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BIOMECHANICS OF THE SPINE AND IMPLANT FIXATION

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DISCLOSURES

- **OKT – Strategic Planning & Regulatory Consulting**
- **OKT^2 – ISO 17025 A2LA Accredited Test Facility**

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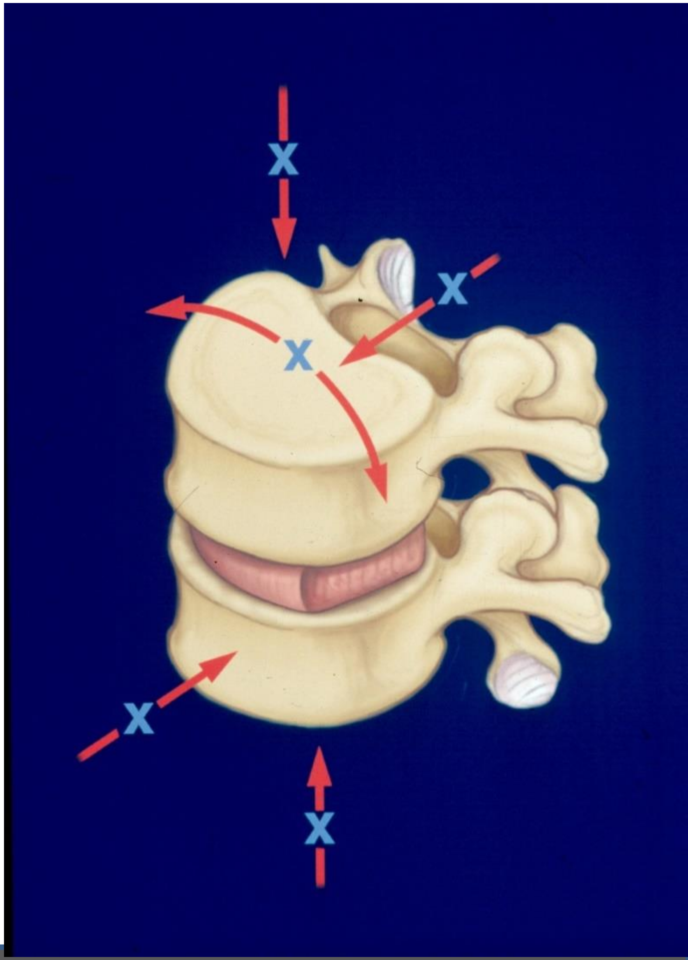
MECHANICS 101

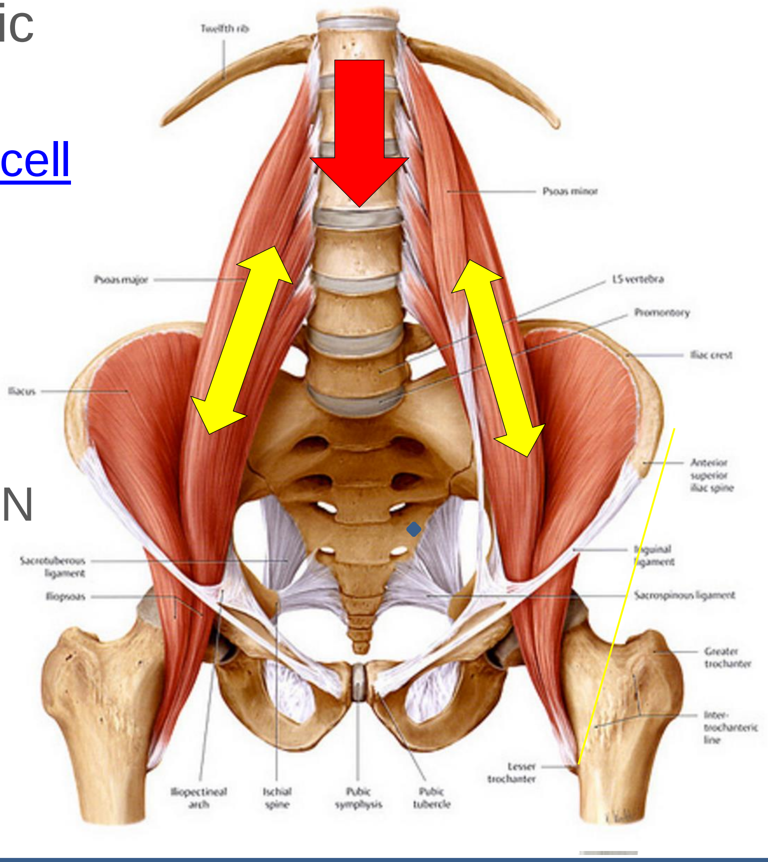
Spinal Motion

- Motion along 3 planes
- 6° Freedom
- Dynamic IAR
- Bending in Disc:
  - Compression & tension on annular fibers
  - Displacement of nucleus
    - Flexion – dorsal
    - Extension - ventral



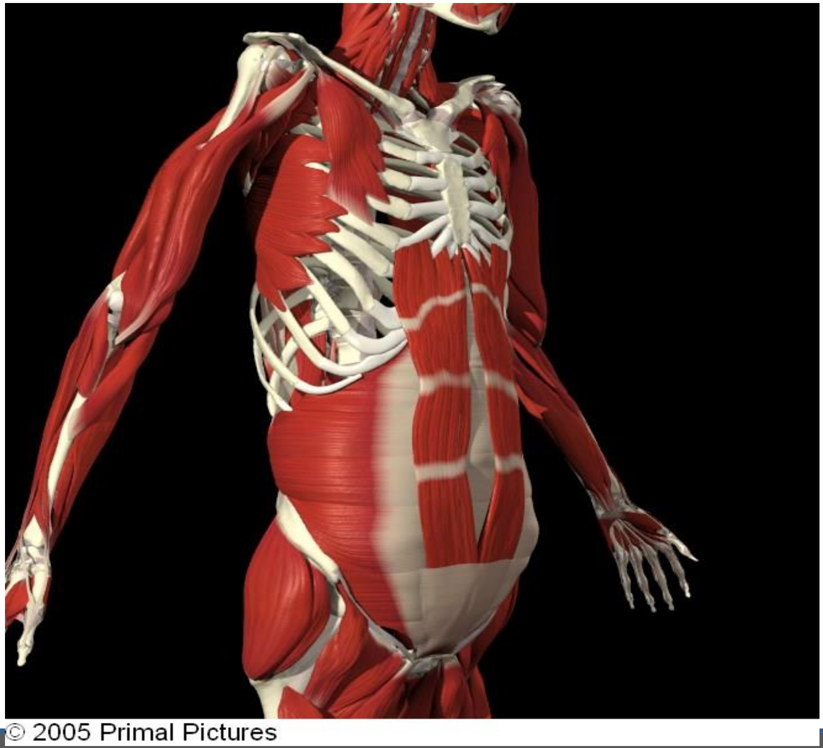
BIOTENSEGRITY

- Application of tensegrity principles to biologic structures
  - muscles, bones, fascia, ligaments, tendons, cell membranes
- Superior strength from unison tension + compression of tissue structures
- Muscular-skeletal system
  - Muscles & connective = continuous TENSION
  - Bones = discontinuous COMPRESSION
- Maintains homeostasis



