ME 411 / ME 511

Biological Frameworks for Engineers

Biological Frameworks for Engineers

Class Organization

- Lab 3 report due Mon
- *Tiny Workhorse* Project
  - Reports due Wed, Nov 26
  - Presentations
    - 10 min with 1-2 min Q&A
    - Mon, Nov 24: Kevin/Ye, Nathan/Kateri, Scott/Spencer, Brian/Wai
    - Wed, Nov 26: Jarrod/Mark, Tadbhagya/Amit, Tzu-Jin/Jiayang, James/Kevin

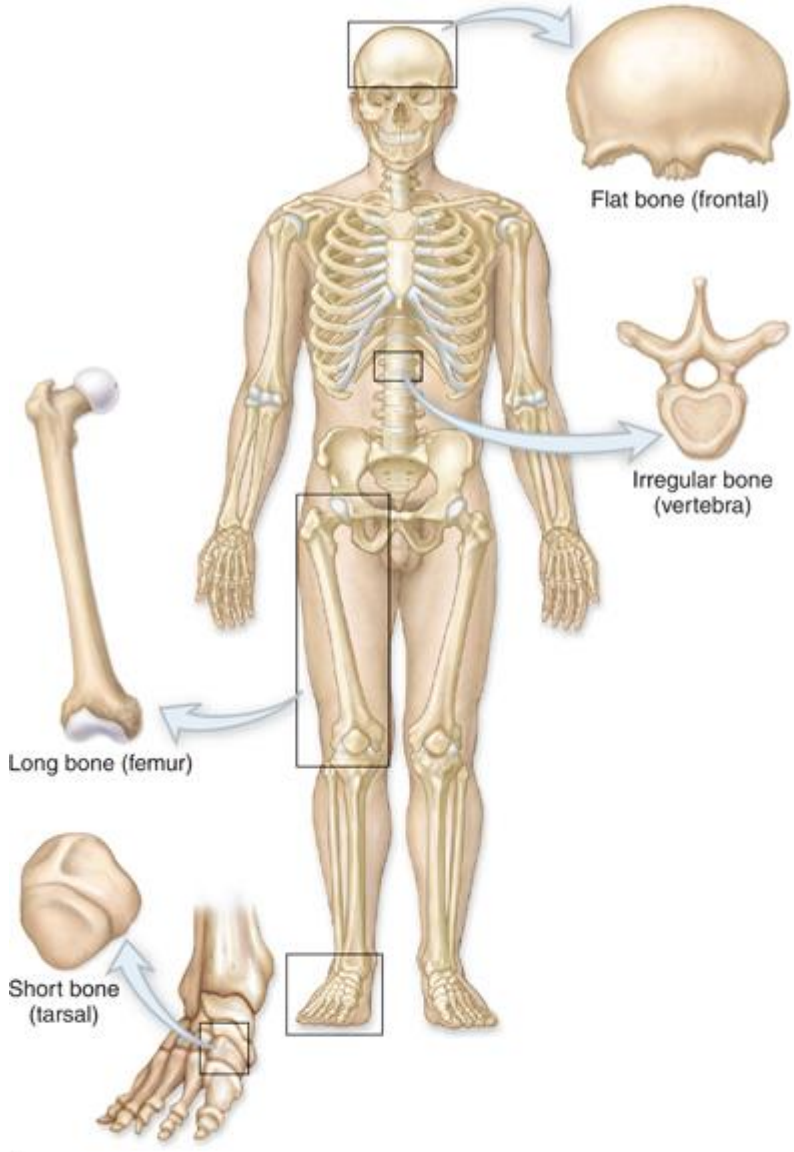
Biological Frameworks for Engineers

ME 411 / ME 511

Bone System

UNIVERSITY OF WASHINGTON

Bones



Living concrete:

Type 1 collagen

hydroxyapatite

$[Ca_3(PO_4)_2]_3 \cdot Ca(OH)_2)$

Functions:

Structural

Motion

Protection

Mineral Storage

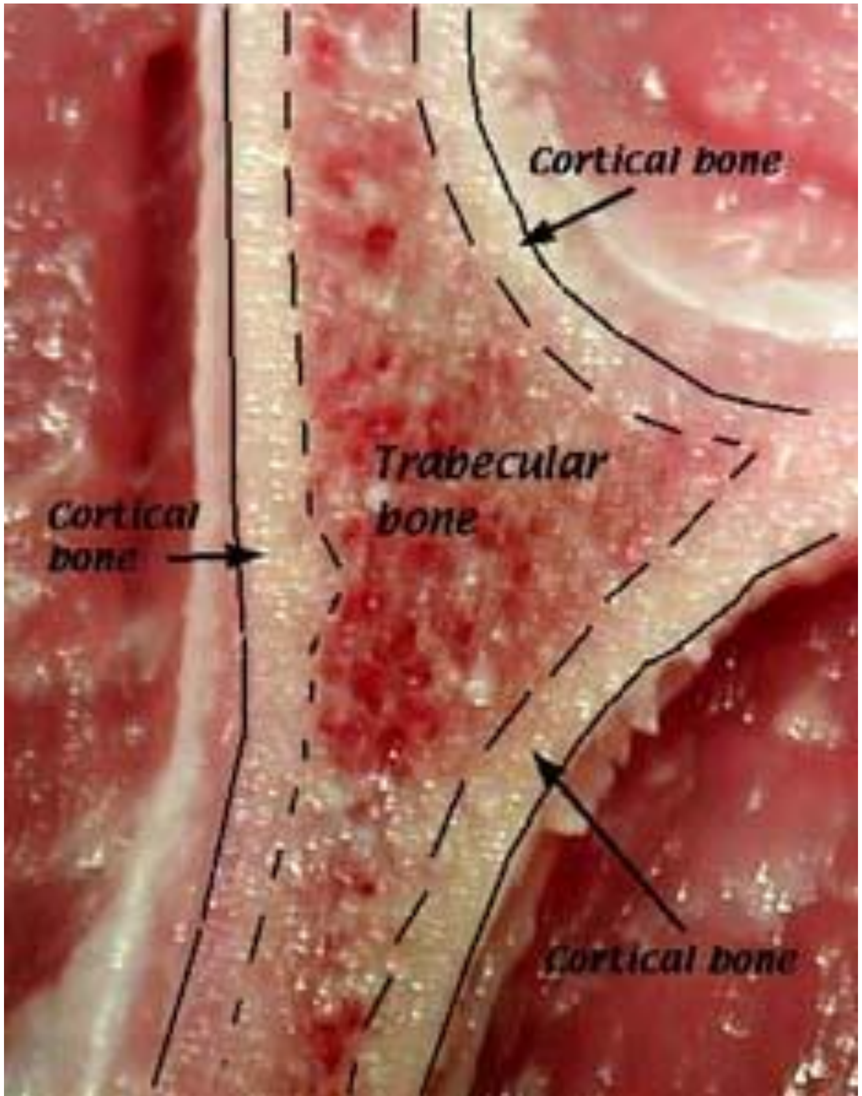
(Cell Factory)

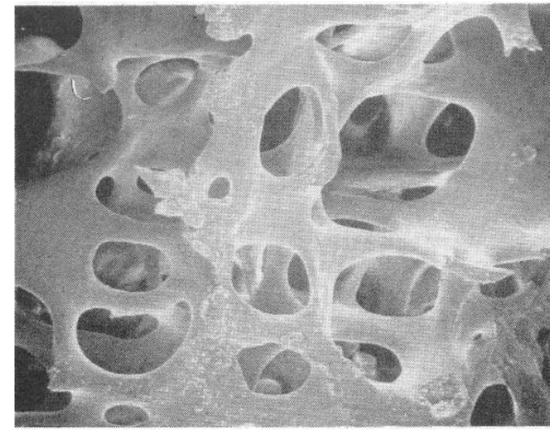
Extracellular Matrix

Table 9.2. Approximate composition of the extracellular matrix of bone tissue based on consensus values from several sources

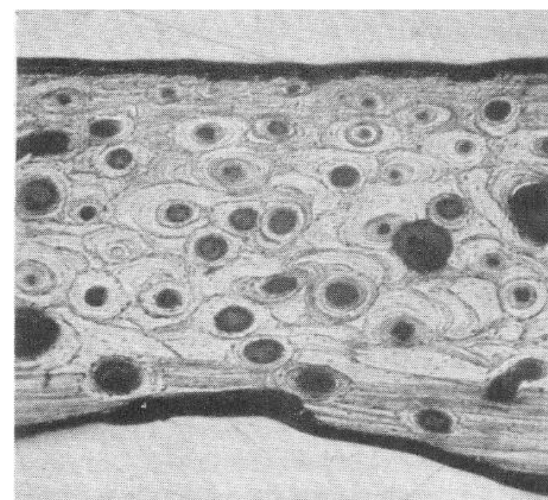
Component	Mass (%)
Mineral phase (hydroxyapatite)	70
Organic matrix (osteoid)	
Collagen (mostly type I)	18
Non-collagenous proteins and proteoglycans	2
Water	10

