Biomechanics of Bone and Skeletal System

Course Text: Hamill & Knutzen (Ch 2)
Nordin & Frankel (Ch 1) or Hall (Ch. 4)

The Musculoskeletal System

- bone
- tendons
- ligaments
- fascia
- cartilage
- muscle

Connective Tissues

- Over the next few weeks we will look at the biomechanical properties of these tissues.

Connective Tissue Composition

- **CELLS** {fixed (fibroblasts, chondroblasts, osteoblasts; migratory(e.g. mast & plasma cells)
- **EXTRACELLULAR MATRIX**
  - fibres {collagen (collagenous & recticular), elastic}
  - ground substance (calcium, lipids, glycoproteins, proteoglycans)
- **TISSUE FLUID** (filtrate of the blood)

Skeletal System Functions

- Movement Related Functions
  - Levers
  - Support
- Non-Movement Related Functions
  - Protection
  - Storage of fat and minerals
  - Blood cell formation

Composition of Human Bone

WATER 25-30%
MINERAL 60-70% (Resists compression)
- Calcium phosphate 85%
- Calcium carbonate 10%
- Calcium fluoride 2-3%
- Magnesium fluoride 2-3%

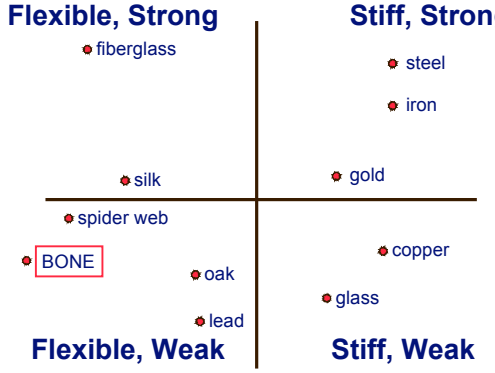
PROTEIN (Collagen) 5-15% (Resists tension)
Bone is termed a two-phase material

Bone Structure (density)

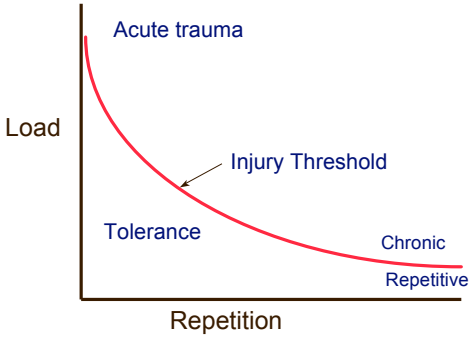
- Compact (Cortical) Bone
  - porosity < 15%
- Spongy bone
  - porosity > 70%

How strong are my bones?

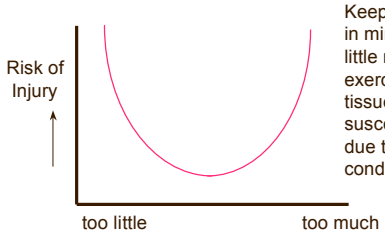
Probably not as strong as you thought!



Tissue Tolerance



Tissue strength (conditioning) is also a factor in risk of injury



Keep the big picture in mind. If you have little movement/ exercise then the tissues become more susceptible to injury due to poor conditioning.

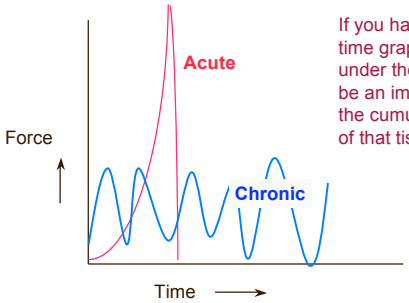
Movement (repetition), force (lifting) physical activity, sitting or standing

Hippocrates (460-377 B.C.)

"All parts of the body which have a function, if used in moderation and exercises in labours to which each are accustomed, thereby become healthy and well-developed: but if unused and left idle, they become liable to disease, defective in growth, and age quickly. This is especially the case with joints and ligaments, if one doe not use them."

LeVay 1990. p30.

