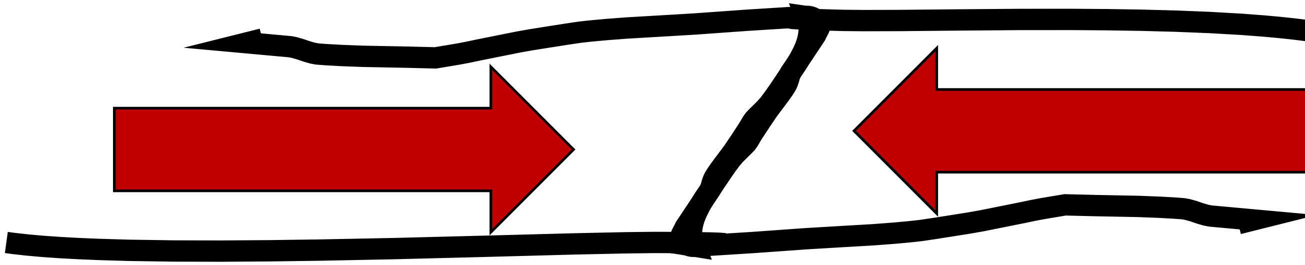
- Optimal interfragmentary motion is 0.2 - 1 mm
- More motion increases healing
- Large gaps heal slowly, less callus
- Healing occurs peripherally (periosteal callus)
- Goal is axial motion



<u>Shear will prevent bone healing!</u>

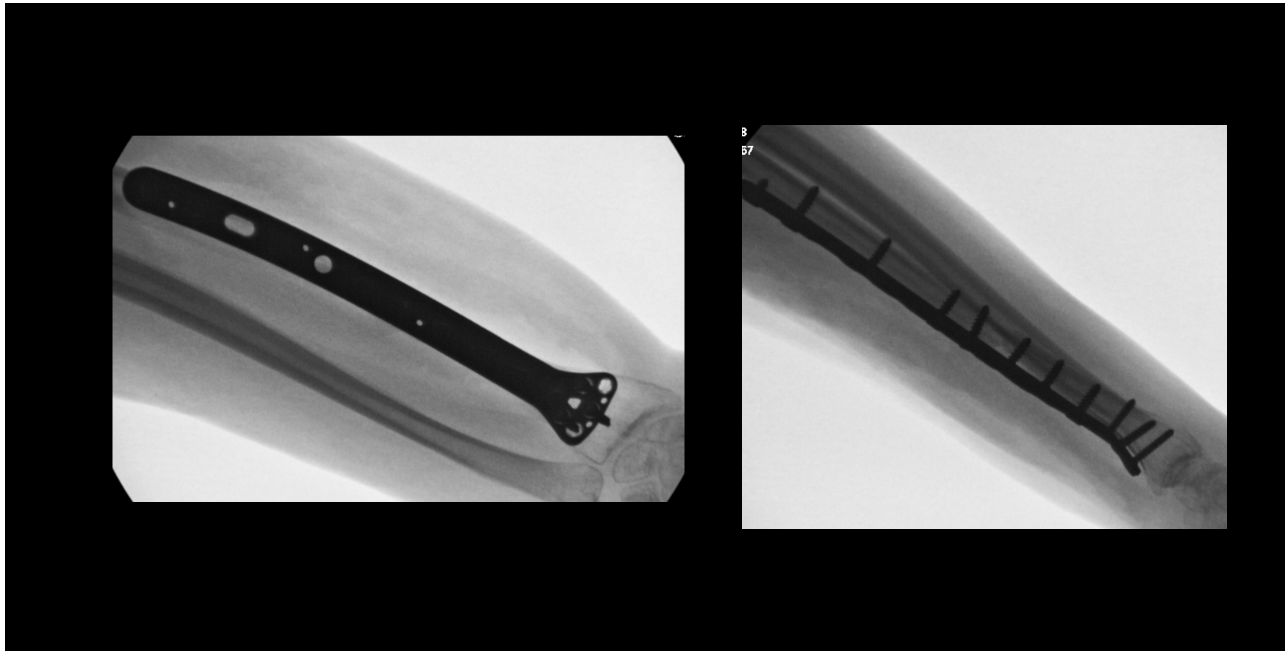
Primary Bone Healing

- Creates stability through anatomic reduction
- Compression of fragments
- Immediate STABILITY as no intermediate tissue
- Interfragmentary motion < 0.15 mm
- No gaps (minimize)
- SLOWER process



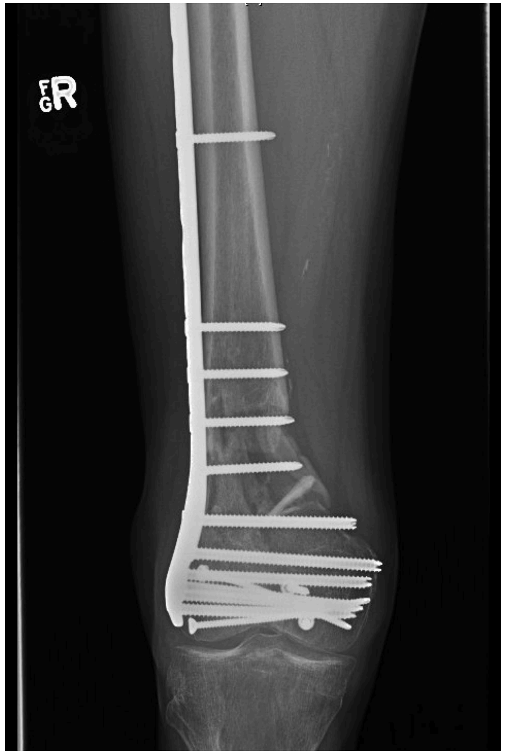
Primary Bone Healing

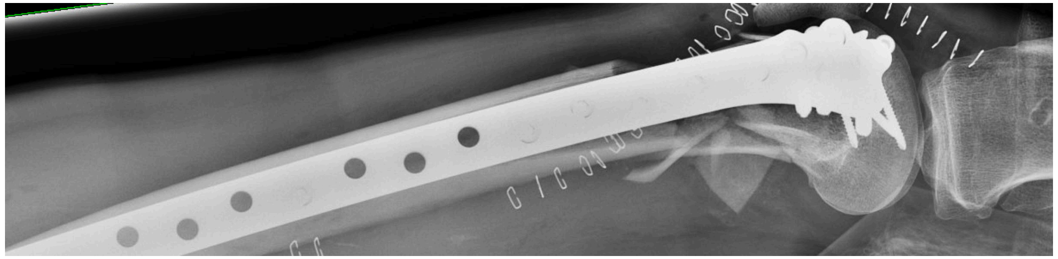
- Cutting Cones: osteoclasts cut across fracture, allow for osteoblasts
- Gap healing: lamellar bone perpendicular to axis of fracture to allow for cutting cones
- SLOWER PROCESS
- PLATE Fixation
- Plates should be on for 2 years