MUSCULATURE

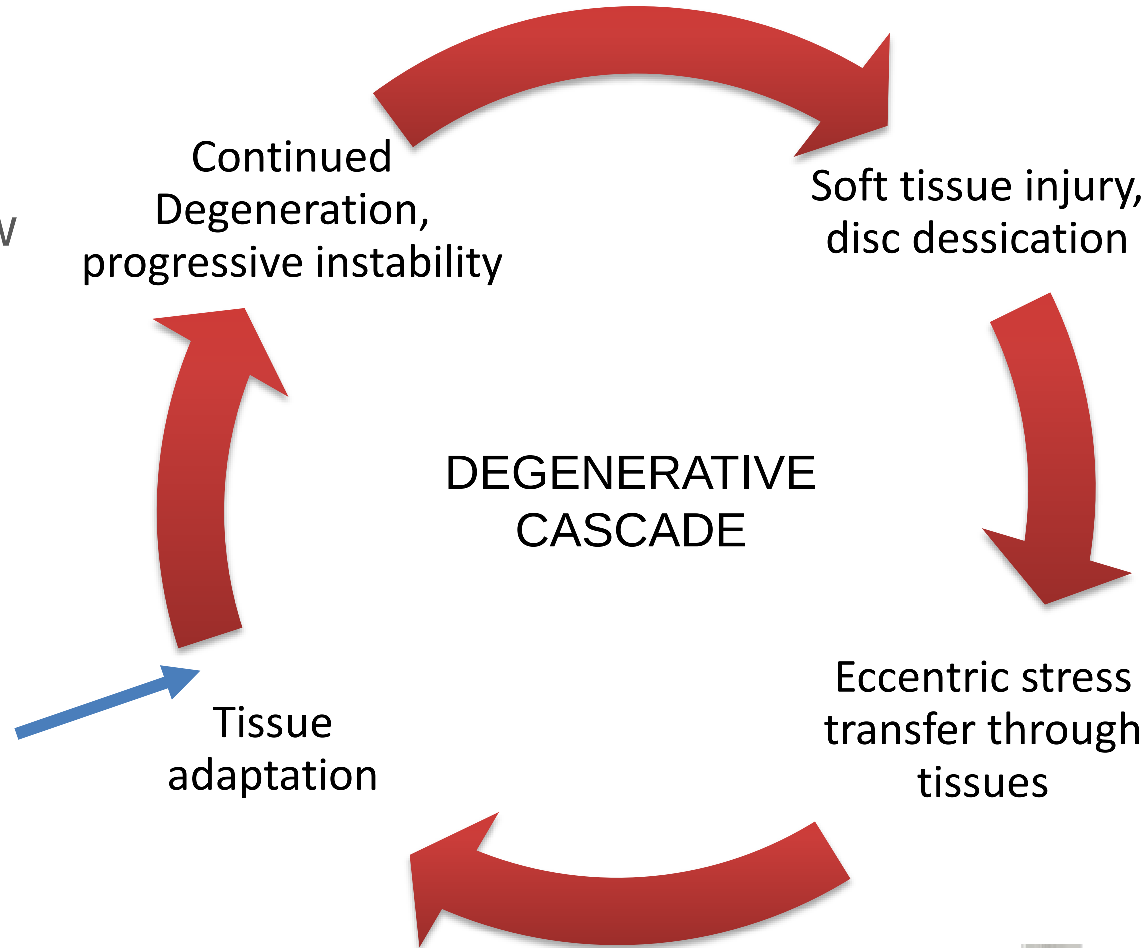
- Intrinsic & Extrinsic Muscles serve as pulleys to spine for stabilization
- Apply constant tension for mobilization
- Transfer stress to surrounding structures – load sharing



STRESS & DEGENERATION

- Stress Transfer
- How does the stress flow through the tissue?

Wolff's Law
Inefficient adaptations (osteophytes)



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LOAD BALANCE AND CENTER OF ROTATION FOR FSU

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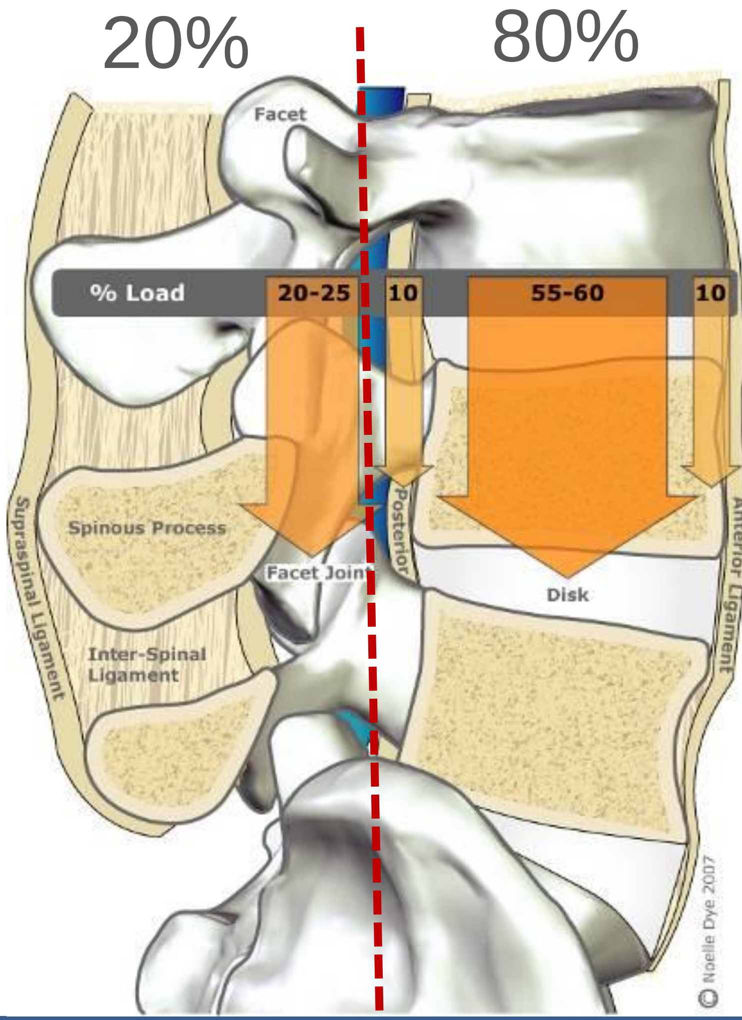
LOAD BALANCE (STRESS TRANSFER) – HEALTHY

- Vertebra + Disc = 55 - 60%
- Cortical shell = 10%
- Posterior Ligaments = 10-15%

} 80%

- Facets = 20-25% Load transmitted uniformly across endplates & disc
- Uniform load transmits to annulus
- Isotropic stress profile
- Ligaments pull stress away from disc
- 80% Anterior : 20% Posterior



Shirazi-Adl, Farfan, McBroom

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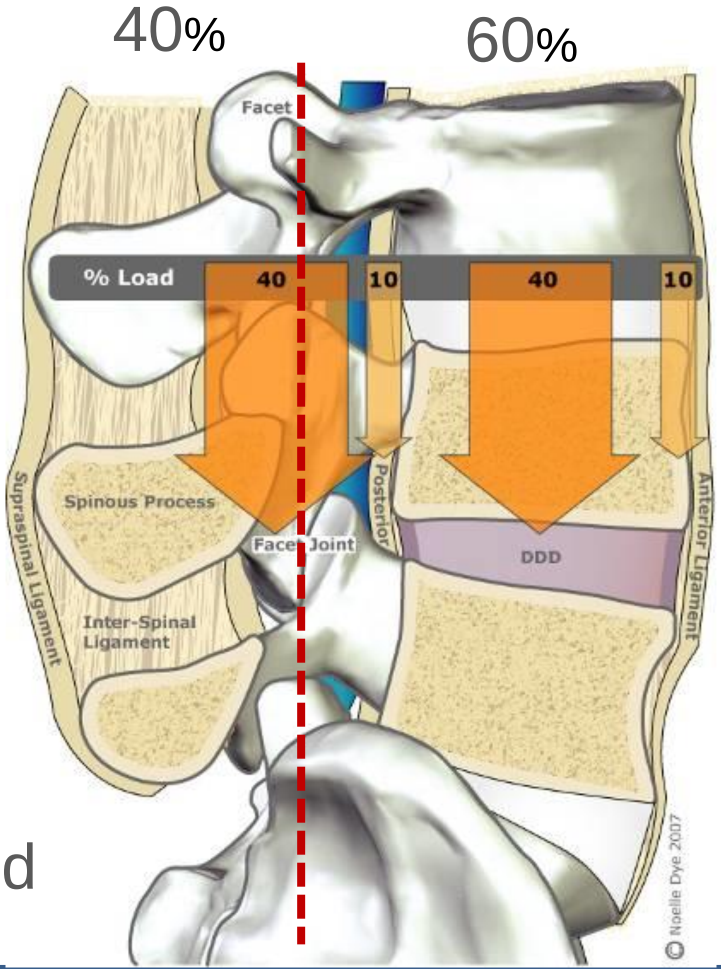
LOAD BALANCE - DEGENERATIVE

- Less Efficient
- Vertebra + Disc = 40%
- Cortical shell = 10%
- Posterior Ligaments = 10%
- Facets = 40%
- Facets > load transmission
- Stress profile anisotropic
- Excessive stress & COR transmitted posteriorly



