Biomechanics of Fractures and Fixation

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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 ($\sigma$) = Force/Area
  • Strain ($\varepsilon$) = Change in Height ($\Delta L$) / Original Height ($L_0$)

• Elasticity (Young’s Modulus or E modulus)
  • $E = (\sigma) / (\varepsilon)$

• Strain expressed without units

• Stress and E modulus expressed as Gigapascals

• Example stainless steel ($E=200$ GPA) 2x Titanium
Compressive Strength

Strain ($\varepsilon$) =

Change in Height ($\Delta L$)

_____________________

Orginal Height ($L_0$)

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)

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Strength (MPa)</th>
<th>Failure Strain (%)</th>
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<tr>
<td>UHMW polyethylene (arthroplasty)</td>
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<td>25</td>
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<td>5</td>
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<tr>
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<tr>
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Rockwood and Green table 1-1

From: 1 Biomechanics of Fractures and Fracture Fixation
# Common Materials in Orthopaedics

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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: Biomechanics of Fractures and Fracture Fixation
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\textsuperscript{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.

- **Plates**
  \[ I = \frac{w \times t^3}{12} \]

- **Wires, Pins**
  \[ I = \frac{\pi \times D^4}{64} \]

- **Intramedullary Nails**
  \[ I = \frac{\pi \times (D^4 - d^4)}{64} \]

From: 1 Biomechanics of Fractures and Fracture Fixation
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
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

<table>
<thead>
<tr>
<th>Fracture Type</th>
<th>Transverse</th>
<th>Oblique</th>
<th>Butterfly</th>
<th>Spiral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Tension</td>
<td>Pure compression + Bending</td>
<td>Compression + Bending + Torsion</td>
<td>Compression + Bending + Torsion</td>
</tr>
<tr>
<td>Morphology</td>
<td><img src="image1.png" alt="Transverse" /></td>
<td><img src="image2.png" alt="Oblique" /></td>
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From: 1 Biomechanics of Fractures and Fracture Fixation
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 $3^{rd}$ 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%)
- Increased for locked screws (2.6%) – increased stiffness
- 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

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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

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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 Stability
  • 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: Biomechanics of Fractures and Fracture Fixation
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

Shear will prevent bone healing!
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 4\textsuperscript{th} 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(Threading) 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 $3^{rd}$ power

\[ I = \frac{bh^3}{12} \]

- 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
- Does 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


• Rockwood & Green Fractures in Adults, 9E, 2019. Chapter 1, Biomechanics of Fractures and Fracture Fixation

• Toan Le, Theodore, OTA CORE CURRICULULM VERSION 4