Acute vs. Chronic Injuries



If you had a force vs time graph the area under the curve would be an impulse (Ft => the cumulative loading of that tissue)

Cumulative Loading

- Assessing the effect of cumulative loading is a difficult thing.
- If there is adequate recovery time then even high cumulative loads may be safe.
- On the other hand a one time high peak force over a very short period of time (low cumulative load) may exceed the strength of the tissue and cause injury.

Biomechanical Factors

- Kumar (1999) argues a theory of overexertion that states overexertion can be created by exceeding the normal physical and physiological in any one of: force (Fx), exposure time (Dy), range of motion (Mz).
- The weighting of these three functions is obscure but Kumar symbolically represents overexertion (OE) with the equation below.

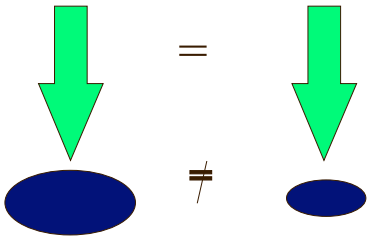
$$OE = \int (F_x, D_y, M_z)$$

Tissue Biomechanics

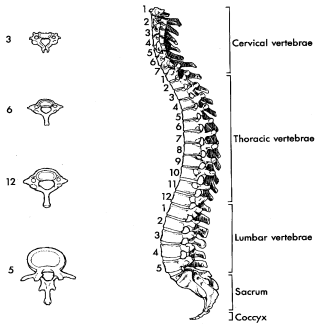
- Any deformation or residual deformation alters the mechanical response of the tissue reducing its stress bearing capacity.
- The tissues that frequently get injured due to occupational biomechanical hazards are ligaments, tendons, muscle and nerves (cartilage and bones less so).
- However, all biological tissues are viscoelastic so we will quickly review the properties of viscoelastic structures during this lecture on skeletal biomechanics.

Stress	Strain
Force/Area	$\frac{\Delta \text{length}}{\text{original length}}$
Same units as pressure	Ratio, no units.

Force vs. Stress



Compression in Vertebrae



Calculation of Vertebral Strengths

Vertebrae	% of Body Weight Carried	Mass kg Carried by 72.7 kg Man	Breaking Strength (N)	Breaking Stress in Compression*	% of L4 Breaking Strength
T1	9	6.5	1,605	25.0	16.6
T2	12	8.7	2,140	25.0	22.1
T3	15	10.9	2,675	25.0	27.7
T4	18	13.1	3,211	25.0	33.2
T5	21*	15.2	3,746	25.0	38.7
T6	25*	18.1	4,459	25.0	46.1
T7	29*	21.0	5,173	25.0	53.5
T8	33*	23.9	5,864*	24.9	60.7
T9	37*	26.9	6,657*	25.2	68.9
T10	40*	29.1	7,277*	25.5	75.3
T11	44*	32.0	7,580*	24.2	78.4
T12	47*	34.2	7,835*	23.4	81.0
L1	50*	36.4	7,982*	22.4	82.6
L2	53*	38.5	8,584*	22.7	88.8
L3	56*	40.7	9,636*	24.1	99.6
L4	58*	42.2	9,667*	23.4	**100.0**
L5	60*	43.6	10,550*	24.6	109.1

*Single asterisk represents data collected experimentally by Ruff (1950).
Unmarked values are calculated or assumed.

Stress Strain

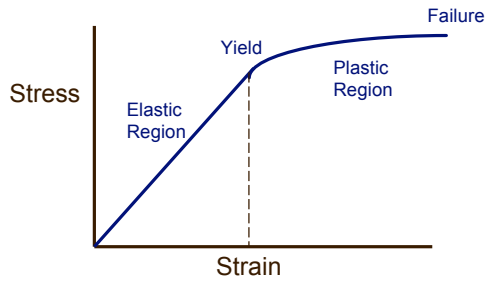
Force/Area

Same units as pressure

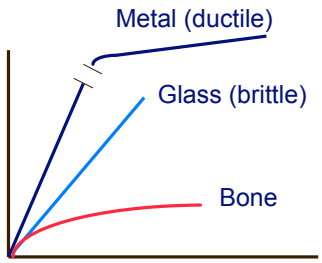
$$\frac{\Delta \text{length}}{\text{original length}}$$

Ratio, no units.