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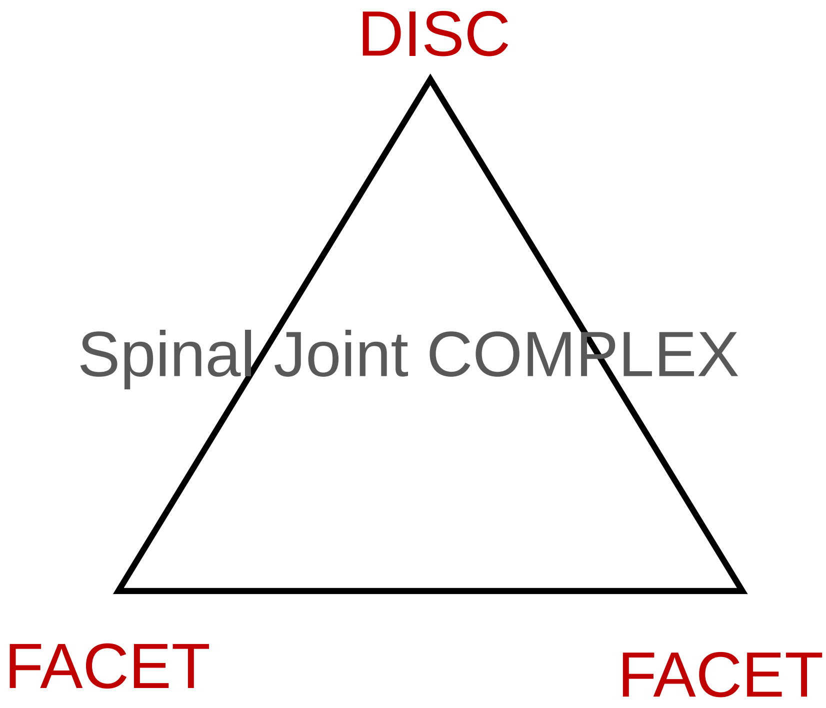
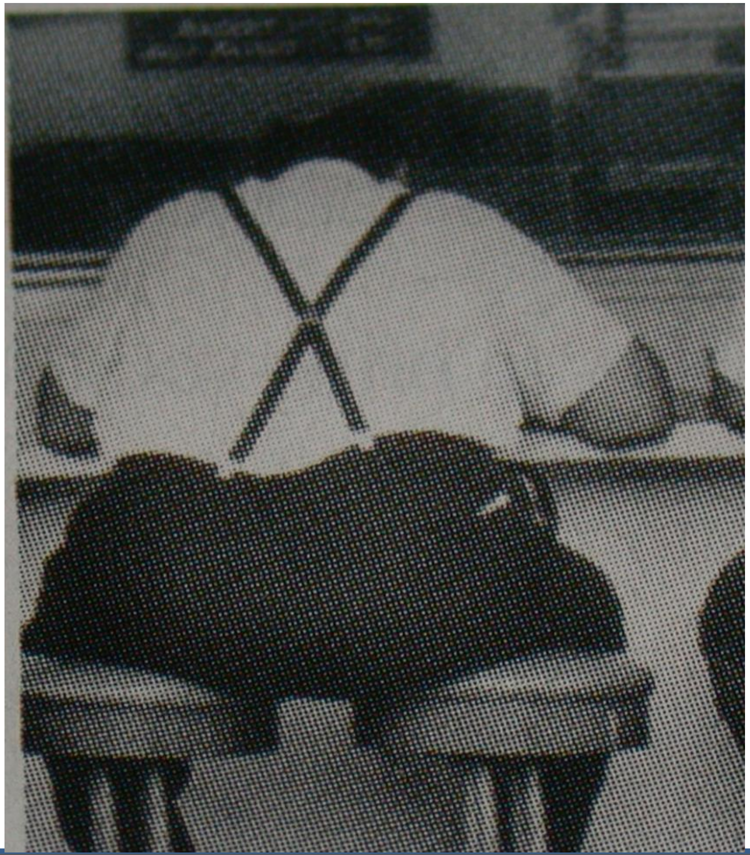
CURRENT CHALLENGES FOR BIOFIDELIC IMPLANT DESIGN

FACET JOINT – COMPLEX JOINT

Interdependence of disc + facets
Soft + Hard tissue





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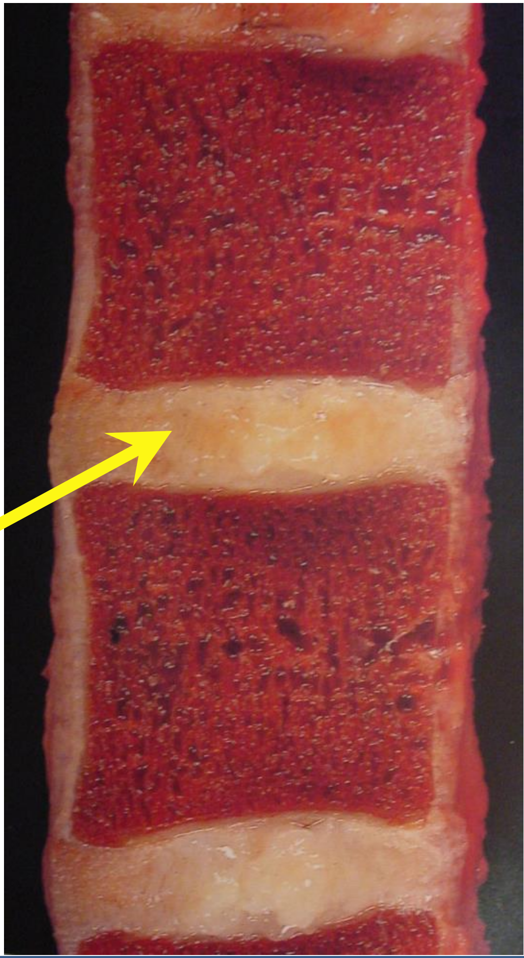
Challenges with Designing Intervertebral Implants

- Unique disc structure & endplate anatomy
- Bone Integrity
- Fit of implant within interspace
  - Cortical Margining
  - Avoid centrum = stress riser
  - Endplate viscoelastic



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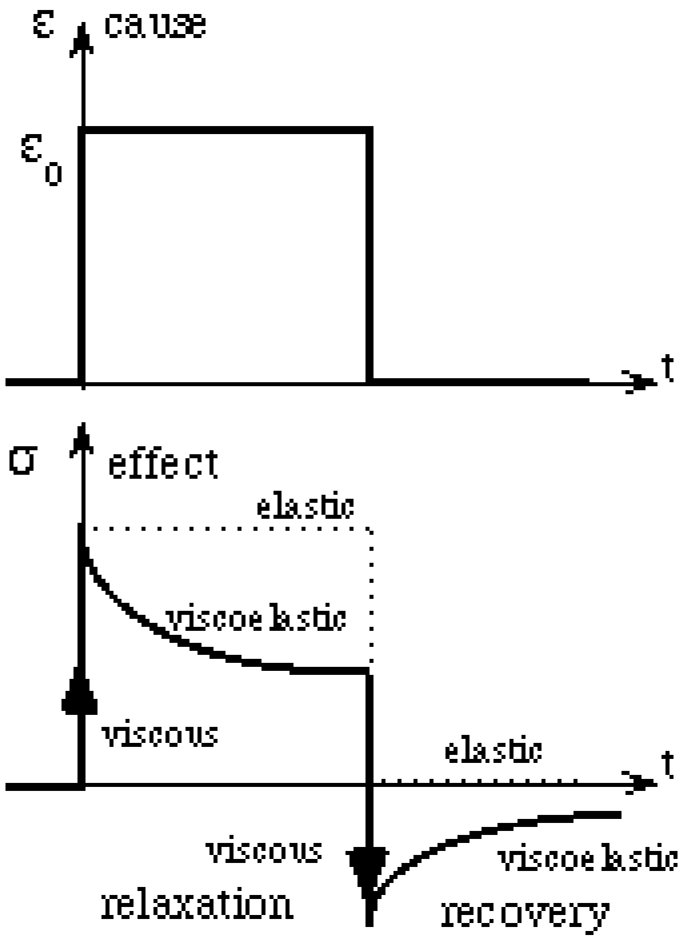
VISCOELASTICITY

- Behaves like fluid & solid
- Stress relaxation
- Load rate dependent
  - Intervertebral Disc
  - Bone
  - Soft tissue
- Ex: Silly Putty