Nonunion / Delayed Union

- Unstable
  - Hypertrophic Nonunion
  - Delayed Unions
  - Large Cartilage Mass
  - Motion > 1mm
- Stiff
  - Atrophic nonunions
  - Stiff + Gap is bad
  - No callus
  - No cutting cones





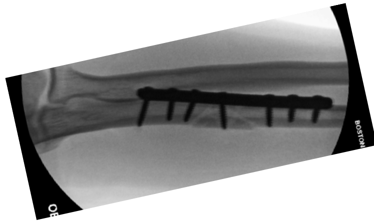
FIXATION STRATEGIES

Fixation Strategies

- Mechanical environment dictates mode of healing
- Patient factors to consider
  - Bone quality
  - Fracture type
  - Comminution
  - Location

Natural Bone Healing Fixation Devices

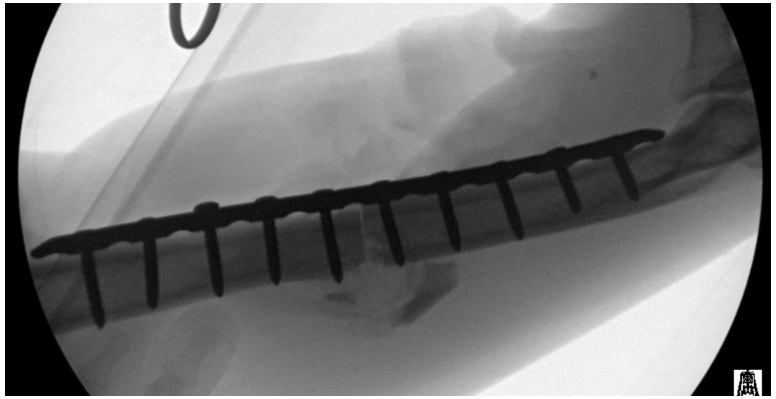
- Casts
- Fracture Bracing
- Intramedullary Nail
- External Fixation
- Flexible Nail Constructs
- Flexible Plate Constructs



Create enough stability to initiate the process otherwise: Too little creates Nonunion

Primary Bone Healing Strategies

- Compression plating
- Locked plating
- Less forgiving
- Anatomic reduction required
- Intra-articular fractures



Is the Construct Durable ?

- The construct has to hold up mechanically until fracture consolidation occurs

- Constructs need to focus on:
  - Minimizing stress concentration
  - Maximizing working length

Minimize Stress Concentrations

- Load distribution
  - Large spread
  - Long and multiple screws in metaphysis
- Reduce stiffness gradients
  - Angled screws at the end of plate
- Prevent preloading
  - Lag before locking

Maximize Working Length

- Large distance between fixation points
  - Number of screws less important than distance
  - Add screws if osteoporotic
- Create long lever arms
- Near-far fixation points

FIXATION CONSTRUCTS

Fixation Constructs: Operative

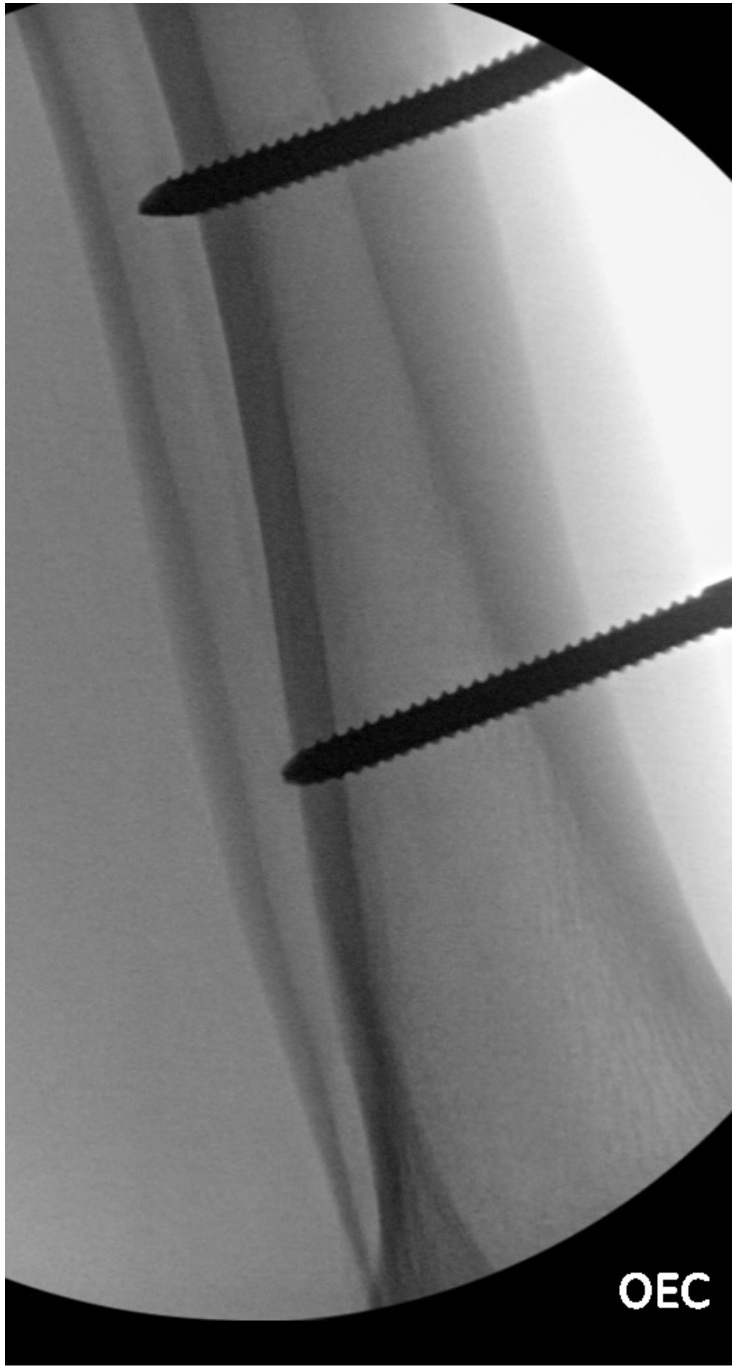
- External Fixation
- Plates
- Intramedullary Nails

External Fixation

- Consider Factors
  - Pin size
  - Number of pins
  - Uniplanar vs multiplanar
  - Spacing of pins
  - Location of the bars
  - Biology: stay out of the zone of injury