Elastic Response



Stress/Strain Curves



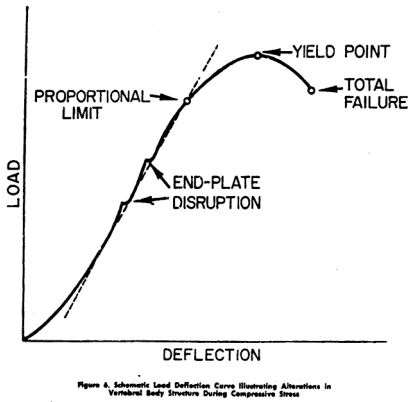
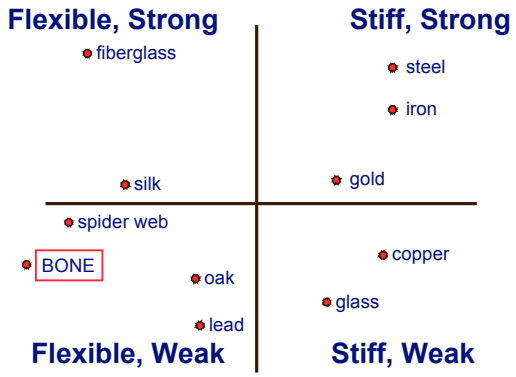


Figure 6. Schematic Load Deflection Curve Illustrating Alterations in Vertebral Body Structure During Compressive Stress

Strength & Stiffness

- Strength
  - Defined by the failure point. Also can be assessed by energy storage (area under curve).
- Stiffness (modulus of elasticity)
  - determined by the slope of the load deformation curve

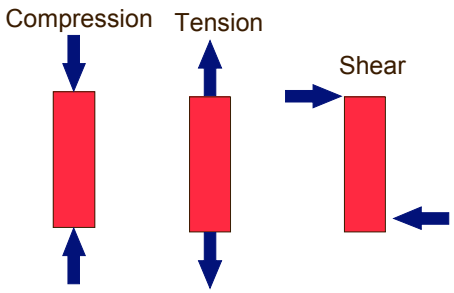


Young's Modulus

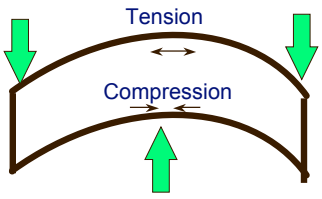
Young's Modulus is the ratio of:
tensile stress / tensile strain

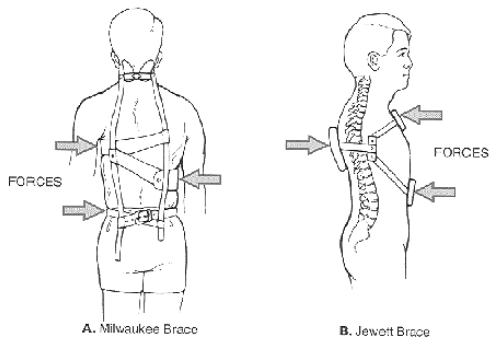
	Young's Modulus	Tensile Strength
Tendon	2×10^9	1×10^8
Bone	1.7×10^{10}	1.8×10^8
Carbon Steel	2×10^{11}	3×10^9
Soft rubber	$c.10^6$	