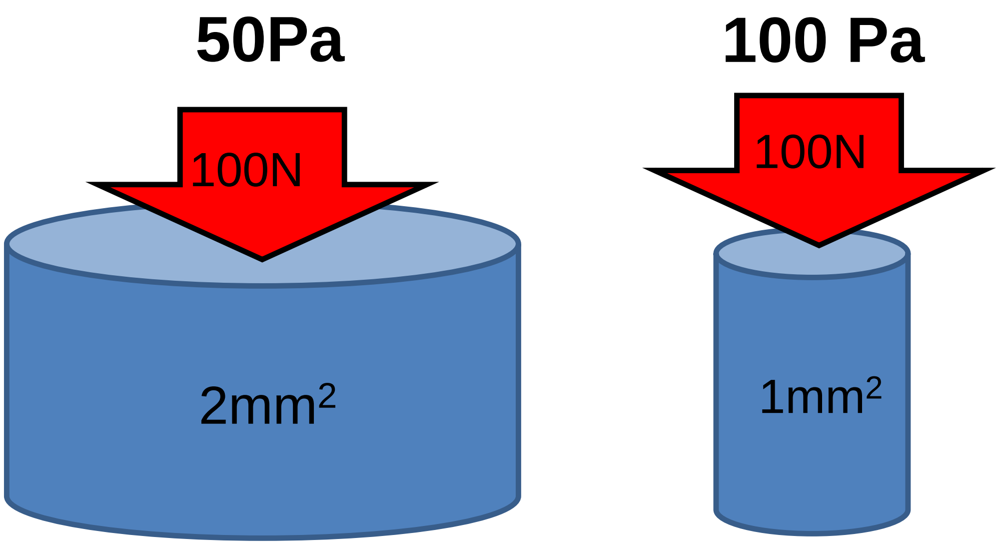


ELASTIC MODULUS

- Defines compliance ‘elasticity’ of material
- EM = Stress / Strain
- Material Modulus – Ti = Stress/strain of bulk material
- Global modulus – Stress/Strain of implant
- Localized modulus – Stress/strain of strut member

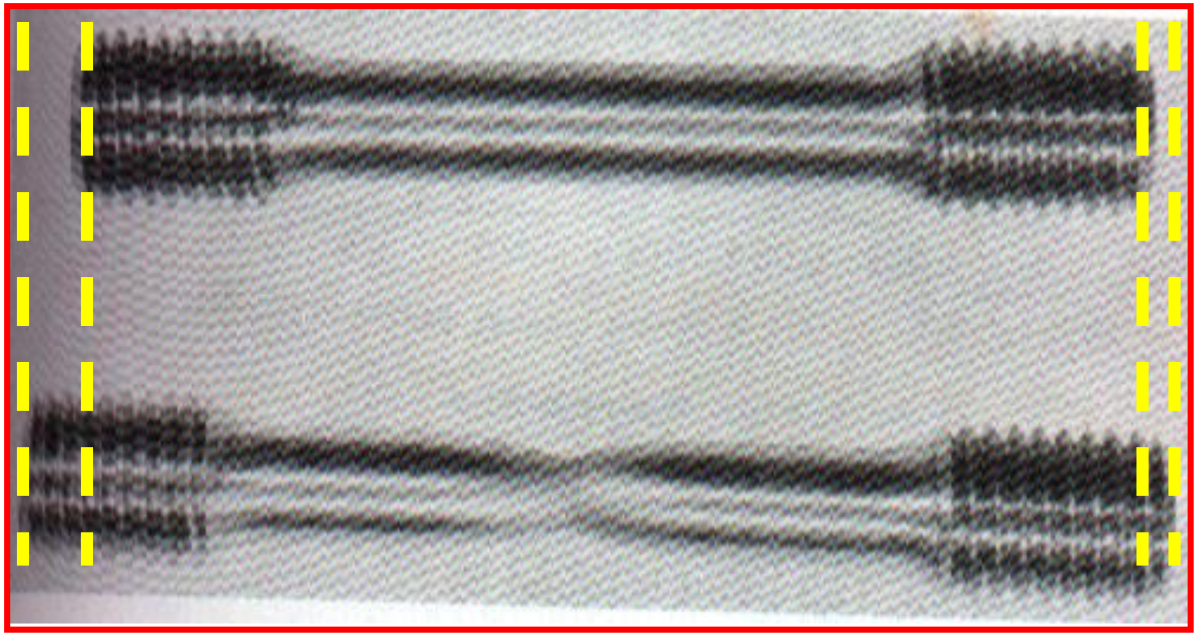
STRESS

- Force / Area
- Units: N/mm^2, Pascals
- σ = Force / Area



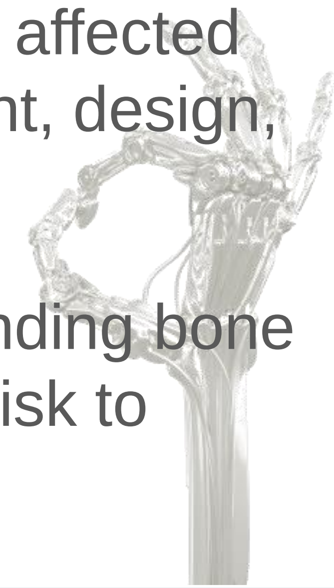
STRAIN

- Linear: Δ length / original length
- Rotational: angle / original angle
- $\in = \Delta L / L0$



BIOMECHANICAL MYTHS

- Modulus Matching – PEEK vs.Titanium
  - Myth - Believed to be necessary to provide improved load sharing, reduce incidence of stress risers/shielding
  - Fact – Behavior at the bone-implant interface affected by many factors; bone quality, implant footprint, design, geometry, edges.
  - Large footprint will decrease stress to surrounding bone and capture stronger peripheral bone = less risk to subsidence



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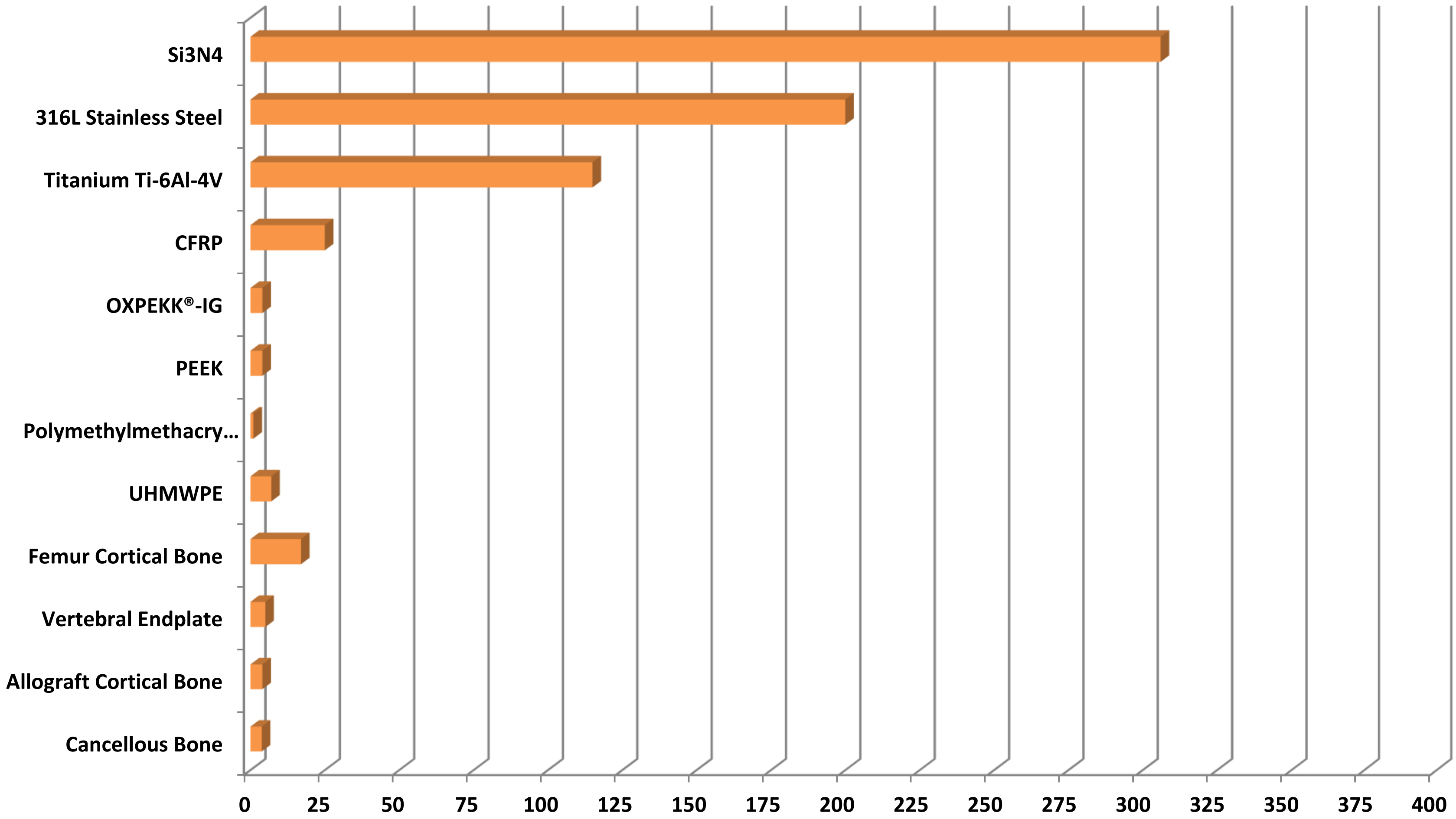
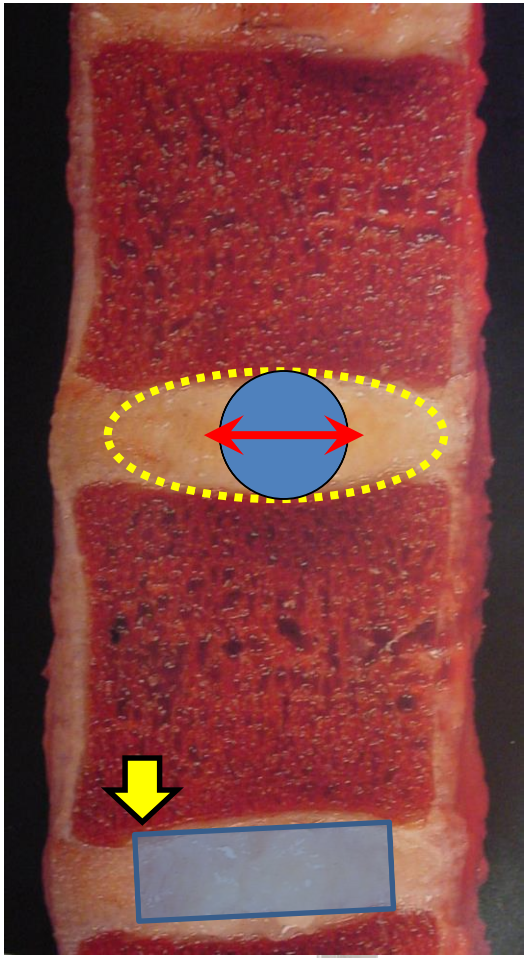
BULK ELASTIC MODULUS (GPa)