External Fixation

- Consider Factors
  - Pin size
  - Number of pins
  - Uniplanar vs multiplanar
  - Spacing of pins
  - Location of the bars
  - Biology: stay out of the zone of injury

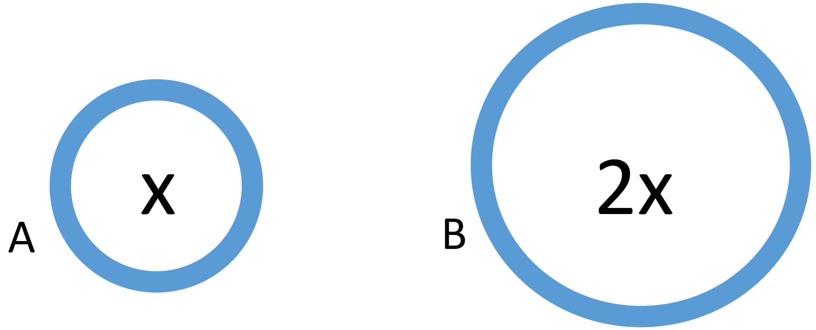


External Fixation

- Consider Factors
  - **Pin size**
  - **Most significant factor for frame stability**

Thickness of pin increases the strength (**R^4)**

Doubling the diameter 1mm to 2mm will increase strength by 16 fold



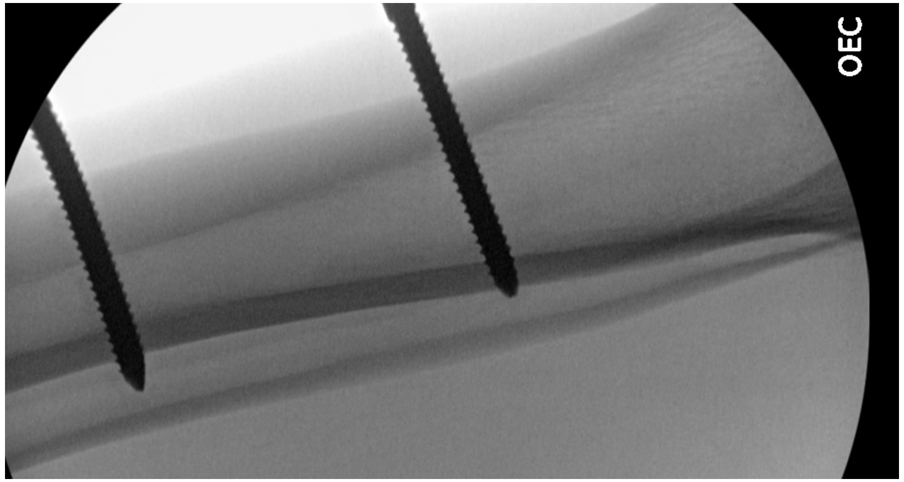
B is 16x stronger than A

External Fixation

- Consider Factors
  - *Pin size*
  - **Number of pins**

More pins in the segment = more stable

Minimum number of 2 pins required



External Fixation

- Consider Factors
  - Pin size
  - Number of pins
  - **Uniplanar vs multiplanar**

- Adding pins in multiple planes will also increase the stability of the segment

External Fixation

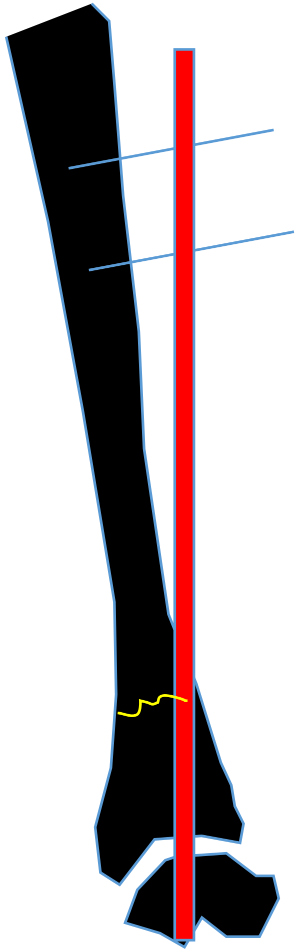
- Consider Factors
  - Pin size
  - Number of pins
  - Uniplanar vs multiplanar
  - **Spacing of pins**

One pin close to the fracture and one further from fracture

Same concept as working length

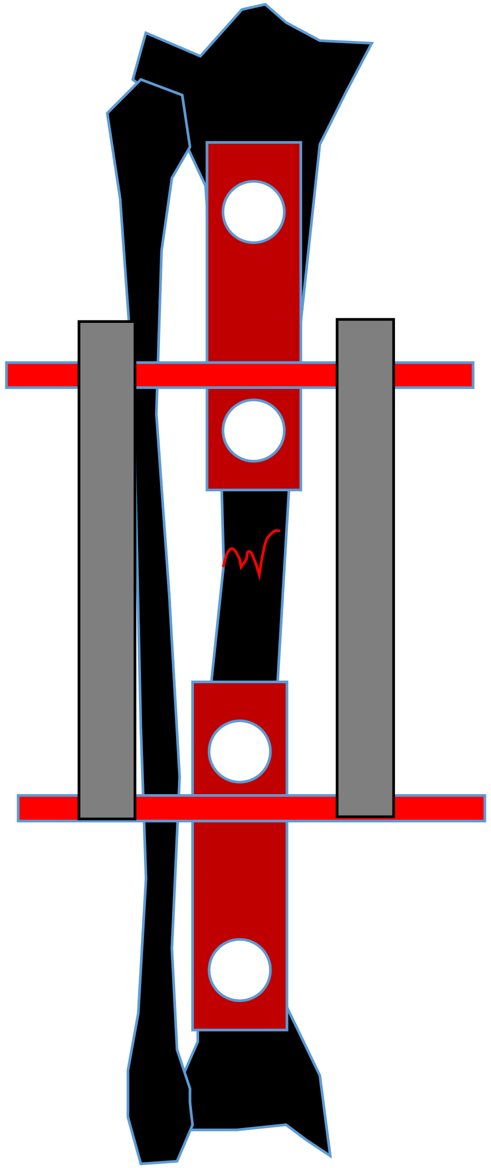
External Fixation

- Rod (red)
- IN-line and as close to bone



External Fixation

- Optimize frame mechanics
  - Largest possible pin diameter
  - Large spread
  - If more stability, add pins
  - Multiple planes
  - Minimize distance from bone to rod
  - Stack the frame
  - Make a Short / Fat / Box



Intramedullary Nails

- Load sharing implant
- Modern nails are hollow (older nails slotted)
  - Lighter
  - Stronger in bending
  - Stiffness proportional to the 4th Power
  - Increased torsional strength