Types of Bone



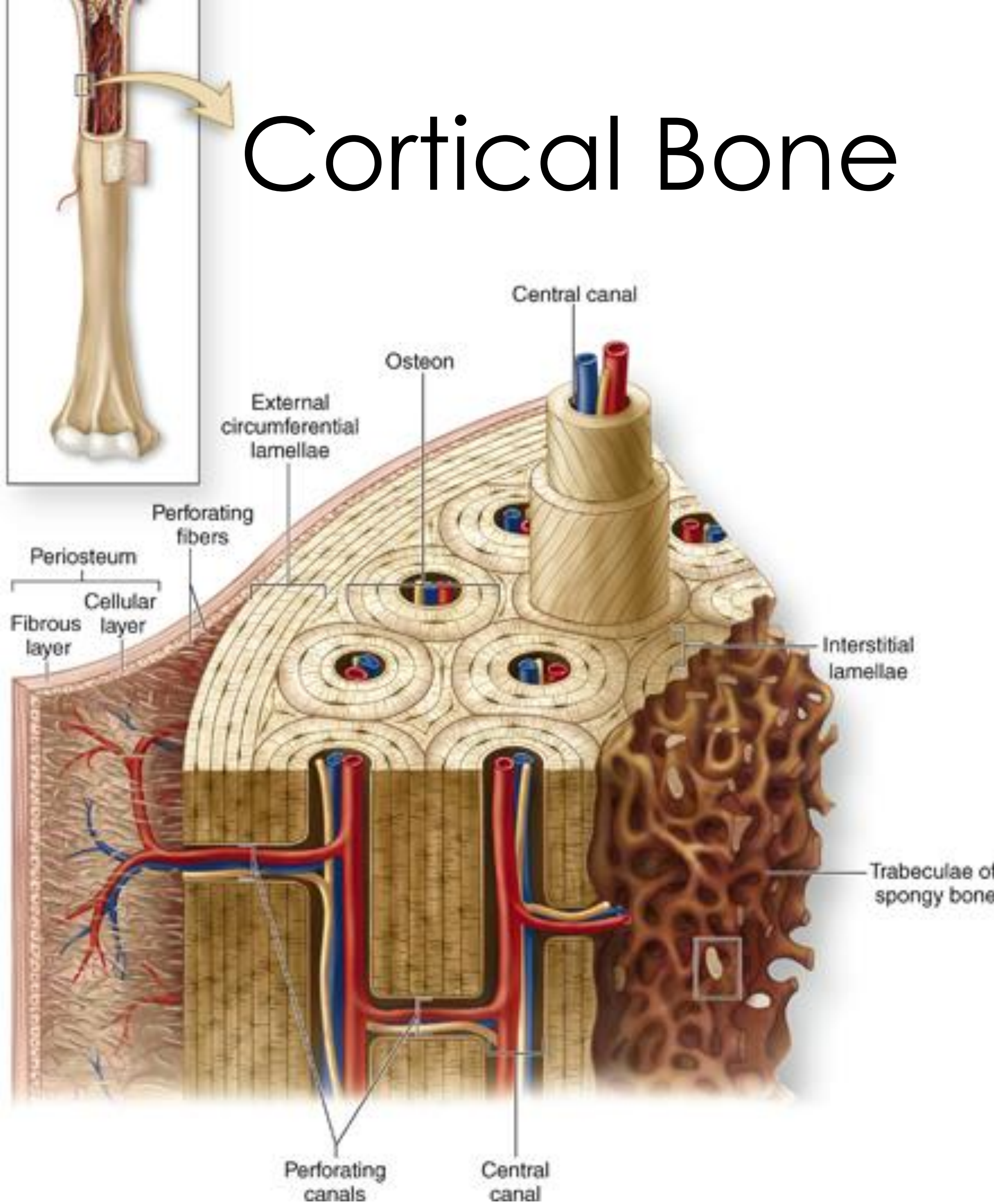


Trabecular

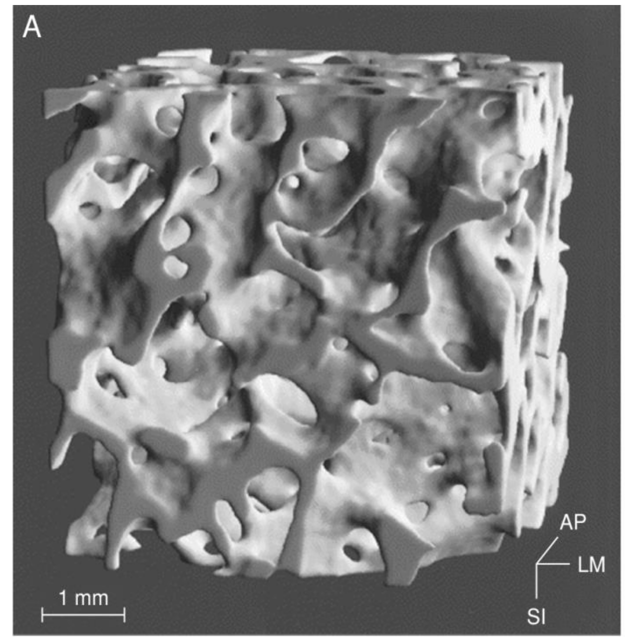


Cortical

Cortical Bone



Trabecular Bone



Biomechanics of Cortical

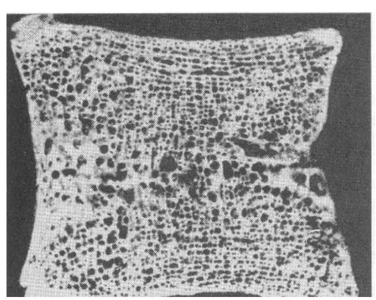
Table 9.3. Summary of mechanical properties of human cortical bone based on data from Reilly and Burstein, *Journal of Biomechanics*, 8(1975), 393–405.

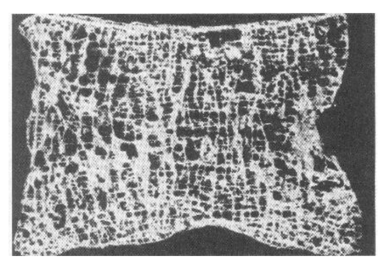
Parameter	Value
Modulus (GPa)	
Longitudinal	17.0
Transverse	11.5
Shear	3.3
Poisson's ratio	0.3–0.6
Ultimate strength: longitudinal (MPa)	
Tension	133
Compression	193
Shear	68
Ultimate strength: transverse (MPa)	
Tension	51
Compression	133

Biomechanics of Trabecular

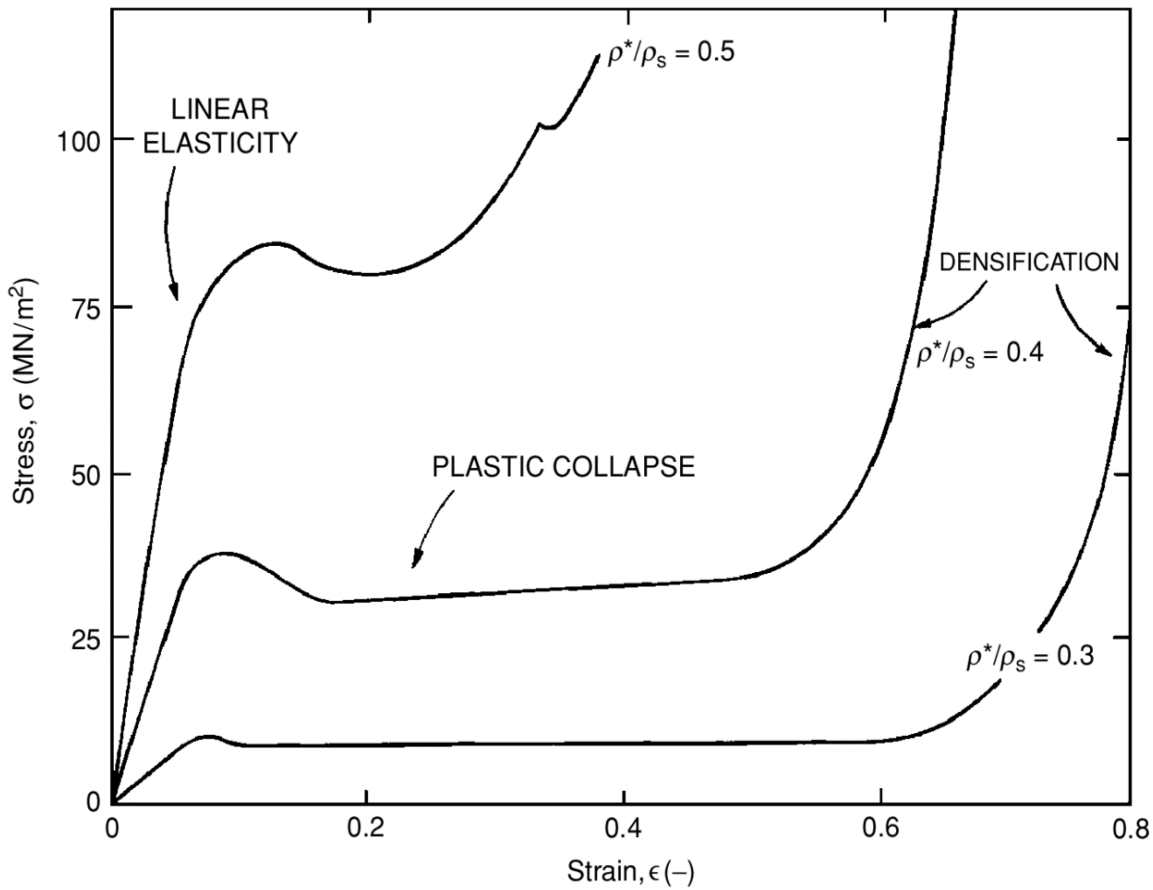
Table 9.4. Summary of mean compressive properties of human trabecular bone from different anatomic locations. Values in parentheses are standard deviations. Femur specimens were pooled from both the proximal and distal femur. The specimens from the tibia, distal femur, and spine were tested in the longitudinal (inferior-superior) direction. The proximal femur specimens were oriented along the neck of the femur. Adapted from Keaveny [11]. Copyright 2001 from *Bone Mechanics Handbook* by Cowin. Reproduced by permission of Routledge/Taylor & Francis Group, LLC.