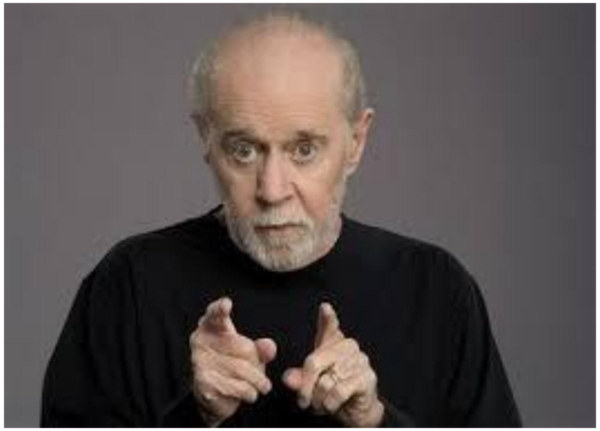
Biomechanical Challenges for Implants

- Matching elastic moduli (??)
  - Increase implant footprint
  - Engage cortical margin
  - Avoid implant stress risers
  - Understand implant EM
- Matching endplate shape (curvature)
  - Increase contact surface area
  - Reduce stress (or stress risers) to endplate
  - Avoid abrupt interfaces
- Avoid concentrated stress at centrum
  - Endplate weakest at center



SETTLING VS. SUBSIDENCE

- Settling
  - Natural occurrence of the human tissue to creep under compressive loads due to the viscoelasticity of the tissue
  - Natural settling 1- 2mm - cervical fusion / 1.5-2.5mm lumbar / viscoelastic endplates



- Subsidence
  - Exceeds the natural viscoelastic limit of the tissue
  - Enters the plastic deformation stage
  - Potential ‘penetration’ into the weaker substrate
  - Footprint greatest influence on subsidence
  - But there is balance between footprint & other factors (EM, design, shape)
  - STRESS TRANSFER

IMPLANT FOOTPRINT & FUSION STABILITY

- Multi-directional bone exchange & incorporation = better biomechanical stability
- Improved stability allows for further ingrowth towards center- throughout implant
- Greater fusion footprint – better stress distribution throughout implant
- Surface texture can aid with attachment – earlier stability

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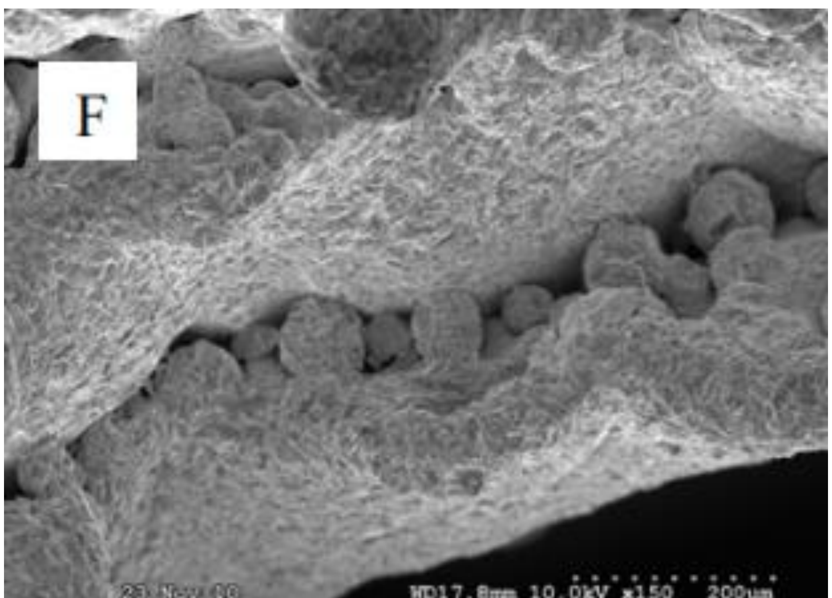
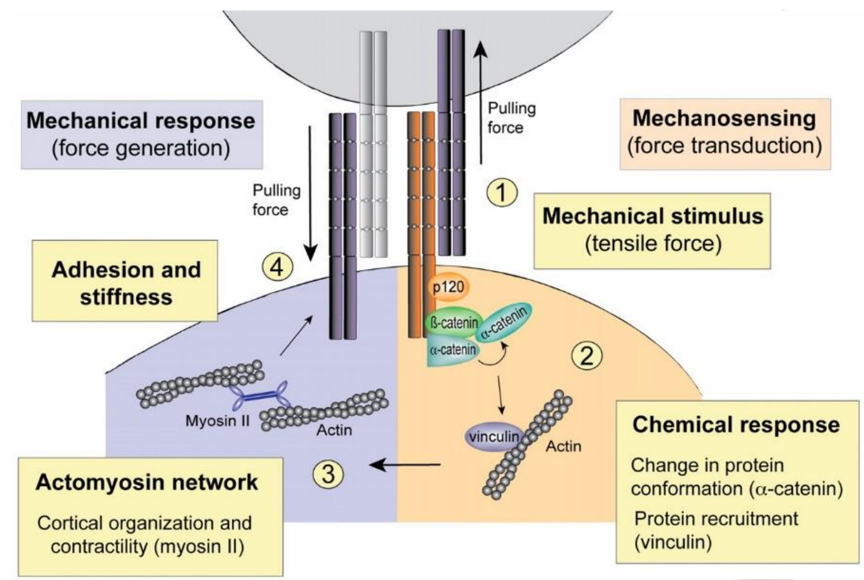
Surface Finish / Biomechanics / Mechanotransduction

- Surface finish / texture correlates with grip strength of implant component
- Improves bone attachment
- Rough = high coef. of fiction – reduces sliding of substrate on material
- Process where mechanical energy is converted -electrical & biochemical.
- Mechanical stimuli ⟷ Tissue ⟷ individual Cells





Cellular Mechanotransduction

- All eukaryotic cells - mechanosensitive
- Forces (gravity, tension, compression, shear,) influence cell behavior (growth and tissue remodeling).
- Cellular Mechanotransduction – the mechanism by which cells convert mechanical signals into biochemical responses.
- Cells respond to applied force stimuli to tissue --- AND---
- Internal forces generated from cell cytoskeleton respond by generating contractile forces for motility, matrix formation
- Continuous, dynamic cyclical process

BIOMECHANICAL MYTHS

- Stiffness – Ex: PEEK vs. Titanium
  - Myth - A stiff implant will have increased risk to stress shielding & subsidence
  - Fact – stiffness is related to combination of material properties + implant design (footprint) + stress transfer through implant