Intramedullary Nails

- Stiffness of nails
  - Material
  - Location of fracture
  - Interlocking technique
    - Unlocked
    - Locked
  - Blocking screws

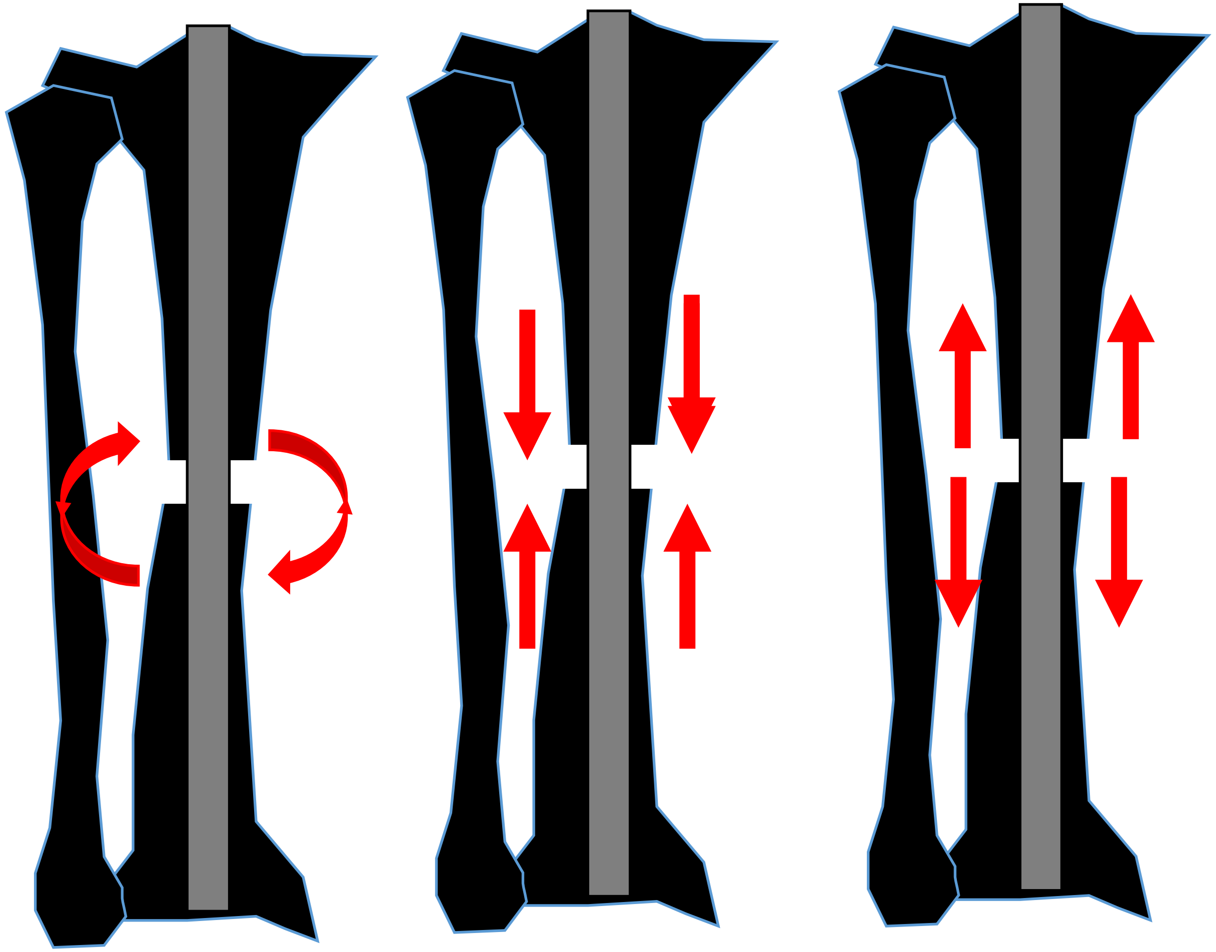
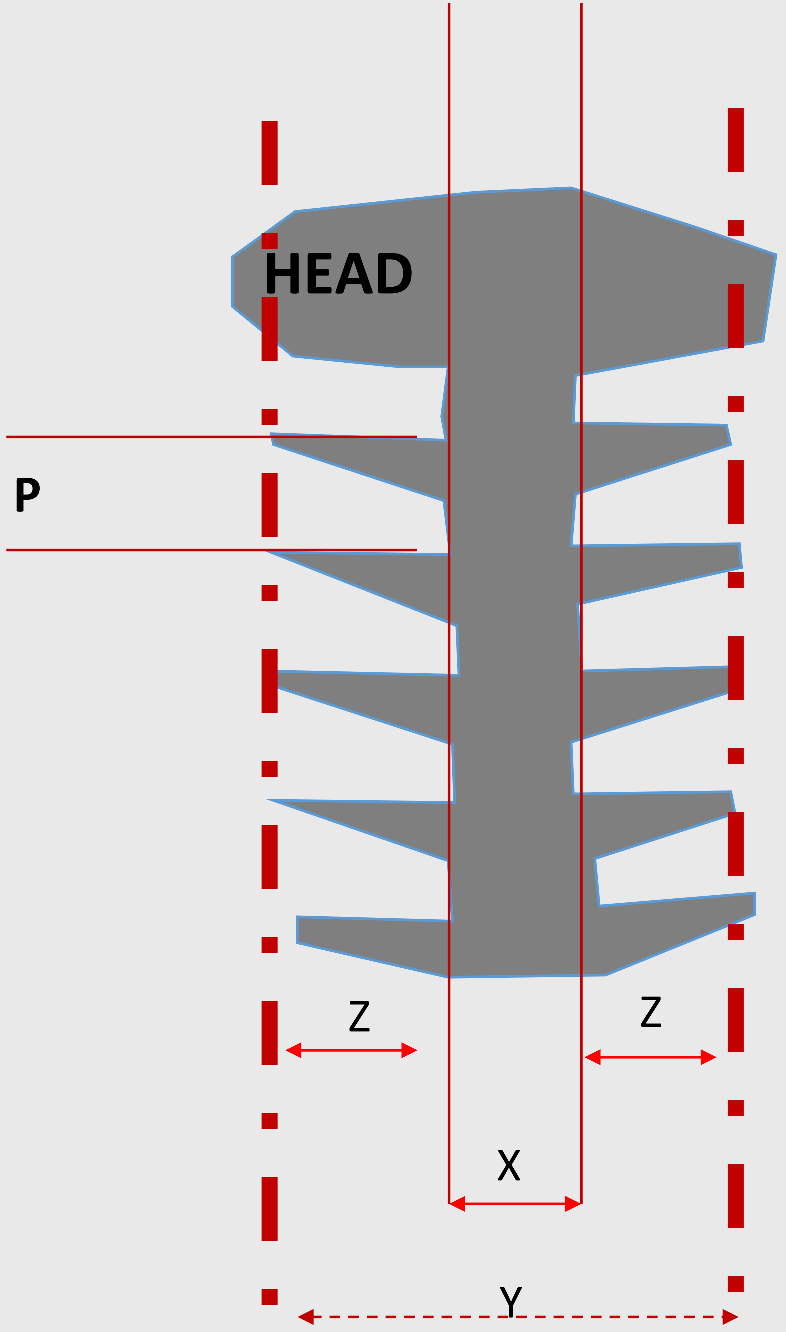