Direction of Force

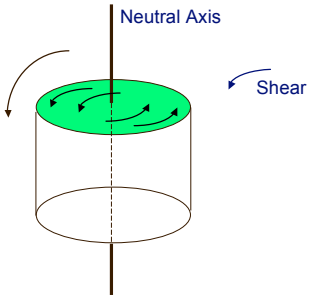


Bending

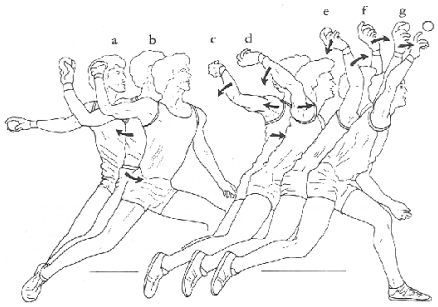




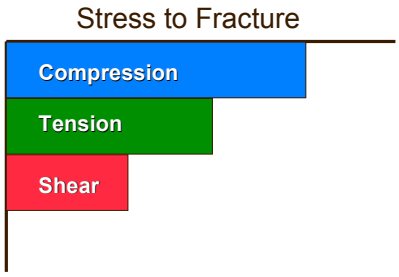
Torsion



Torsion



Anisotropic Characteristics



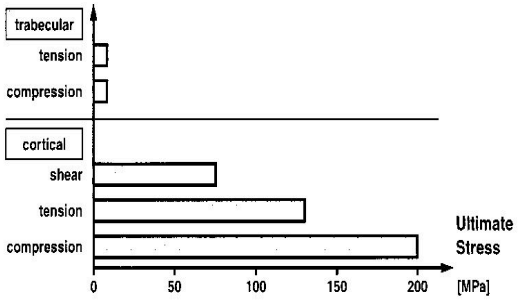


Figure 2.3.2 Order of magnitude of ultimate stress for cortical and trabecular bone (based on data from Yamada, 1970; Steindler, 1977; Reilly and Burstein, 1975; Martin and Burr, 1989, with permission of Williams & Wilkins, Baltimore, Maryland).

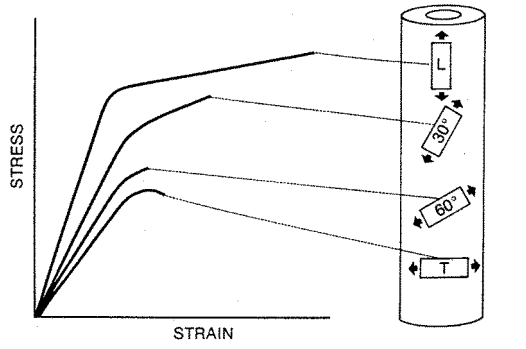
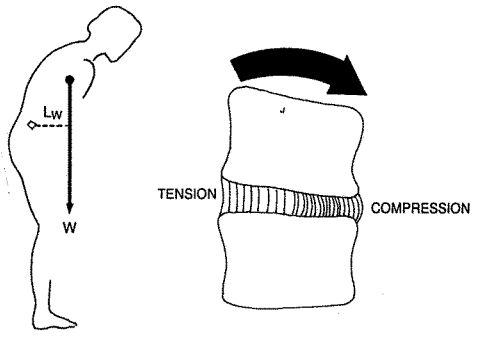
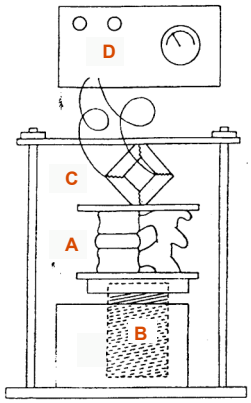


FIG. 1–9
Anisotropic behavior of cortical bone specimens from a human femoral shaft tested in tension (pulled) in four directions:



Bone Injury and Low Back Pain

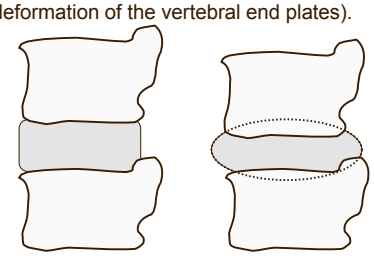
- Bone injury (e.g. endplate fracture) is far from the common cause of most back pain.
- However, extensive research has been conducted into disc compression as it is thought to be largely responsible for vertebral end-plate fracture, disc herniation, and resulting nerve root irritation.
- Back compression has been argued to be a good predictor of low-back and other overexertion injuries [Herrin+, 1986]
- Due to the clinical interest in this area data exists on the compressive strength of the lumbar vertebral bodies and intevertebral disks



Compression apparatus in which the specimens were subjected to pressure (maximum 300 kp) recorded by a measuring brined at the same times as Röutgen plates were made.

A = Specimen
B = Mechanically Driven Screw
C = Strain gauge
D = Measuring Bridge

Axial compression of the spinal unit results in a loss of height measured between the vertebrae. As the disc material itself is essentially incompressible, height decrease must result in a radial bulge of the disc and a corresponding axial disc bulge (an inward deformation of the vertebral end plates).