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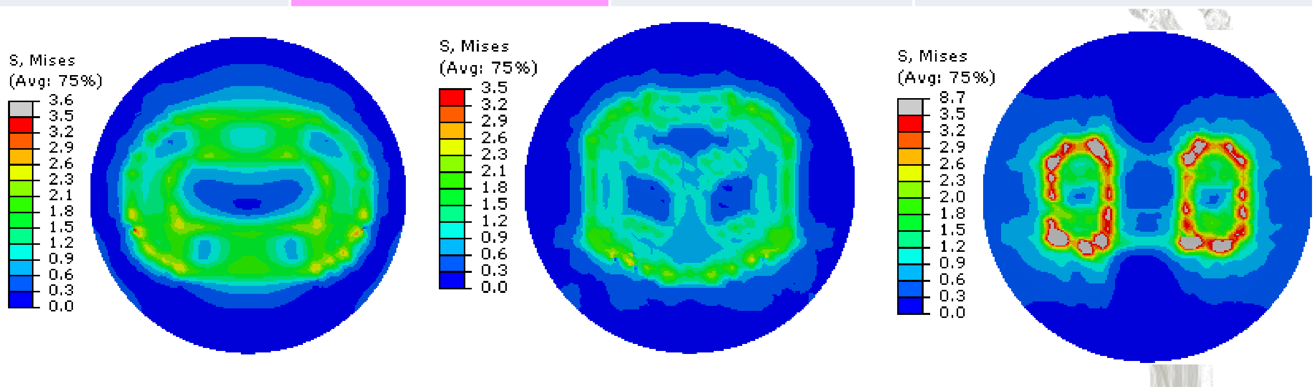
STIFFNESS & STRESS

Loading Mode	Ti ALIF	PEEK ALIF	Ti Cylinder
Axial Compression (KN/mm)	6.3	4.1	3.8
Flexion (Nm/Deg)	8.3	5.5	2.7
Lateral Bending (Nm/Deg)	15.5	7.1	8.3
Axial Rotation (Nm/Deg)	48.7	36.2	24.6

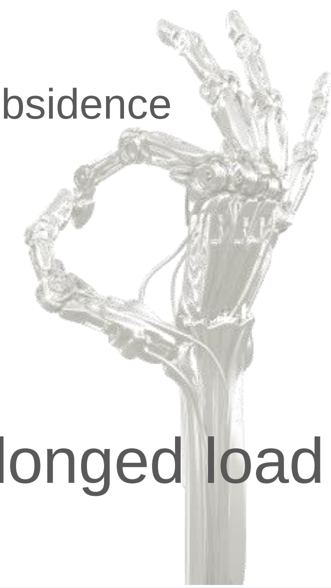
FEA of STRESS PROFILE FOR ENDPLATE



The larger Ti ALIF highest stiffness, largest bone volume containment = less stress at endplate, less stress than Ti cylinders

SUMMARY

- Understand your biomechanical environment
  - Bone & soft tissue integrity (tissue stiffens with dessication)
  - Implant design & position within space
  - Stress transfer to surrounding structures
    - Bigger IBF footprint = less stress to endplates = less risk to subsidence
  - Too rigid can be as bad as not rigid enough
  - Implantation - More is not always better
  - Strive for load balance
  - Implants should load share with tissue – prolonged load bearing will = IMPLANT FAILURE



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THANK YOU

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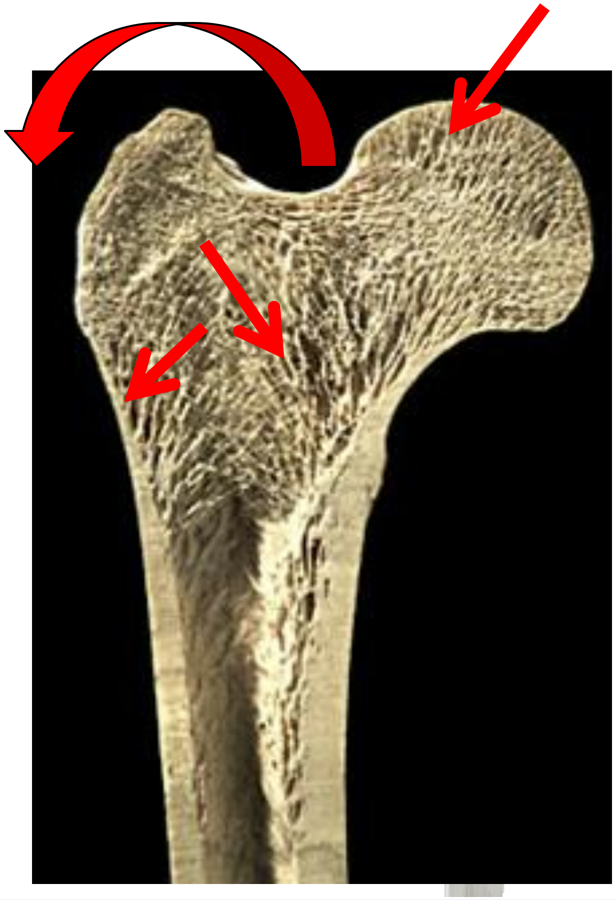
IMPLANT DESIGN CHALLENGES

- Biocompatibility
- Optimized material & design for osteoblast recruitment
- Balance – re-establish a healthy loading pathway along the spine to slow the degenerative cascade.
  - Ideal stress transfer to surrounding tissues within biomechanical thresholds
- Implant mechanics should match the kinetics of spine for site specific performance
- Ease of Fabrication in reproducible, consistent manner
  - Adequate Sterilization, surface finish, cost of production
- Ease of Repair / Revision for failed implants

THE GOOD, THE BAD, THE UGLY

OPTIMIZING OSSEOINTEGRATION

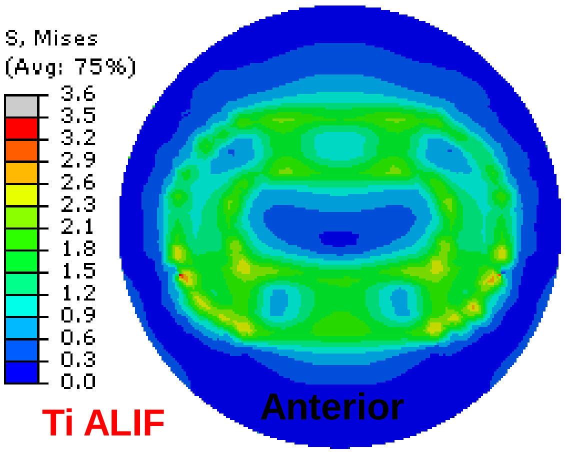
- RESPECT & UNDERSTAND WOLFF'S LAW
  - Bone growth responds to stress and strain
  - Region specific – different bone responds to different stress/strain
- MATERIAL + DESIGN = OSSEOINTEGRATION
  - Cascade of events for bone integration
  - Immobilize/stabilize – optimal strain for osteoblast differentiation/recruitment
  - Material favored by osteoblasts
  - Design provides uniform distribution of optimal strain + allows for multiplanar bone ingrowth = early anchoring for stability and continued



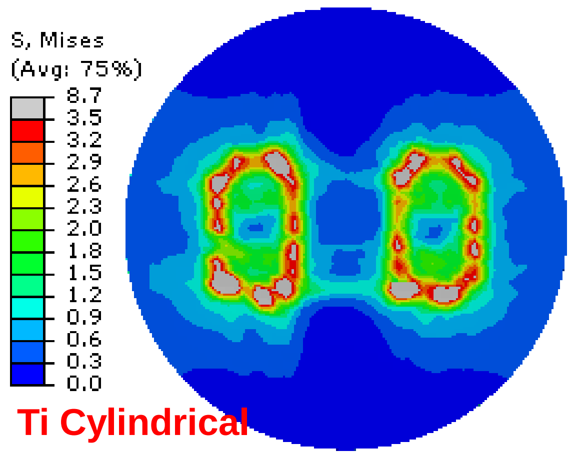
BULK MODULUS (MATERIAL)

Material	Elastic Modulus (GPa)
316L Stainless Steel	200
Titanium Ti-6Al-4V	115
Allograft Cortical Bone	4.0-8.0
PEEK	4.0
PEKK	4.0
Polymethylmethacrylate	1.0
Cancellous Bone	0.1