Plate and Screw Fixation

- Screws
  - Cortical
  - Cancellous
  - Cannulated
  - Locking Screws
- Conventional Plates
- Locking Plates

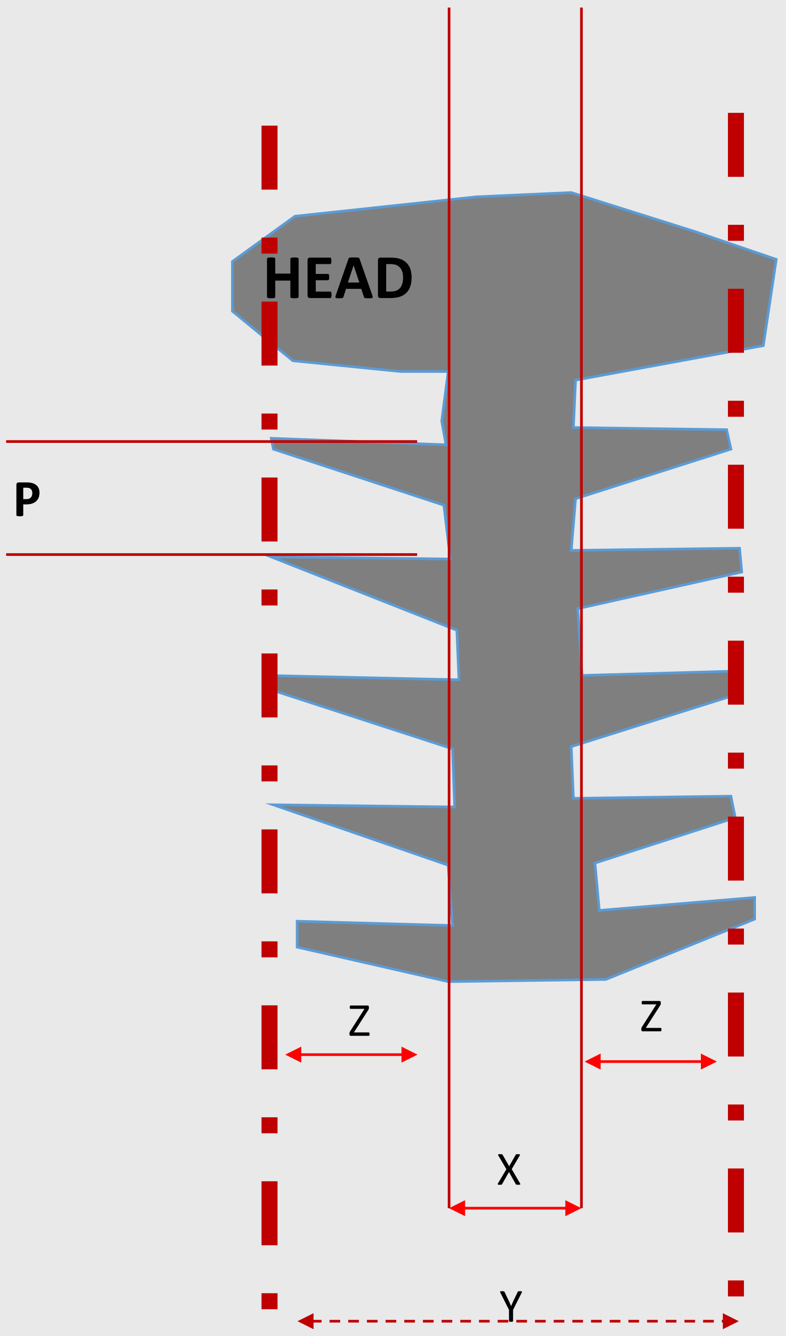
Screws

- Anatomy of a Screw
  - Head
  - Thread Height Z
  - Inner (Core) Diameter -X
  - Outer(Thread) Diameter-Y
  - Pitch (P)