Anatomic site	Relative density	Modulus (MPa)	Ultimate stress (MPa)	Ultimate strain (%)
Proximal tibia	0.16 (0.056)	445 (257)	5.33 (2.93)	2.02 (0.43)
Femur	0.28 (0.089)	389 (270)	7.36 (4.00)	Not reported
Lumbar spine	0.094 (0.022)	291 (113)	2.23 (0.95)	1.45 (0.33)





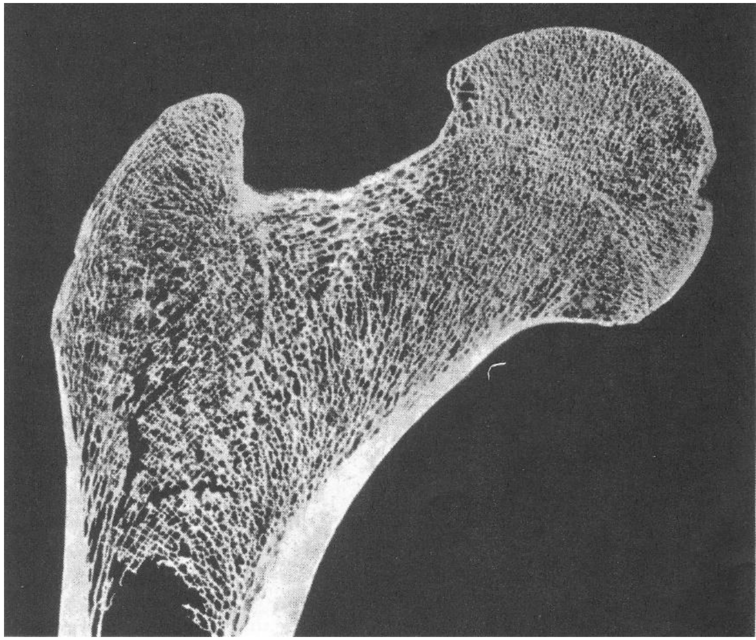
Biomechanics of Trabecular



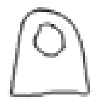
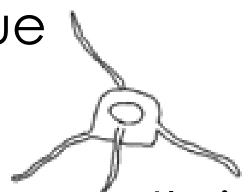
Compressive stress–strain curves for trabecular bone of different relative densities. Relative density is the ratio of the apparent density (ρ^* in this figure) to the density of solid cortical bone (ρ_S).

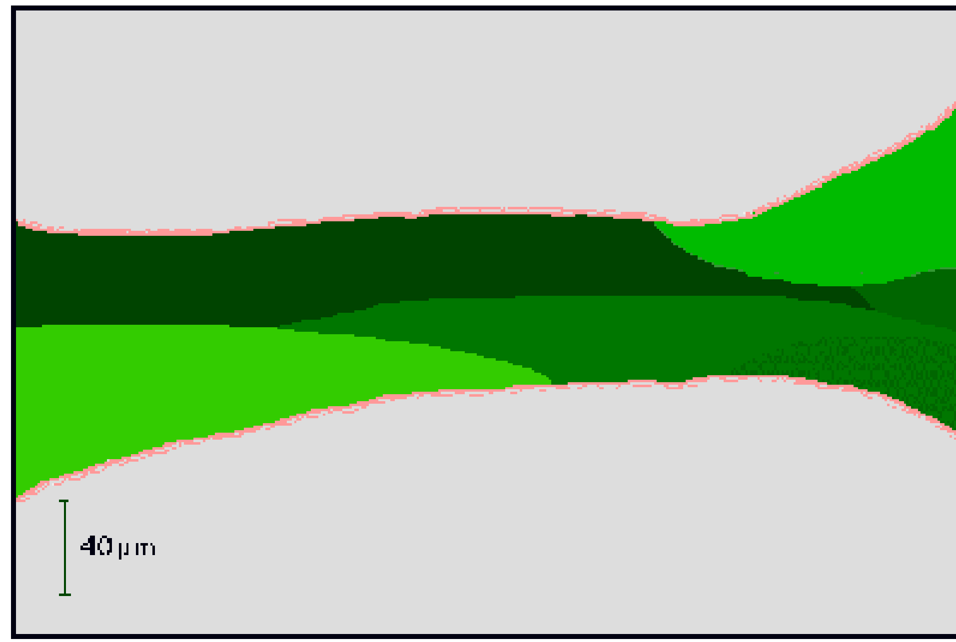
Bone Remodeling

- Maintenance of mineral homeostasis
- Reconstruct in the face of mechanical stimulation
- Maintain structural integrity in the face of accumulated microdamage
- Enhance healed bone



Remodeling

- Osteoclasts 
  - Recruited to dissolve bone
- Osteoblasts 
  - Recruited to synthesize bone
- Lining Cells 
  - Reside on surface of bone tissue
- Osteocytes 
  - Reside permanently inside bone tissue
  - Long branches sense pressures or cracks and direct osteclasts

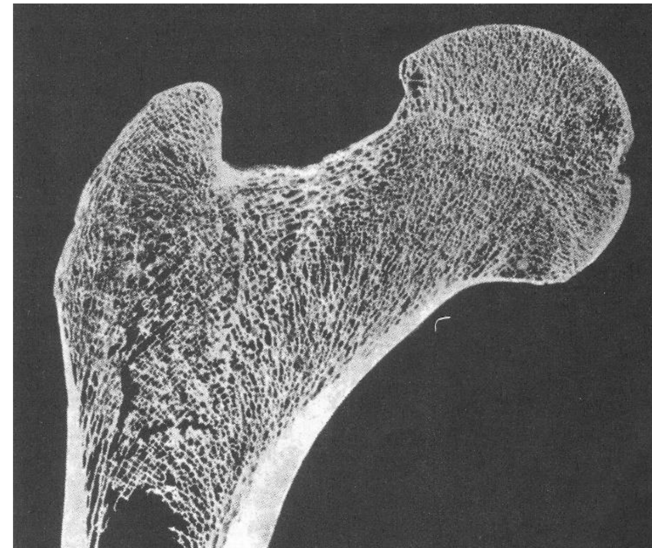


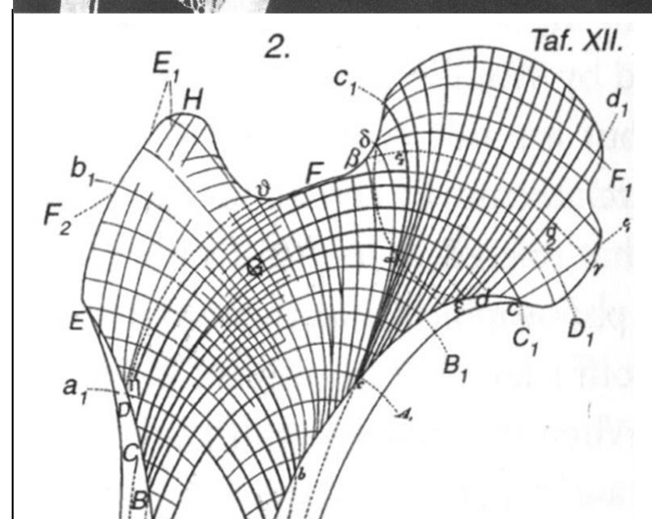
Mechanobiology

Wolff's Law:

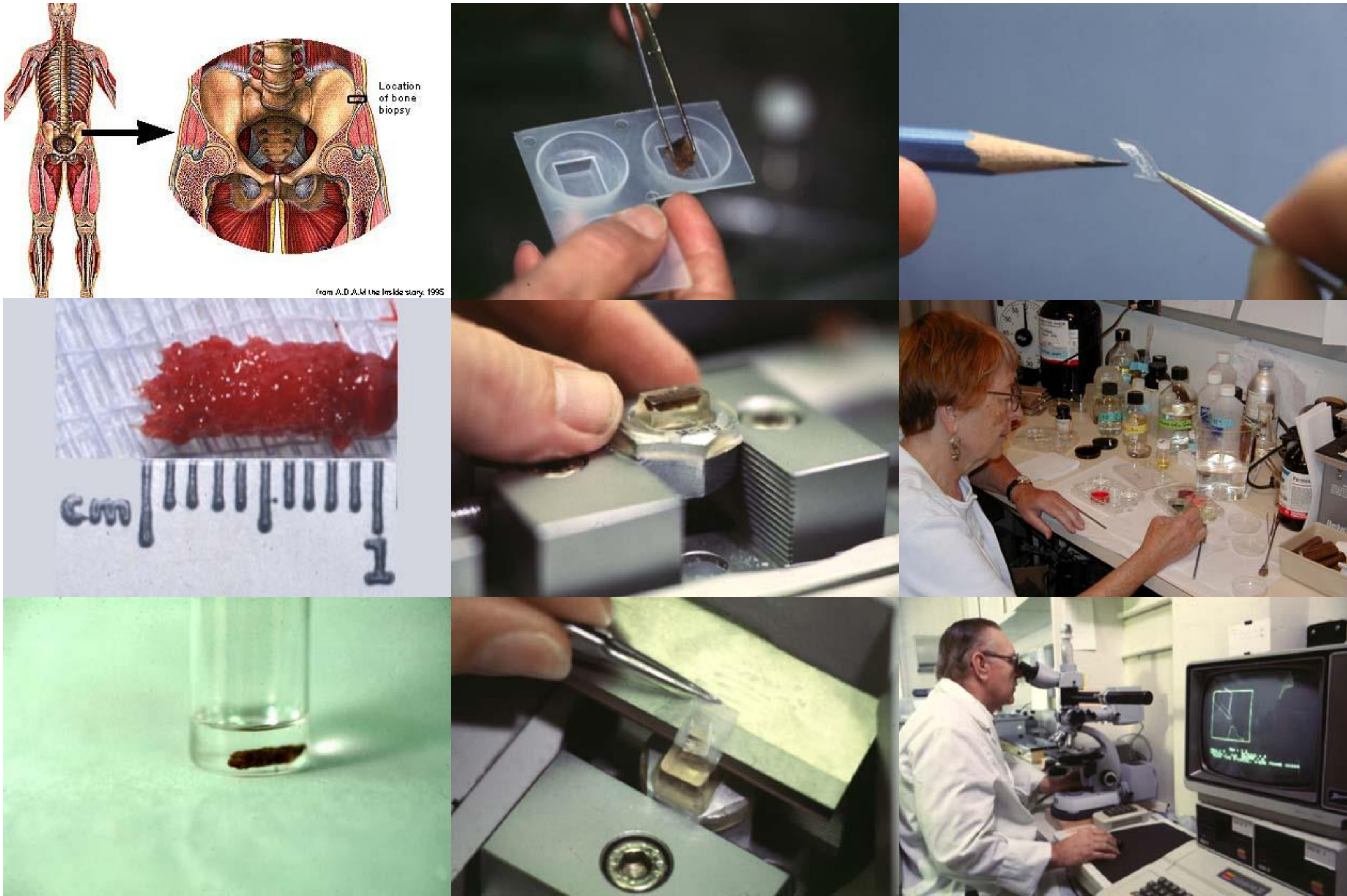
"Every change in the form and the function of a bone or of their function alone is followed b certain definite changes in their internal architecture, and equally definite secondary alterations in their external confirmation"

…bone will adapt its internal architecture in response to external constraints and loads.