A centrally situated, postmortem fracture of the end-plate

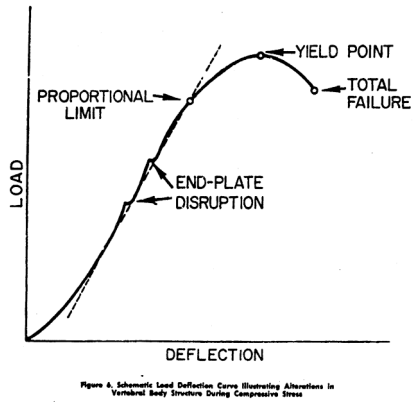
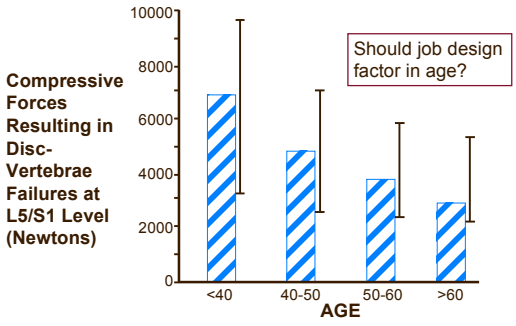


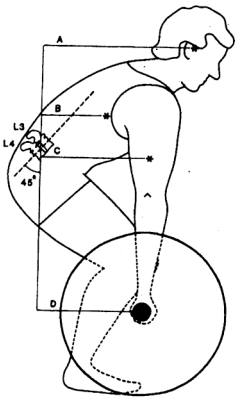
Figure 6. Schematic Load Deflection Curve Illustrating Alterations in Vertebral Body Structure During Compressive Stress

Mean and Range of Disc Compression Failures by Age (Adapted from Evans, 1959, and Sonoda, 1962)



Compressive Strength (N) Estimated for L4/L5 Spinal Unit from Mechanical Testing of Lumbar Spinal Units (males 20-40 years, n = 17). Porter, Hutton and Adams, 1989: Hutton and Adams, 1982

	Age	Compressive Strength (N)
Mean	28	10,093
Std. Dev.	9	1,924



Model opposite shows the lever arms (A-D) from L3-L4 for the head, trunk, arms and lifted weight.

Data in table overleaf was from calculated for world championship level power lifters.

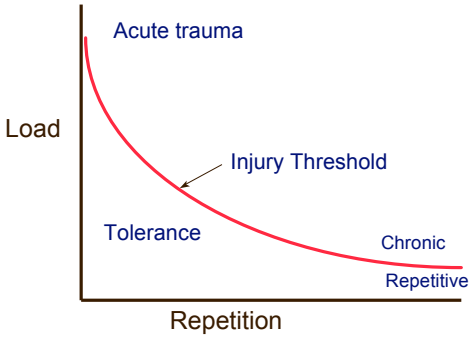
The Age, Body Weight, Height, Bone Mineral Content (BMC) in L3, Maximum Lifted Weight, Calculated Load on L3 and Annually Lifted Weight in the Eight Analyzed Power Lifters

Age (yrs)	Body weight (kg)	Height (cm)	BMC L3 (g/cm)	Maximum lifted weight (kg)	Load on L3 (kN)	Annually lifted weight (ton)
30	93	177	7.76	335	27.5	2,150
40	84	165	6.25	290	27.0	450
33	59	160	6.11	212	18.8	300
24	60	156	6.70	230	28.9	1,000
25	69	165	6.44	305	22.9	1,200
30	90	172	8.42	335	36.4	4,000
24	88	183	7.98	-	-	5,000
23	90	172	6.86	-	-	2,000

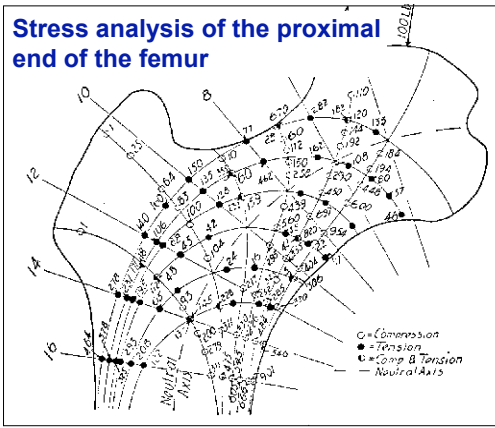
Fatigue Failure

- Compression fracture is the common failure mode of the vertebra-disc complex in severe axial loading. This mechanism does not apply to repetitive loading within the linear portion of the stress-strain curve. Low back pain and back disorders associated with frequent lifting, whole-body vibration and repeated shocks point to a chronic degeneration of tissues, rather than acute failure.

