ME 411 / ME 511

Biological Frameworks for Engineers

UNIVERSITY OF WASHINGTON

Class Organization

- Lab 3 Reports due today
- Tiny Workhorse Projects on Wed and Fri next week (Grad only)

ME 411 / ME 511

Musculoskeletal System

Part 2: Muscle/Bone Interactions

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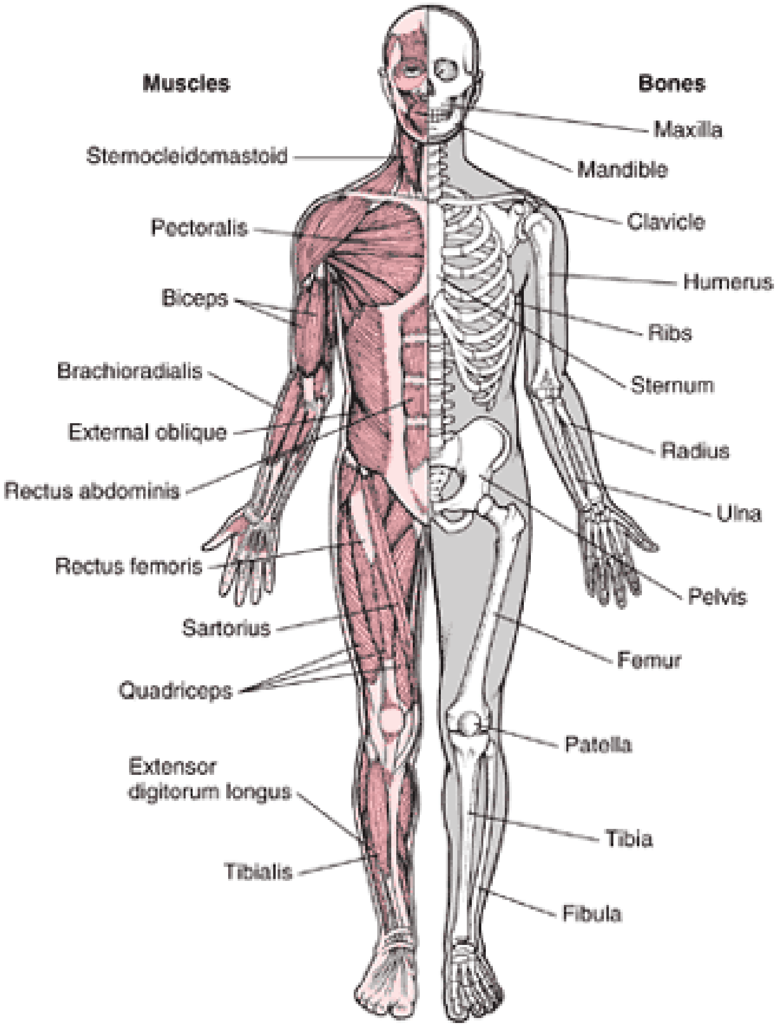
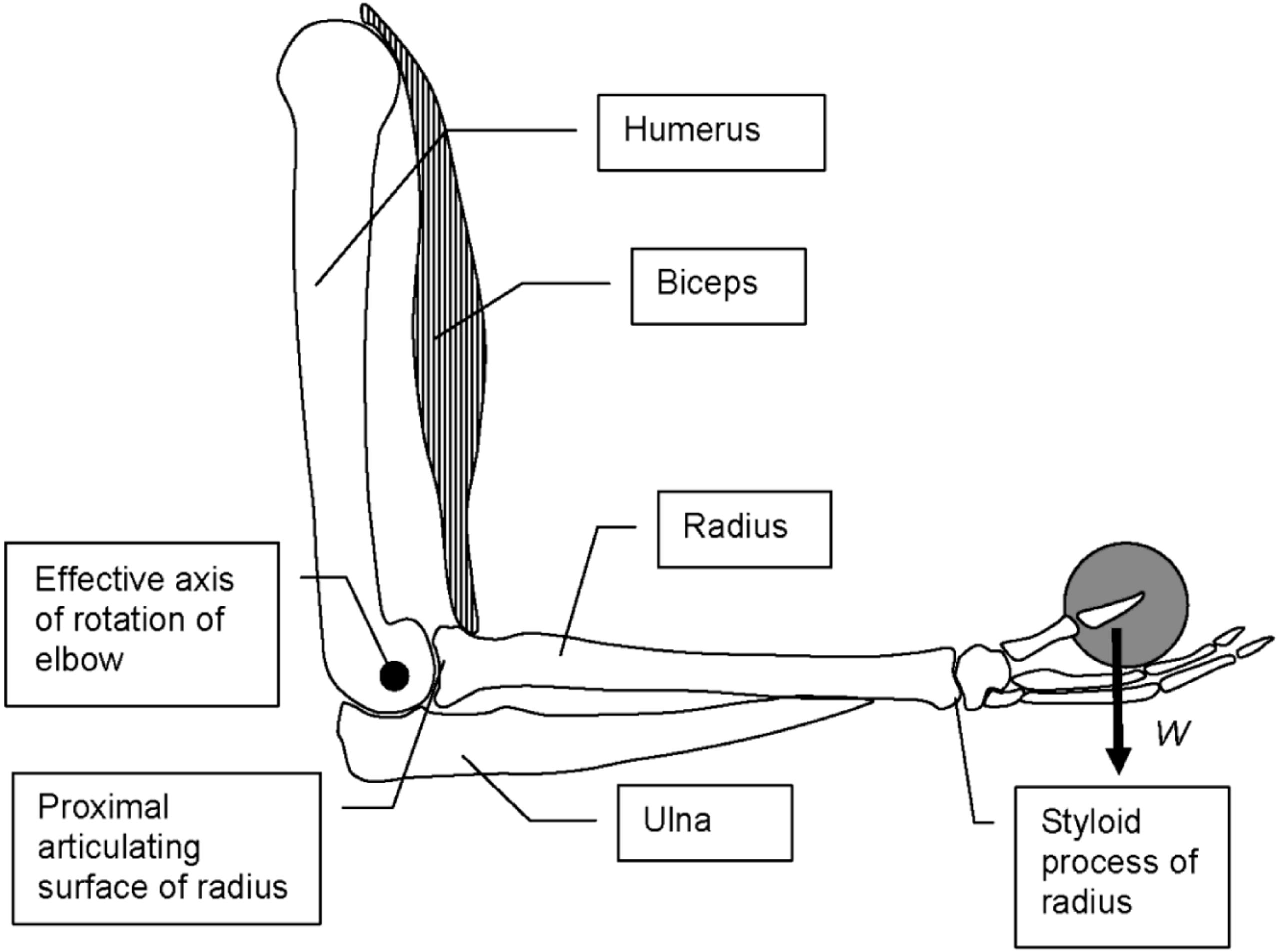
Musculoskeletal System