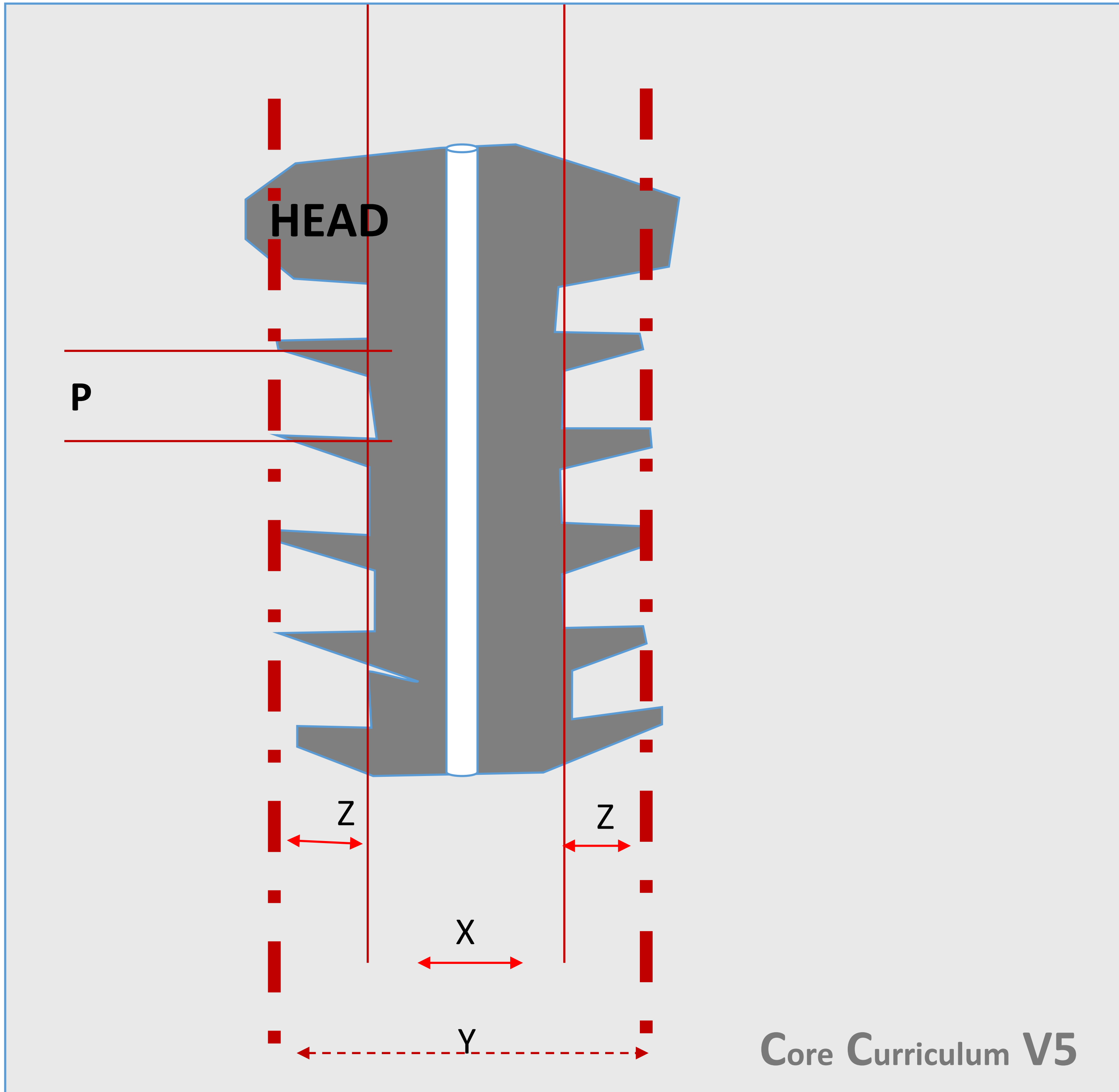
Screws

- Cortical Screws
  - Smaller pitch
  - Smaller thread height
- Cancellous Screws
  - Larger pitch
  - Larger thread height
  - Smaller core diameter
  - Larger pitch



Screws

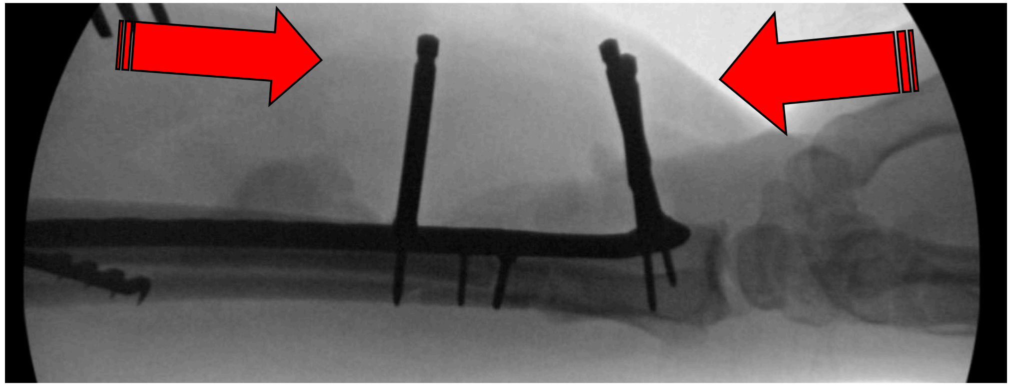
- Cannulated Screws
  - Wide core diameter
  - Better in bending
  - Decreased pitch
  - Decrease thread height
  - Lower pullout strength

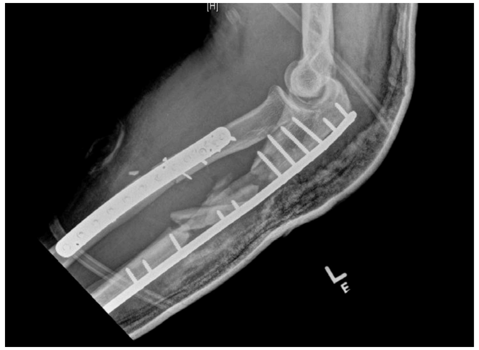


Screws

- Generate torque
- Compress bone
    - Lag by technique
    - Lag by design
- Compress plate to bone
- If locked into plate: Bicortical to disperse forces
    - Stiffer

Plate Fixation





- Compression
- Neutralization
- Buttress
- Anti-Glide
- Relies on friction between plate and bone

Plates

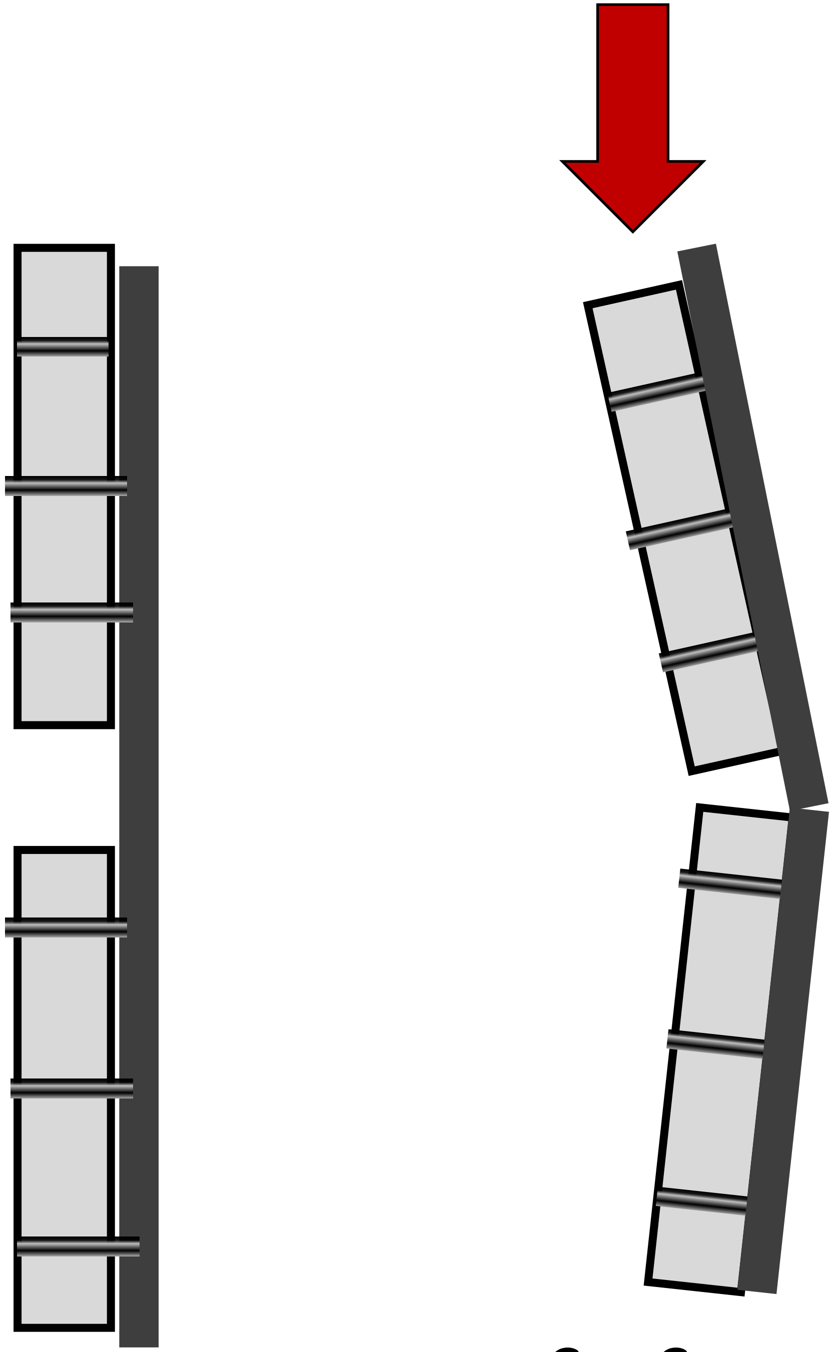
- Bending stiffness of plate
  - *Thickness to the 3rd power*
  - **$I = bh^3 / 12$**