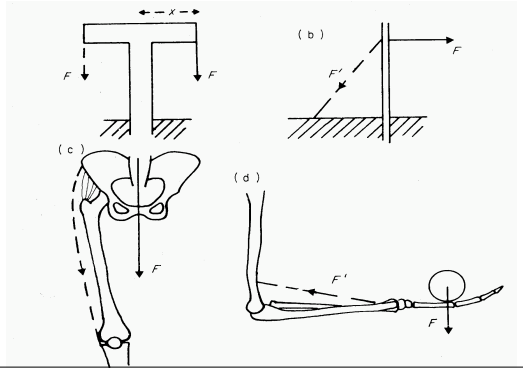
Tissue Tolerance



Stress analysis of the proximal end of the femur



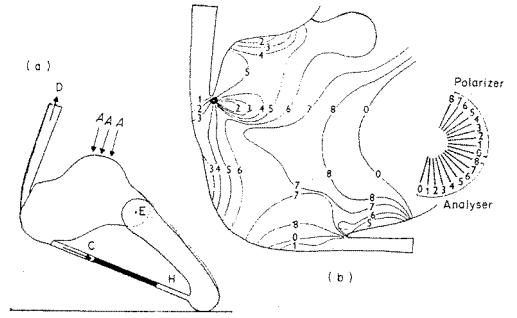
Avoiding Tension and Shear

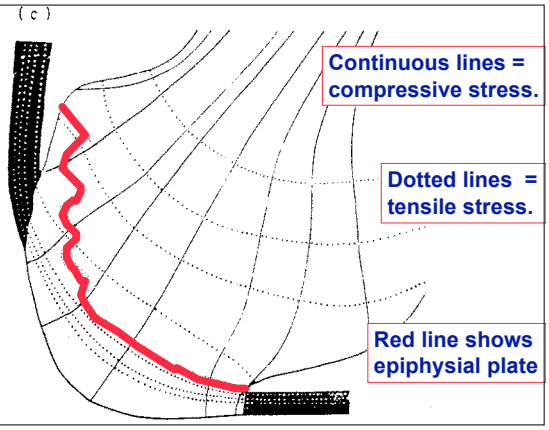


Balanced Loads

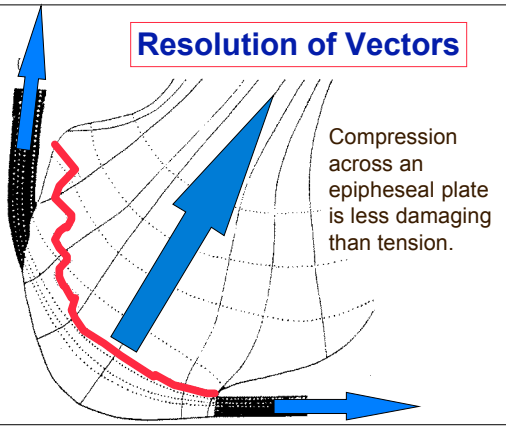
There are many examples where carrying is designed to carry two balanced loads in each hand rather than one heavier load in one hand.

Stress in the Human Heel. The model (left) with forces applied indicated by arrows. Stress pattern indicated by polarized light (right).



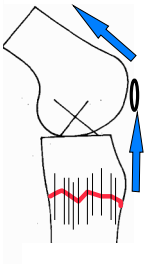


Resolution of Vectors



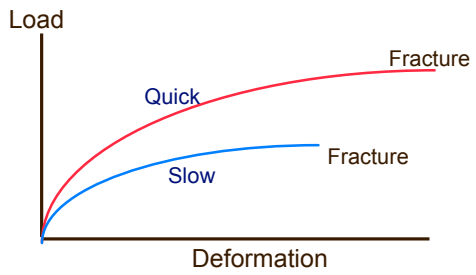
Compression across an epipheseal plate is less damaging than tension.

Where there is tensile stress across an epiphysial plate (such as the proximal end of the tibia) a lot of collagen fibres are present to protect the plate from excess tension.