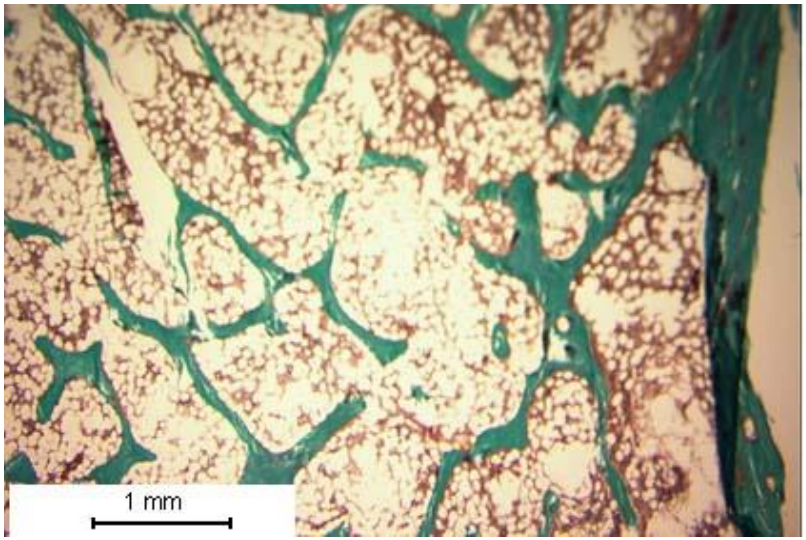




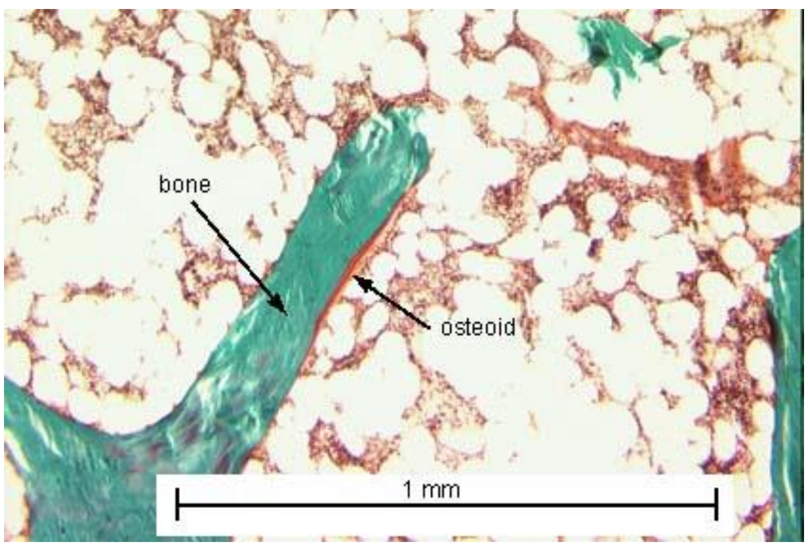
Histology

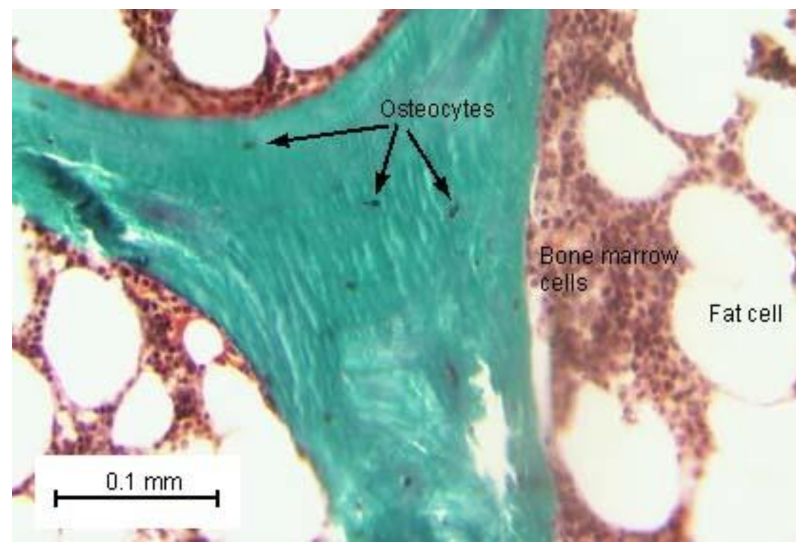


Normal Bone



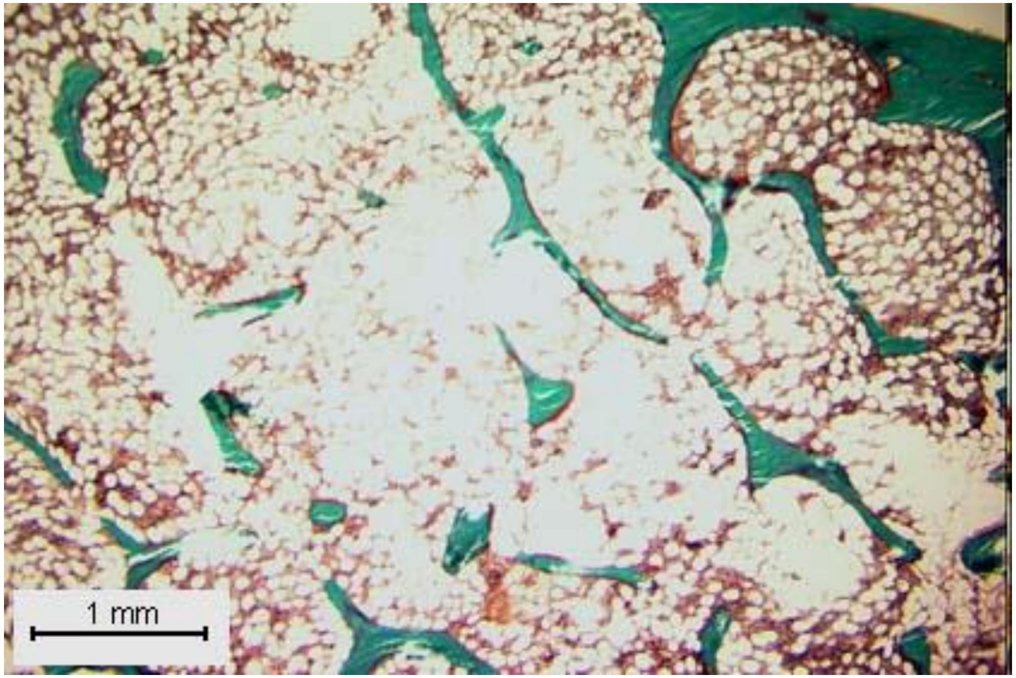
- Calcium is green.
- Fat cells in bone marrow are white
- Dark Red are other bone marrow cells
- Osteoid is new collagen





Bone Pathologies

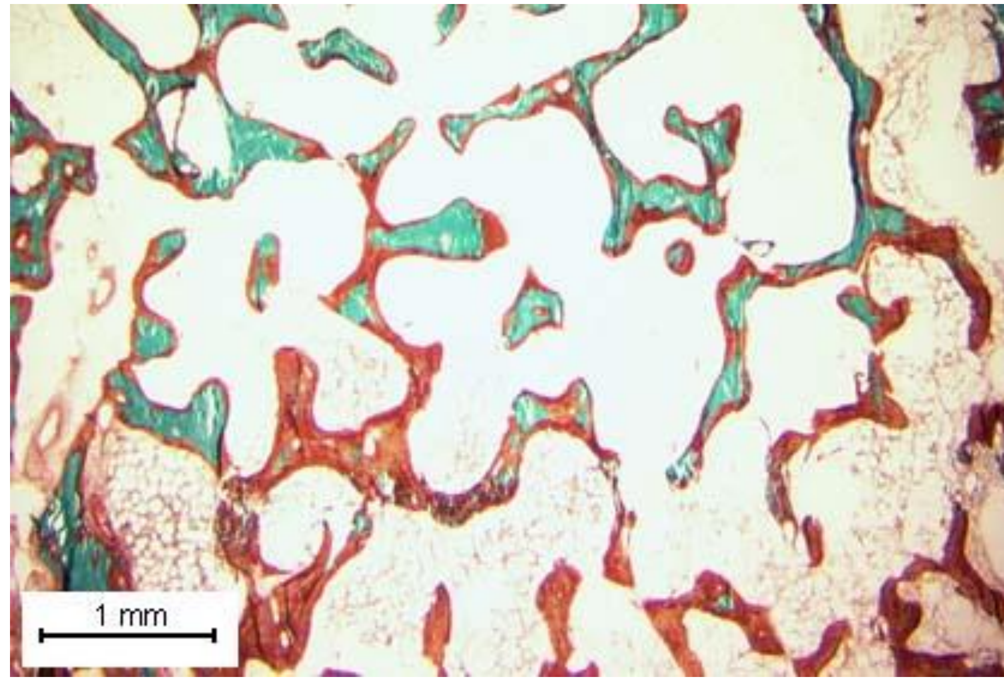
- Osteoporosis
  - Loss of bone mass per unit volume
  - Ratio of mineral to organic phase maintained



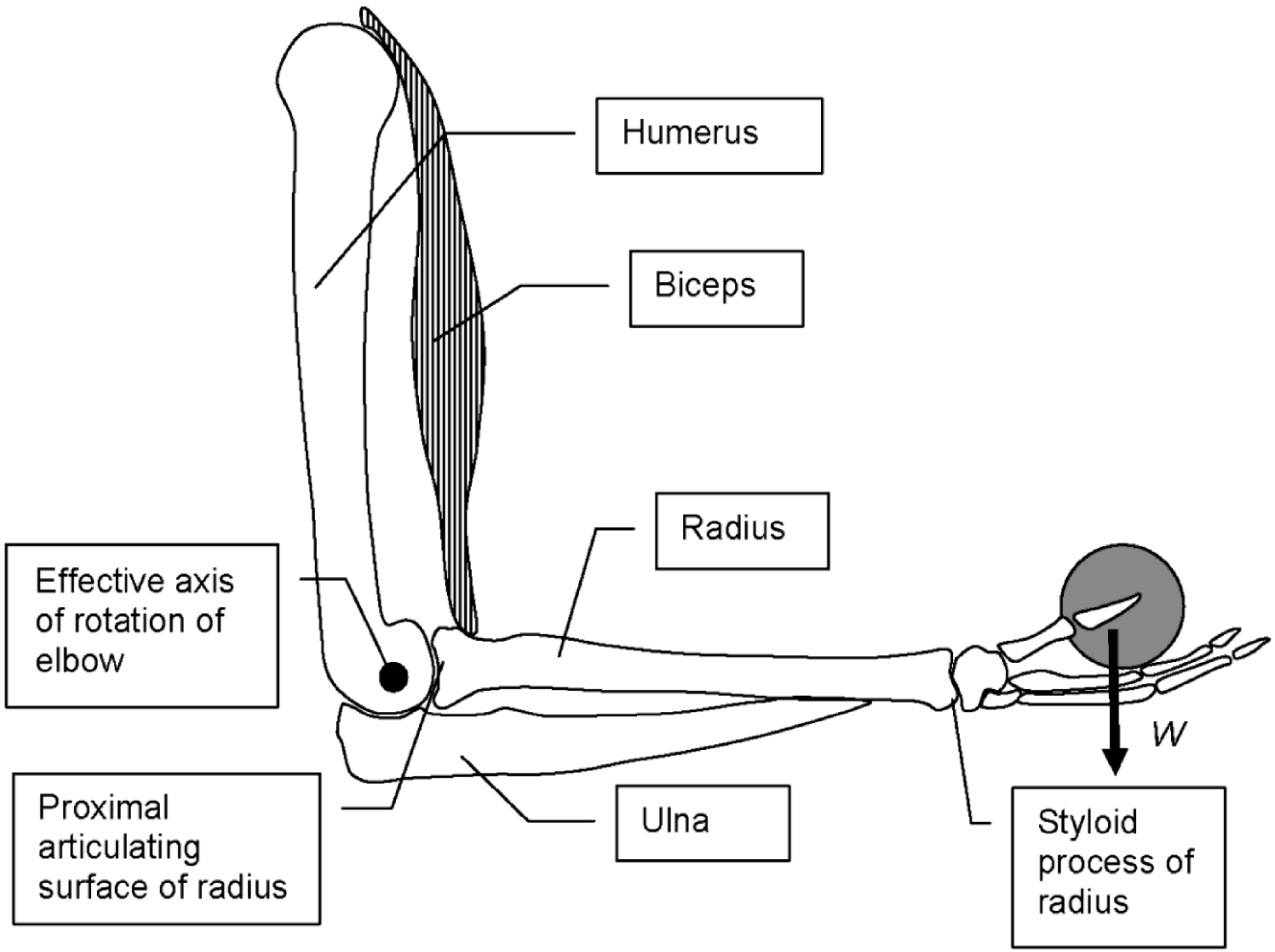
  - Decreased strength, density, and stiffness
  - True osteoporosis is accompanied by fracture
  - Bone loss without fracture is osteopenia

Bone Pathologies

- Rickets (*Osteomalacia*)
  - Mineralization of the matrix of the skeleton is defective
  - Cannot metabolize Calcium or Vitamin D
  - Lack of calcium → collagen does not stain "green"
  - Decreased strength, density, and stiffness