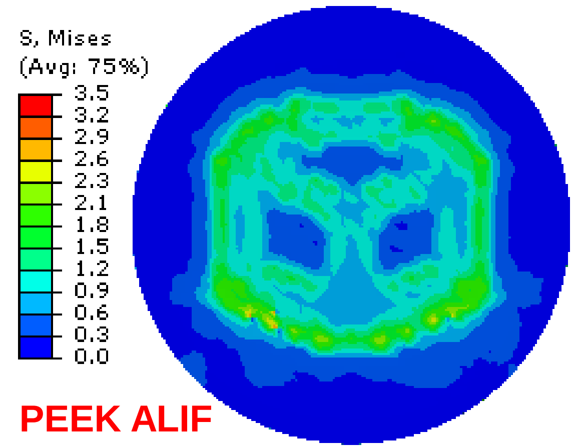
FORCE DISTRIBUTION AT BONE INTERFACE GEOMETRICAL INFLUENCES (vs. modulus matching)



Ti ALIF

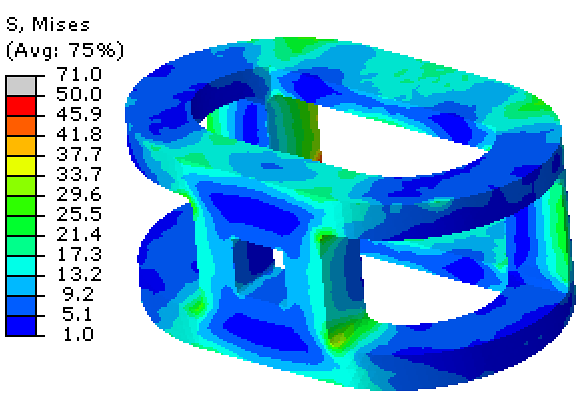


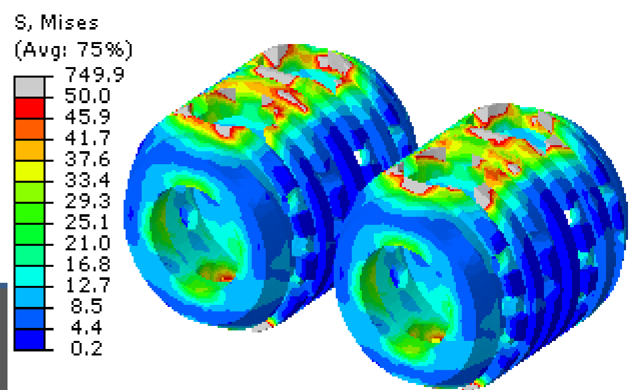
Ti Cylindrical

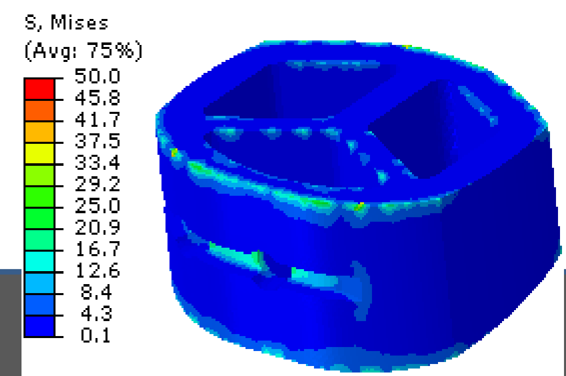


PEEK ALIF

- **Stress risers – small geometry at bone interface**
- **Result in subsidence, pistoning through bone**
- **Stress risers at bone and implant interface**







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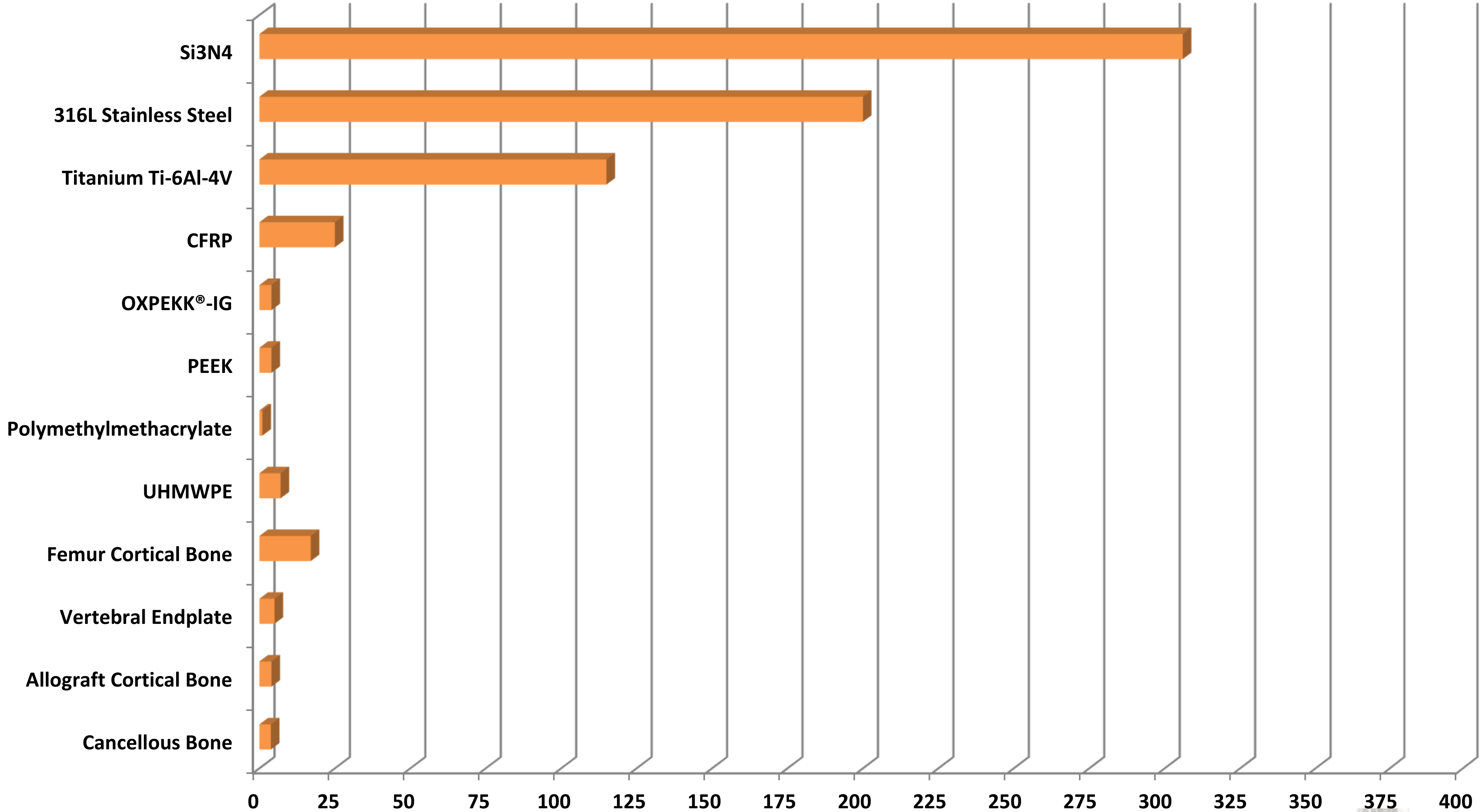
BIOMECHANICAL MYTH 2

Stiffness of the Implant:

- A stiff implant will have increased risk to stress shielding and subsidence
- Fact – stiffness is related to the combination of the material properties + implant design

ELASTIC MODULUS (GPa)