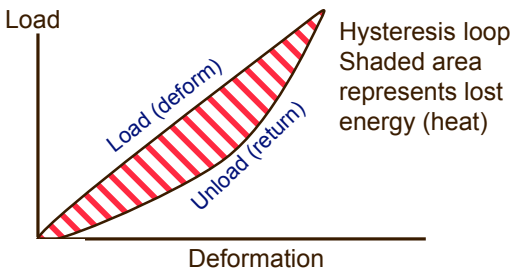


Quadriceps muscle force pulls on insertion point (via patella tendon)

Viscoelastic Characteristics



Viscoelastic Characteristics



Hysteresis loop
Shaded area represents lost energy (heat)

Stress Fractures

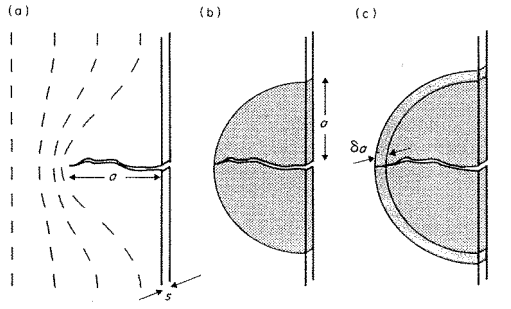
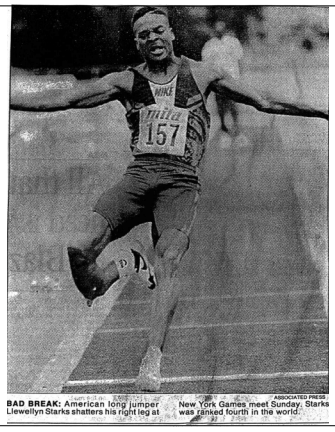


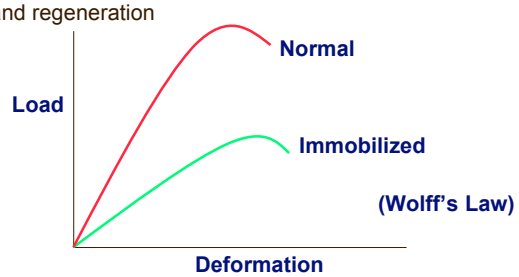
Fig. 4.2. A crack in the edge of a stressed plate, illustrating the Griffith theory of fracture.



BAD BREAK: American long jumper Llewellyn Starks shatters his right leg at New York Games meet Sunday. Starks was ranked fourth in the world.

Bone Remodeling

Issues of degeneration and regeneration



Loading, Muscular Activity, and Injury

- **Injury vs. Loading**
  - complex problem depending on loading level, direction, speed, skeletal maturity and conditioning.
- **Muscular Activity vs. Loading**
  - muscular activity influences loading (often reducing tensile loading). If muscles fatigue their ability to do this is compromised.

Tibial Boot-Top Fracture

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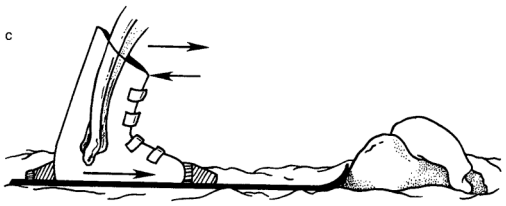

Sample Problem

- What is the compressive force on the L5/S1 vertebral disk of the 50% male?
- What is the compressive stress on this disk if it is aligned horizontally and its cross-sectional surface area is 24 cm^2?
- What is the compressive force on one tibia if the 50% male stands in the anatomical position (symmetrical weight bearing between both feet)?

Answer

Two total arm segments = 7.4 kg

(0.4 + 1.2 + 2.1) x 2

Head, neck and trunk above L5/S1= 33.5 kg

Total mass above L5/S1 = 40.9 kg.

Force on disk = 40.9 x -9.81= -401.2 N

Stress = 401.2/24 = 16.7 N/cm^2

401.2/0.0024 167,179 Pa or 167 kPa

Total mass less two shanks and feet = 74.4 - 8.8 = 65.6 kg $\Rightarrow$ 643.5 N. Per tibia = 321.8 N