- **Much harder to bend and contour a thicker plate**

Plates

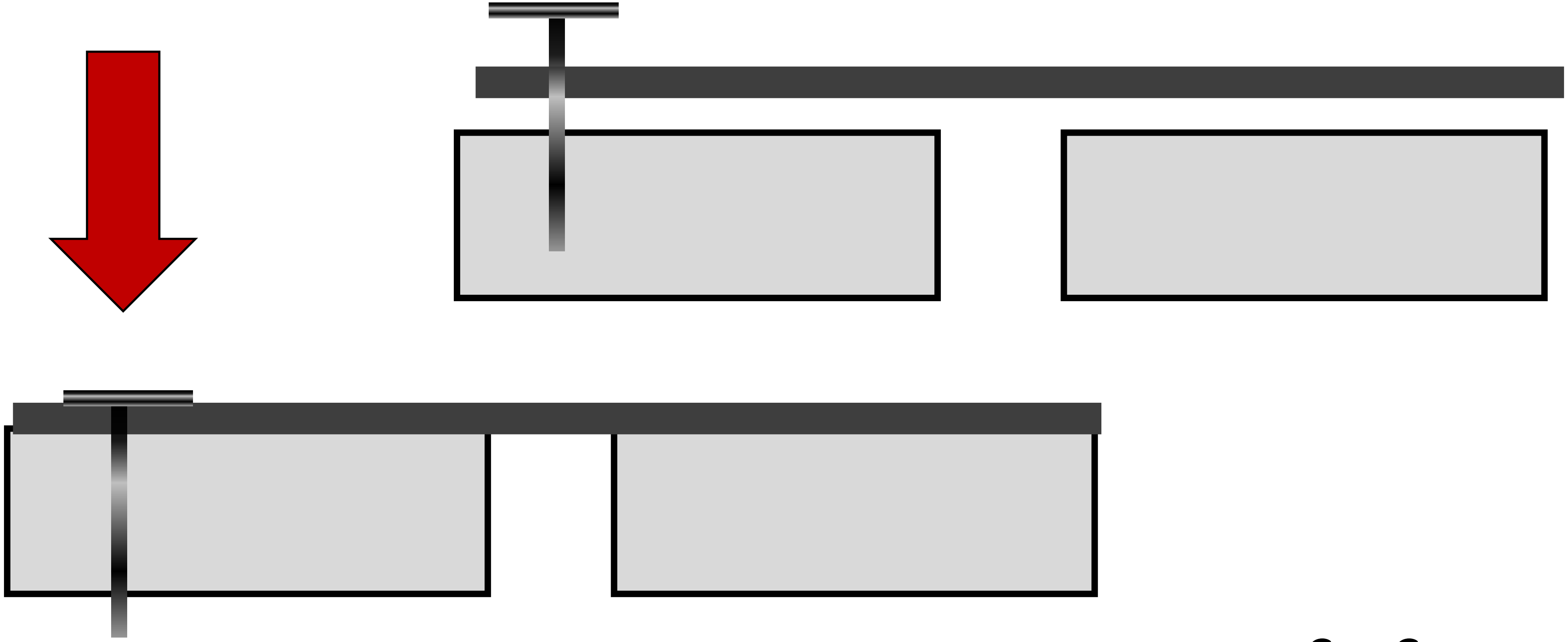
- Gaps are bad
  - Prevents primary healing
  - Allows for fatigue failure (bending)