Forearm Biomechanics



Forearm Biomechanics

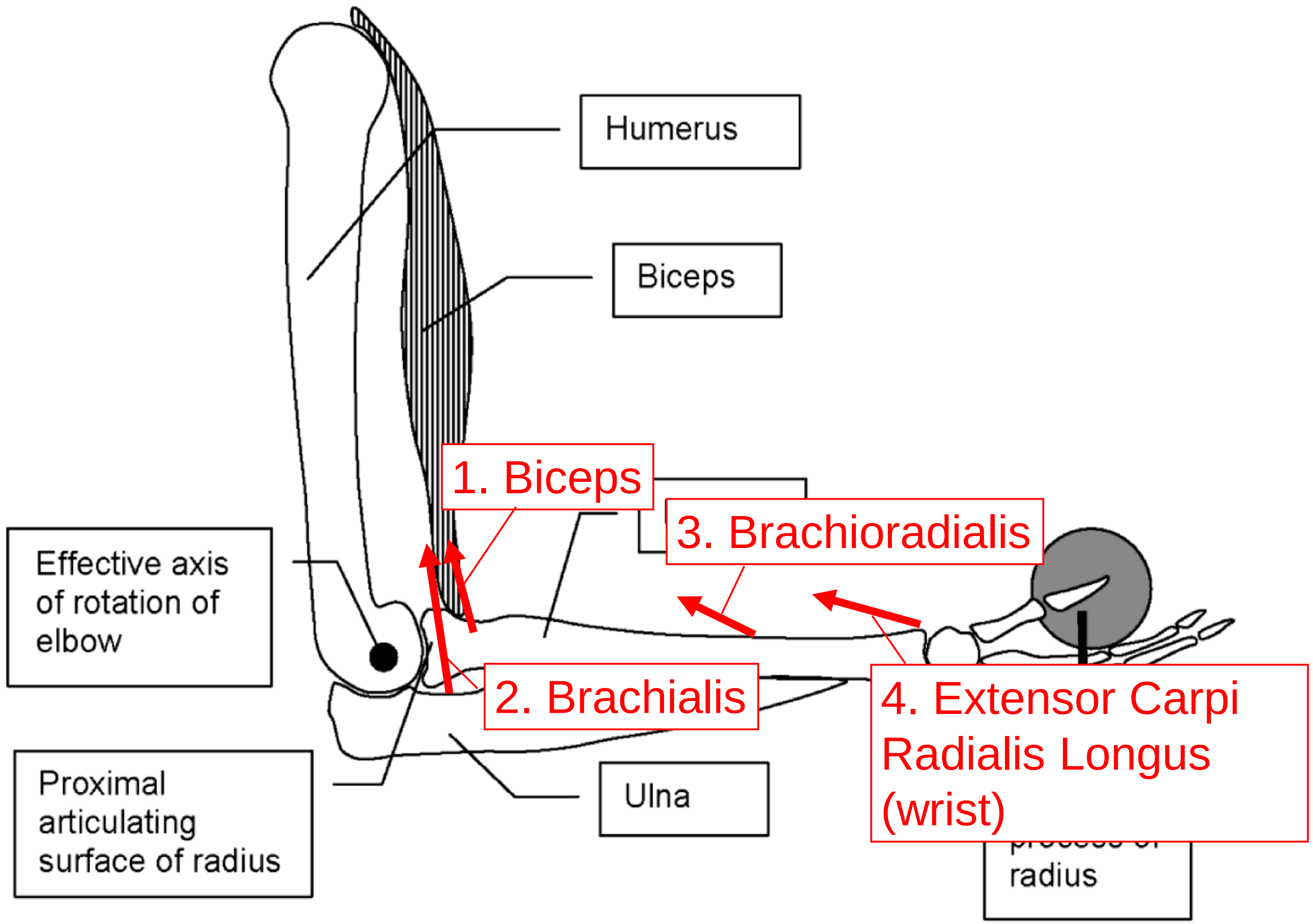


Table 8.1. Origin and insertion points and other characteristics of the four major muscles participating in elbow flexion. L_H is the distance from the effective center of rotation for the elbow to the muscle origin location on the humerus; L_F is the corresponding measurement for the insertion location on the forearm. PCSA is the physiologic cross-sectional area of the muscle (see text). $\theta = \tan^{-1}(L_H/L_F)$ is the angle that the muscle makes with respect to the horizontal when the forearm is in the position shown in Fig. 8.22. "Inserts into" refers to which bone the muscle inserts into in the forearm.

Muscle	L_H (cm)	L_F (cm)	PCSA (cm^2)	θ (°)	Inserts into
Biceps	31[a]	8	12.3	76	Radius
Brachialis	10	5	13.0	63	Ulna
Brachioradialis	8	24	2.9	18	Radius
Extensor carpi radialis longus	3	25[b]	3.6	7	Radius
			A (cm^2)		

[a] The biceps does not originate from the humerus. Its effective point of origin is taken at the top of the humerus.
[b] The ECRL inserts into the wrist; its effective insertion point is taken as the end of the radius.

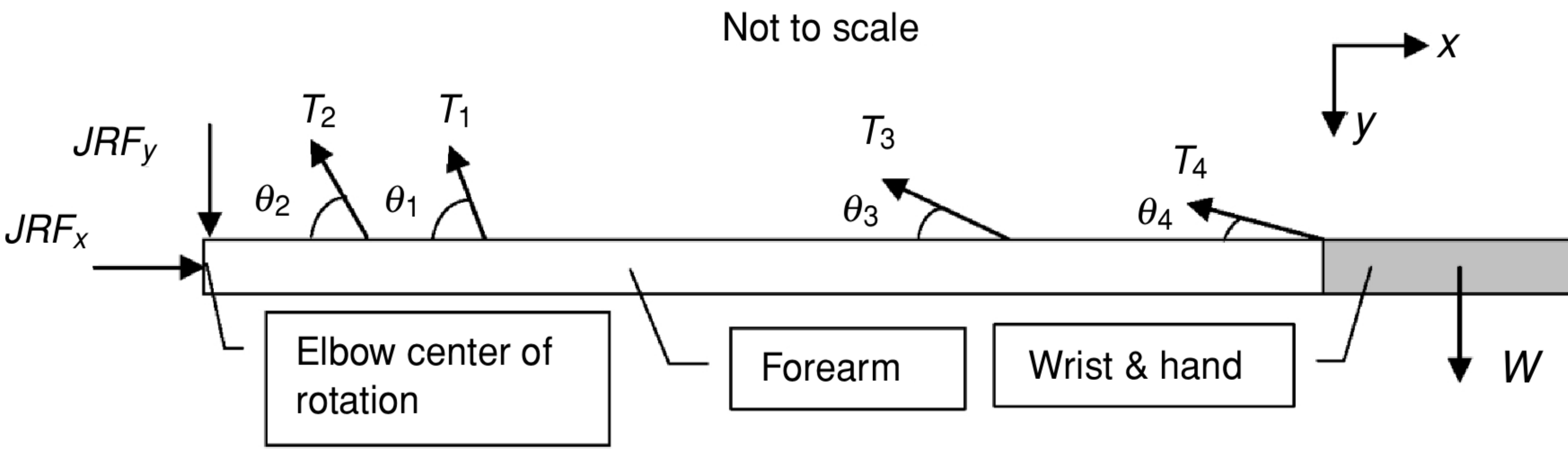
Simplifications:

1. $PCSA = A_{muscle} = V_{muscle} / L_{muscle}$
2. Muscle force areal density:

$$w = 20 \text{ N/cm}^2$$

[McMahon, 1984]

Bending Moment



Simplifications:

1. Neglect arm mass
2. Ignore moment at elbow joint

Knowns:

1. L_{tot} = 31 cm
2. W = 12.2 kg = 119.7 N

$$T_i = T_{xi}\hat{i} + T_{yi}\hat{j}$$

$$T_{xi} = wA_i \cos(\theta_i)$$

$$T_{yi} = wA_i \sin(\theta_i)$$

Calculations

	A (cm^2)	w (N/cm^2)	Lh (cm)	Lf (cm)	Theta (rad)	Fx (N)	Fy (N)	M (N cm)
2. Brachialis	13	20	10	5	1.107	116.3	232.6	1163
1. Bicep	12.3	20	31	8	1.318	61.5	238.2	1906
3. Brachioradialis	2.9	20	8	24	0.322	55.0	18.3	440
4. ECRL	3.6	20	3	25	0.119	71.5	8.6	214
W. 12.2 kg weight							-119.7	
						JRFx (N)	JRFy (N)	
						304	378	

Notes

1. *The Moment is highest at the Bicep connection*
2. *The reaction forces are much larger than the weight held*
3. *"Mechanical Disadvantage" = muscle often act with short lever arm*

Simplified Bending Stress

$$\sigma(x) = \frac{M(x)y}{I_z} + \frac{F_x(x)}{A_{bone}}$$

$$I_z = \int_{A_{bone}} y^2 dA_{bone}$$

Simplifications:
1. Consider radius bone only
2. Hollow circular beam

Knowns:
1. Medullary canal D_i = 0.7 cm
2. Outer diameter D_o = 1.4 cm

$$\sigma = E\varepsilon$$

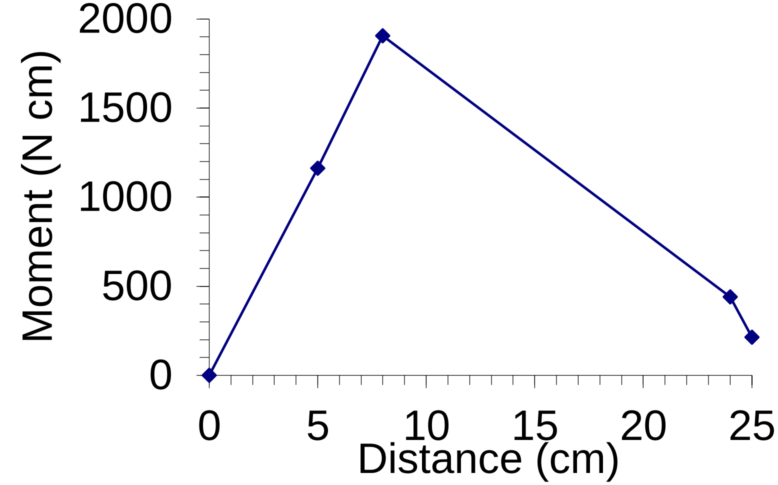
Stress-Strain Assumptions:
1. Linear elasticity