- Si_3N_4
  - 100X stiffer than Cancellous Bone
  -

MODULI COMPARISON

Material	Elastic Modulus (GPa)
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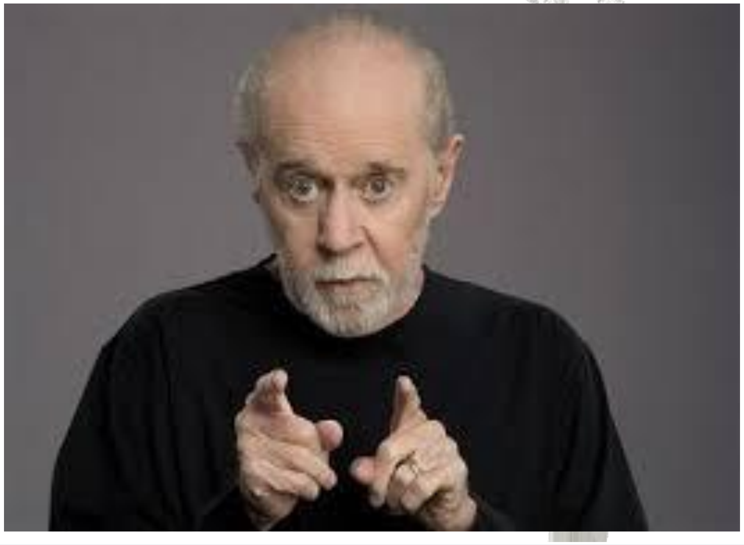
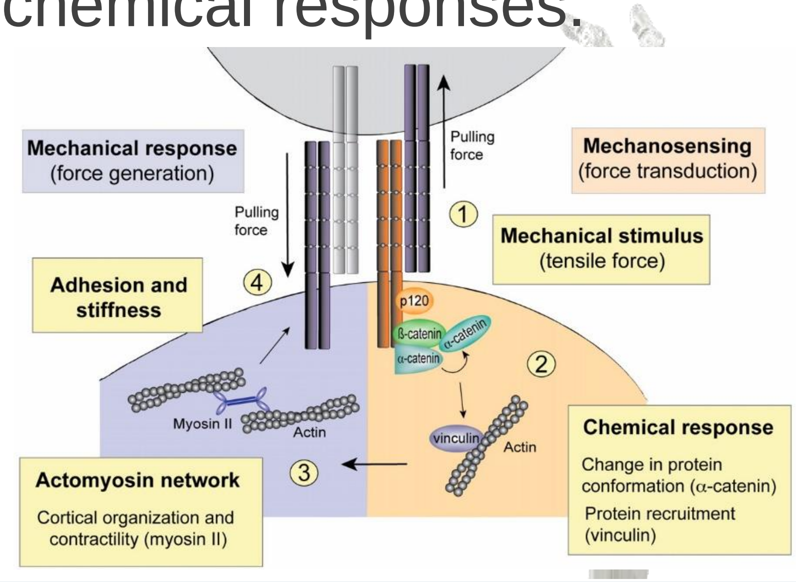
7 WORDS YOU CAN'T SAY TO THE FDA

1. Micromotion
2. Subsidence



Mechanotransduction

- Process where mechanical energy is converted into electrical and biochemical signals.
- Mechanical stimuli ⟺ Tissue ⟺ individual Cells
- Cellular Mechanotransduction – the mechanism by which cells convert mechanical signals into biochemical responses.



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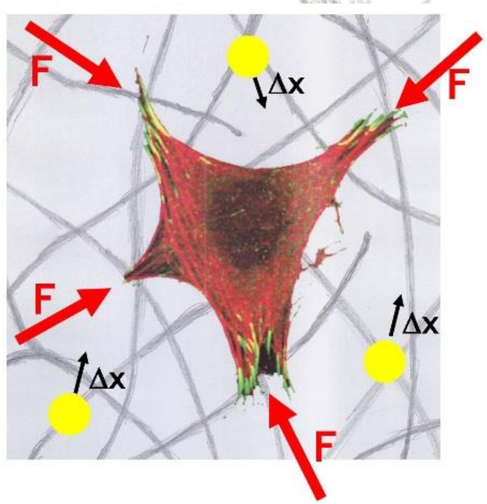
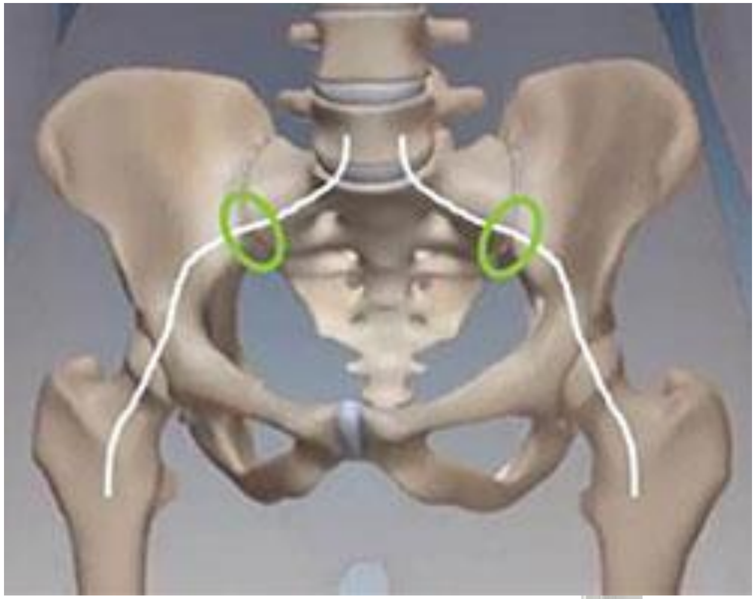


FORCE CLOSURE

- Forces created by contraction of stabilizing muscles
- produce a “self-locking” mechanism for joints,
- resulting in increased joint stability.
- For SIJ - occurs through contraction of deep muscles in low back, hip, pelvis
- controls translation & shear by compressing joint



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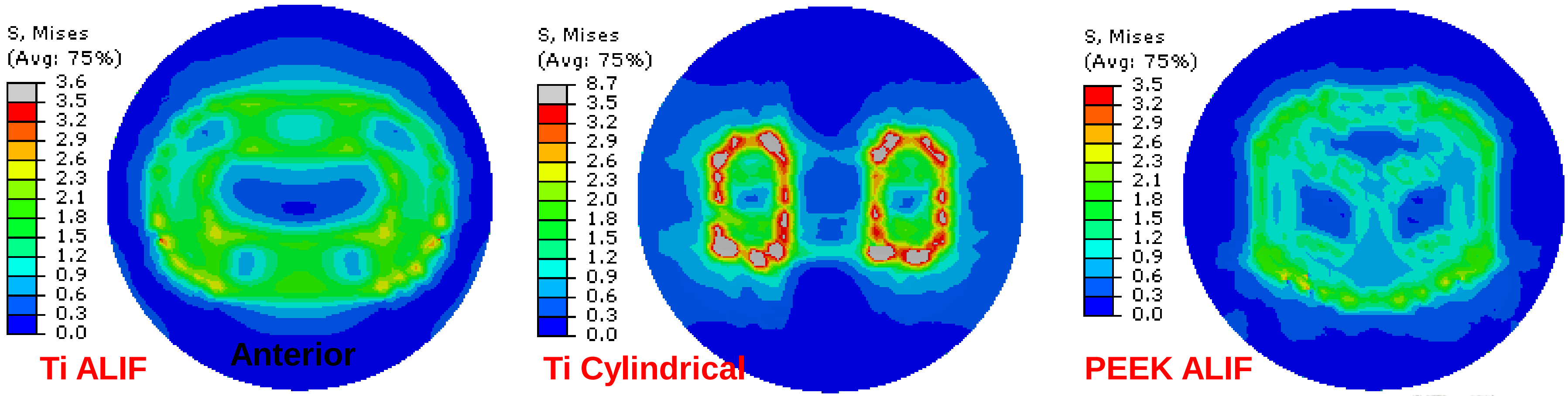

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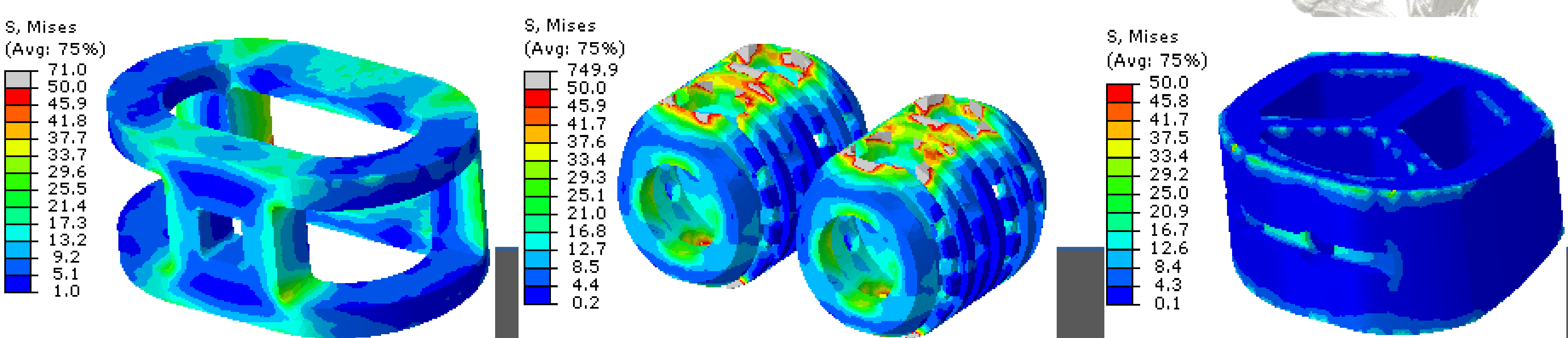

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WOLFF's LAW

Form Follows Function

- Bone will remodel along lines of stress / resorb in lack of stress-strain
- Function – Walking
- Form – Results in Bone remodeling along lines of greatest stress during function
- Dynamic System – Bone remodeling is a constant process responding to constant stimuli