  - Healing prevents fatigue failure



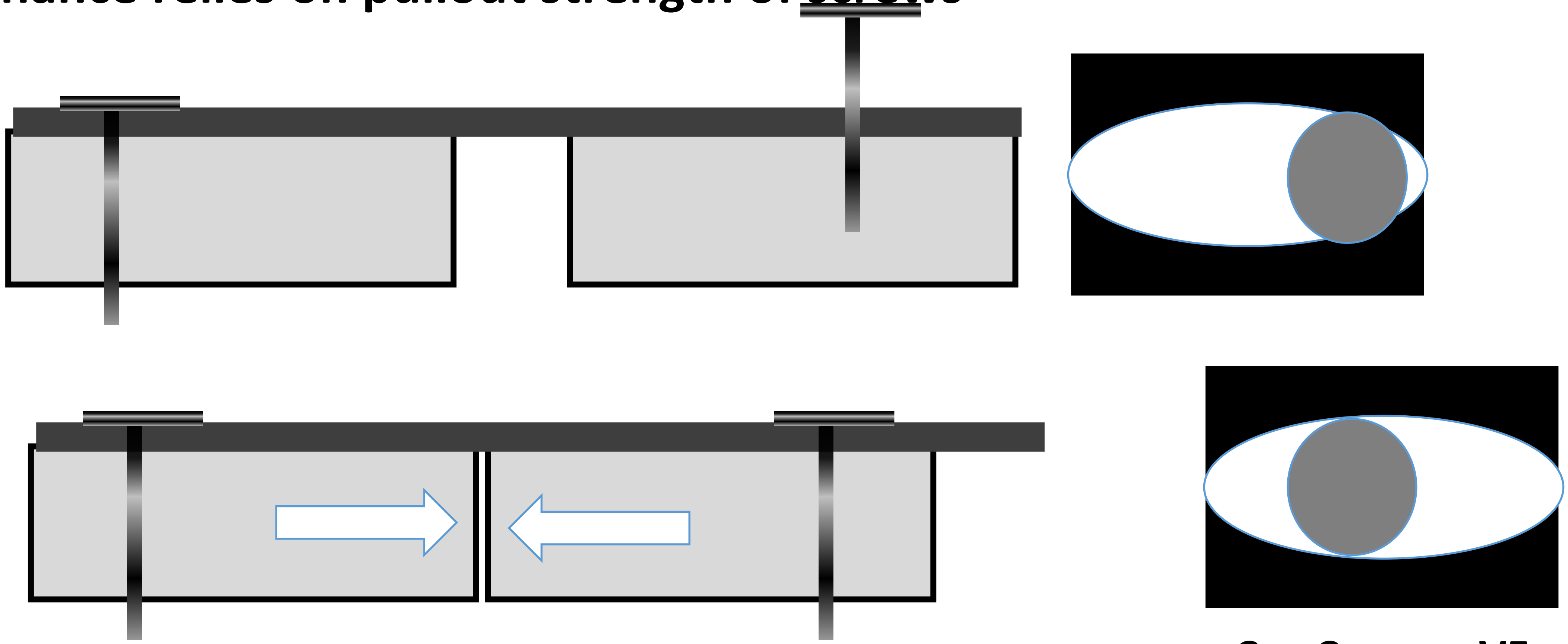
Plating

- Screws compress plate to bone



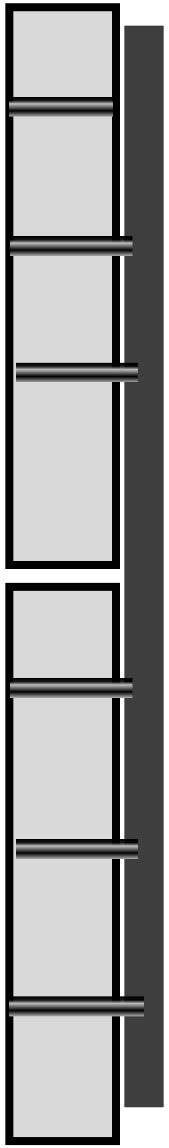
Plates

- Compression of fracture
- Maintenance relies on pullout strength of screws

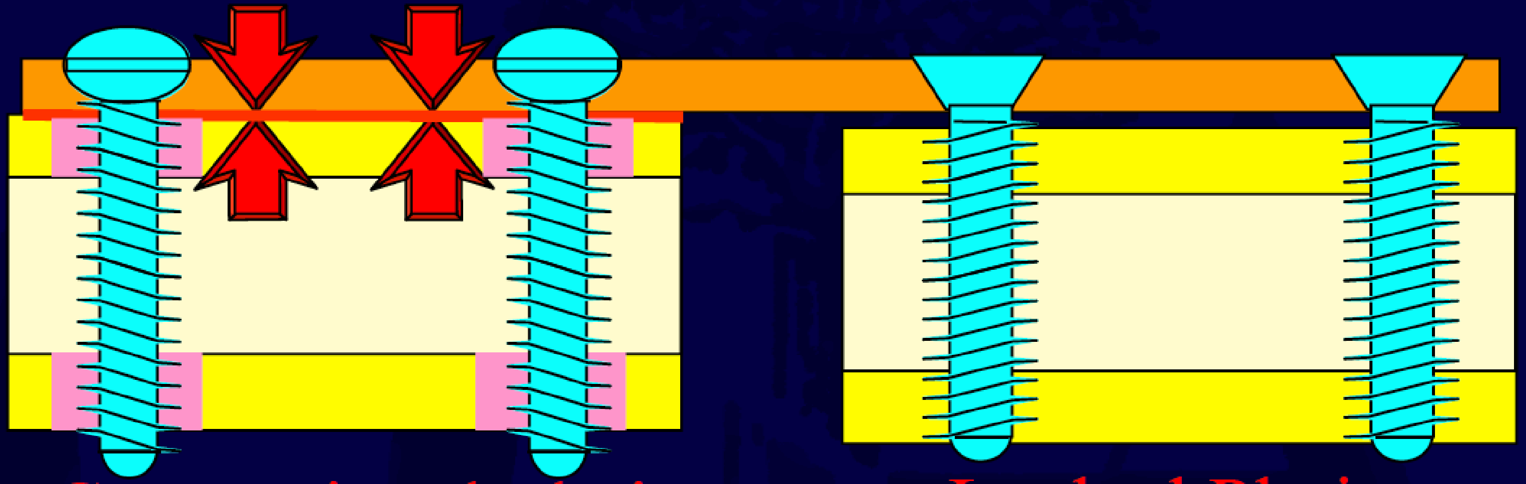


Locking Plates

- Many fixed-angle points of fixation
- Internal external fixator
- Dose not rely on friction
- Can’t not gap
- Lag prior to locking



Comparison



Conventional Plating

- Bone is pre-stressed
- Periosteum strangled

Locked Plating

- Plate (not bone) is pre-stressed
- Periosteum preserved

Locked Plating

- Hybrid screw fixation
- Pre-contoured plates
- ***Lag prior to locking**,* compress plate to bone
- Lock after Lagging and reducing fracture
- Do NOT lock in a GAP → NONUNION machine

Hybrid fixation

- Mix of non-locked and locked screws
- Lag prior to locking
- Locking screw at end of plate increases fixation

Summary

- Balance biology and mechanics
- Geometry and material matter affect stiffness of construct
- Load transfers based on vectors and lever arms
- AVOID shear and promote compression
- Lag prior to locking
- Manage stiffness based on type of bone healing
- Minimize stress risers
- Maximize working length

Annotated References

- Bong MR, Kummer FJ, Egol KA. Intramedullary nailing of the lower extremity: biomechanics and biology. J Am Acad Orthop Surg. 2007 Feb, 15(2):97-106
- Rockwood & Green Fractures in Adults, 9E, 2019. Chapter 1 , Biomechanics of Fractures and Fracture Fixation
- Toan Le, Theodore, OTA CORE CURRICULULM VERSION 4
- Rupprecht M, et al. Biomechanical Evaluation for Mechanisms of Periprosthetic Femoral Fractures. Journal of Trauma. Vol 70, N4, April 2011
- Peck JB, Charpentier PM, Flanagan BP, Srivastava AK, Atkinson PJ. Reducing Fracture Risk Adjacent to a Plate with an Angled Locked End Screw. J Ortho Trauma, Vo 29, N 11,p431 436- Nov 2015,