Knowns:
1. E = 17 GPa

Bone Stress

Notes:
1. Iz = pi/64 * (Do^4 - Di^4)
2. A = pi/4 * (Do^2 - Di^2)

J (cm^4)	Do (cm)	Di (cm)	Iz (cm^4)	A_{bone} (cm^2)
0.35	1.40	0.70	0.175	1.15



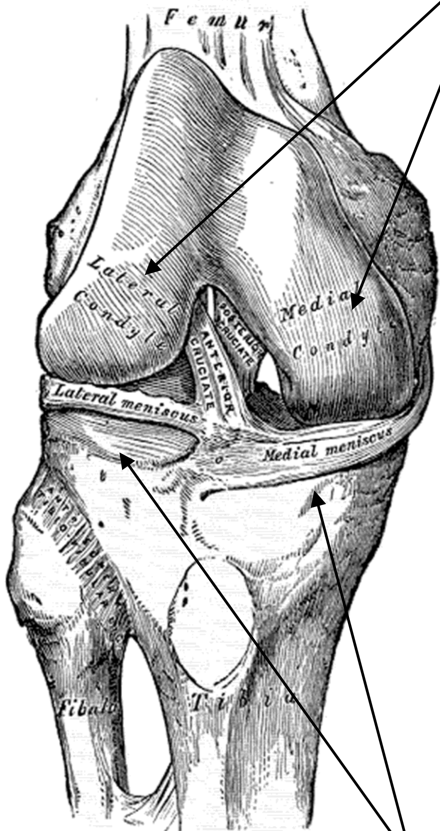
Max M (N cm)	Max y (cm)	Iz (cm^4)	Stress M (N/cm^2)
1906	0.7	0.175	7603

Fx (N)	A (cm^2)	Stress F (N/cm^2)
304	1.15	265

Stress M + F (N/cm^2)	7868
Cortical Stiffness, E (GPa)	17
Strain (microstrain)	4628

The Human Knee

"Bulbs" or condyles

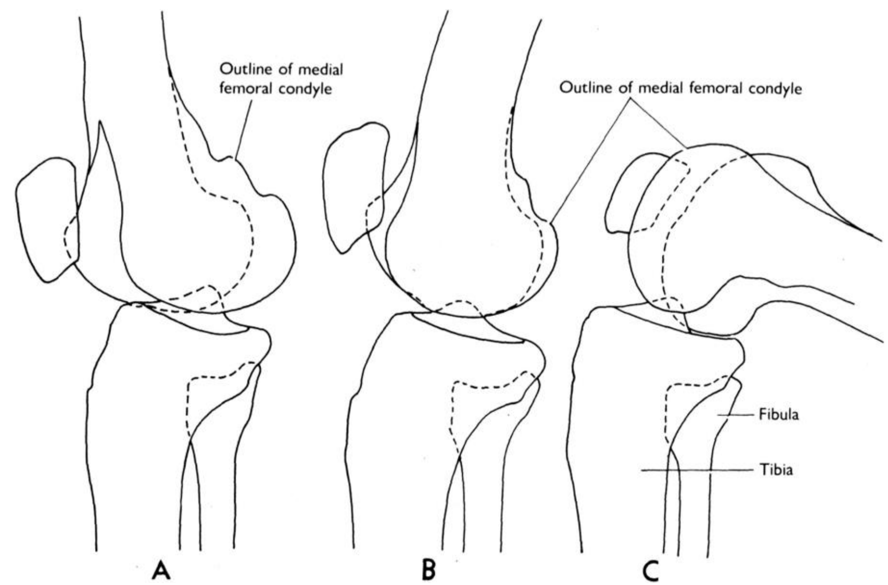


Tibial condyles are concave

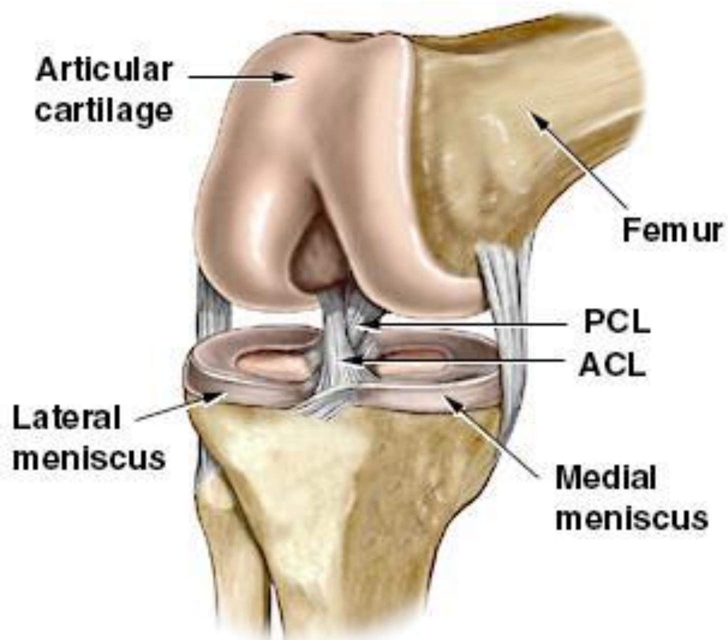
Femur
- lateral condyle
- medial condyle

Tibia
- lateral condyle
- medial condyle

Patella



Cruciate Ligaments



Named because “cross” over one another

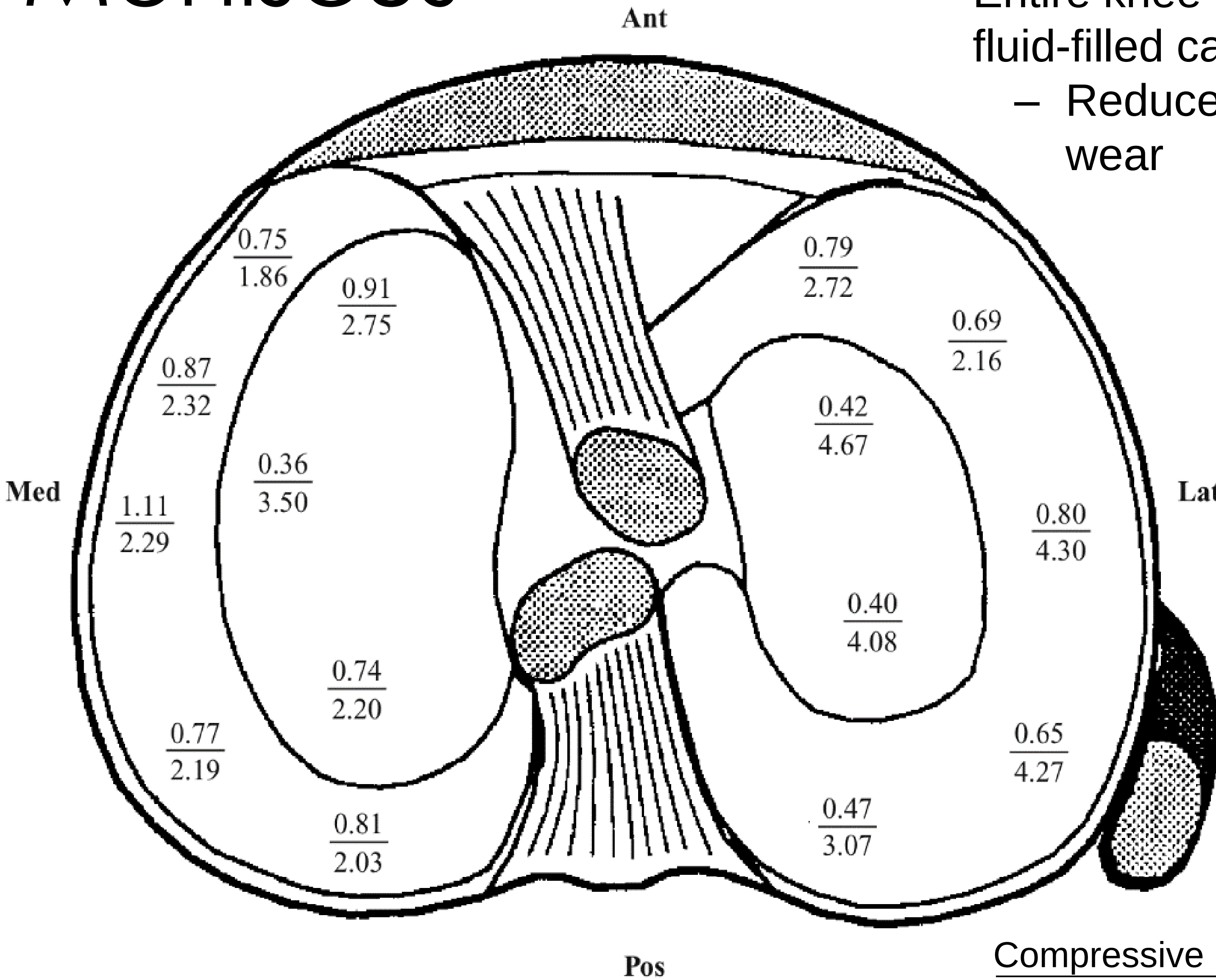
Anterior cruciate ligament (ACL):
- connect tibia to lateral femoral condyle
- knee stabilizer

Posterior cruciate ligament (PCL):
- connect tibia to meidal femoral condyle
- knee stabilizer

Tearing of ACL:
- Sudden direction change
- Deceleration force crosses the knee
- Popping sensation, rapid onset of swelling, and buckling sensation

Meniscus

- Cartilage layer between femur and tibia
- Entire knee enclosed in fluid-filled capsule
  - Reduced friction & wear

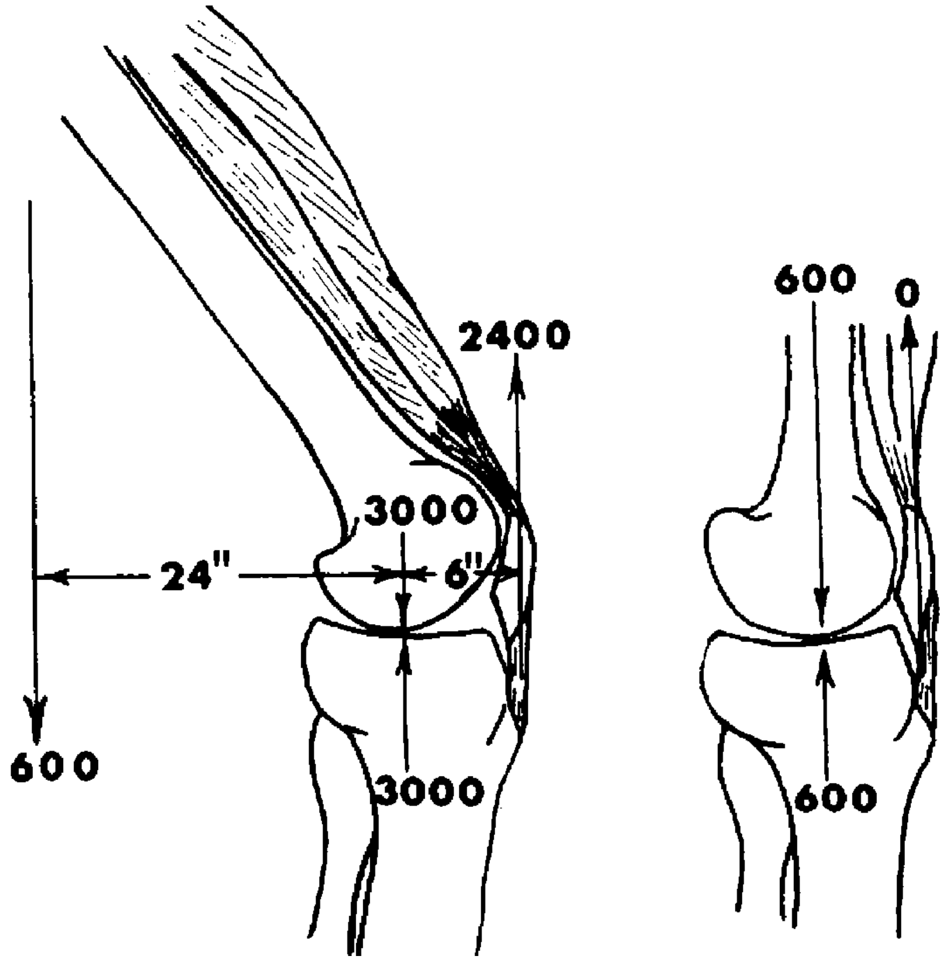


Compressive modulus (MPa) / Cartilage thickness (mm)

Biological Frameworks for Engineers

ME 417/591

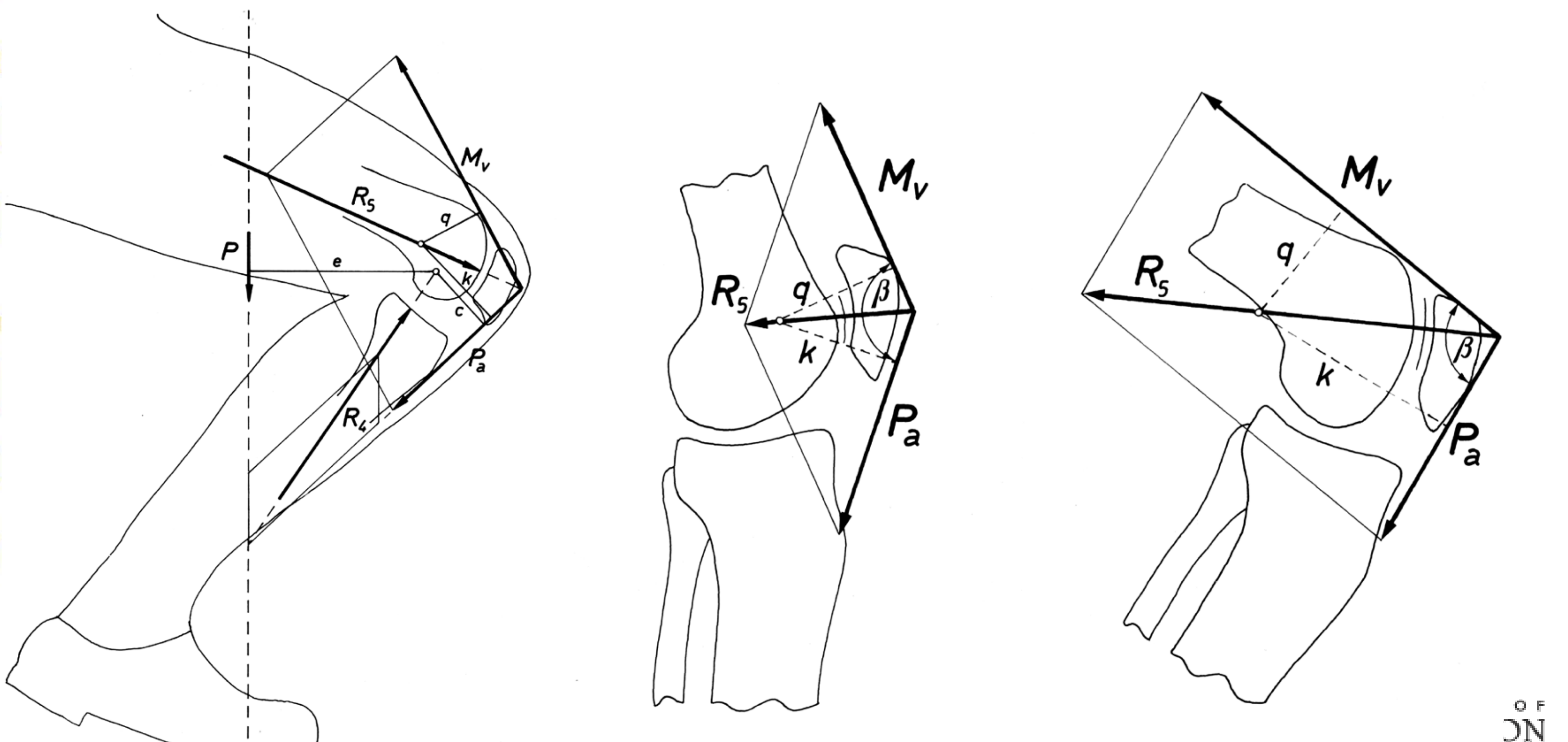
Knee Forces



UNIVERSITY OF WASHINGTON

Table 8.2. Measured femoro-patellar contact loads during squatting, for physiological joint angles. Values in the last column are femoro-patellar contact forces, and should be multiplied by three to get in vivo loads. Values are mean for n = 12 knees (±95% confidence intervals). Reprinted from Huberti and Hayes [35]. With kind permission of Elsevier.

Knee flexion angle (°)	Contact area (cm^2)	Contact area as percentage of total articular area (%)	Average contact pressure (MPa)	Resultant contact force (N)
20	2.6 ± 0.4	20.5	2.0 ± 0.4	497 ± 90
30	3.1 ± 0.3	24.9	2.4 ± 0.6	573 ± 125
60	3.9 ± 0.5	30.4	4.1 ± 1.4	1411 ± 331
90	4.1 ± 1.1	32.2	4.4 ± 1.0	1555 ± 419



Questions?