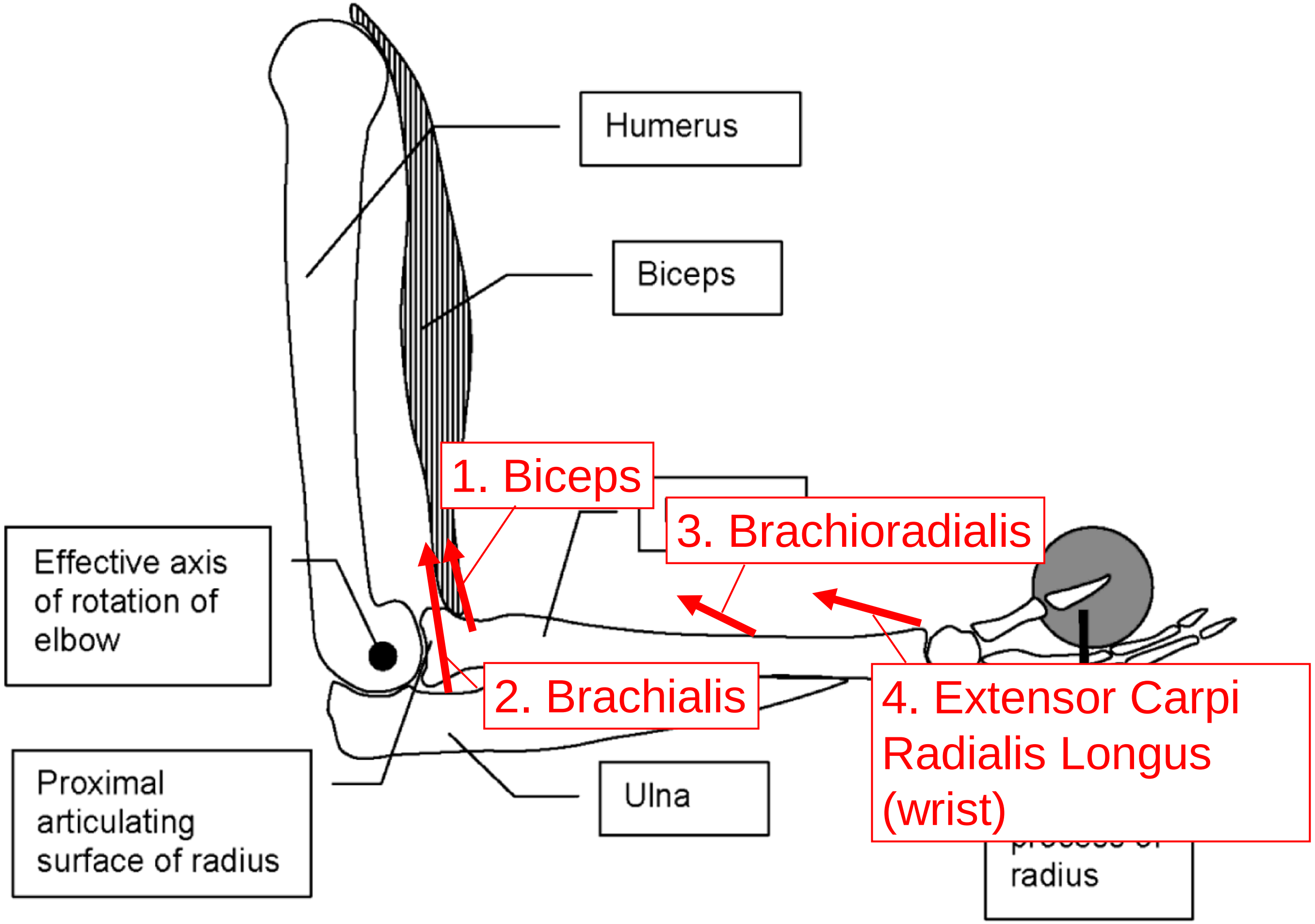
Integrated Parts:

- Skeletal Muscles
- Bones
- Ligaments
- Tendons
- Cartilage
- Neurons

Flexion of Elbow Joint



Flexion of Elbow Joint



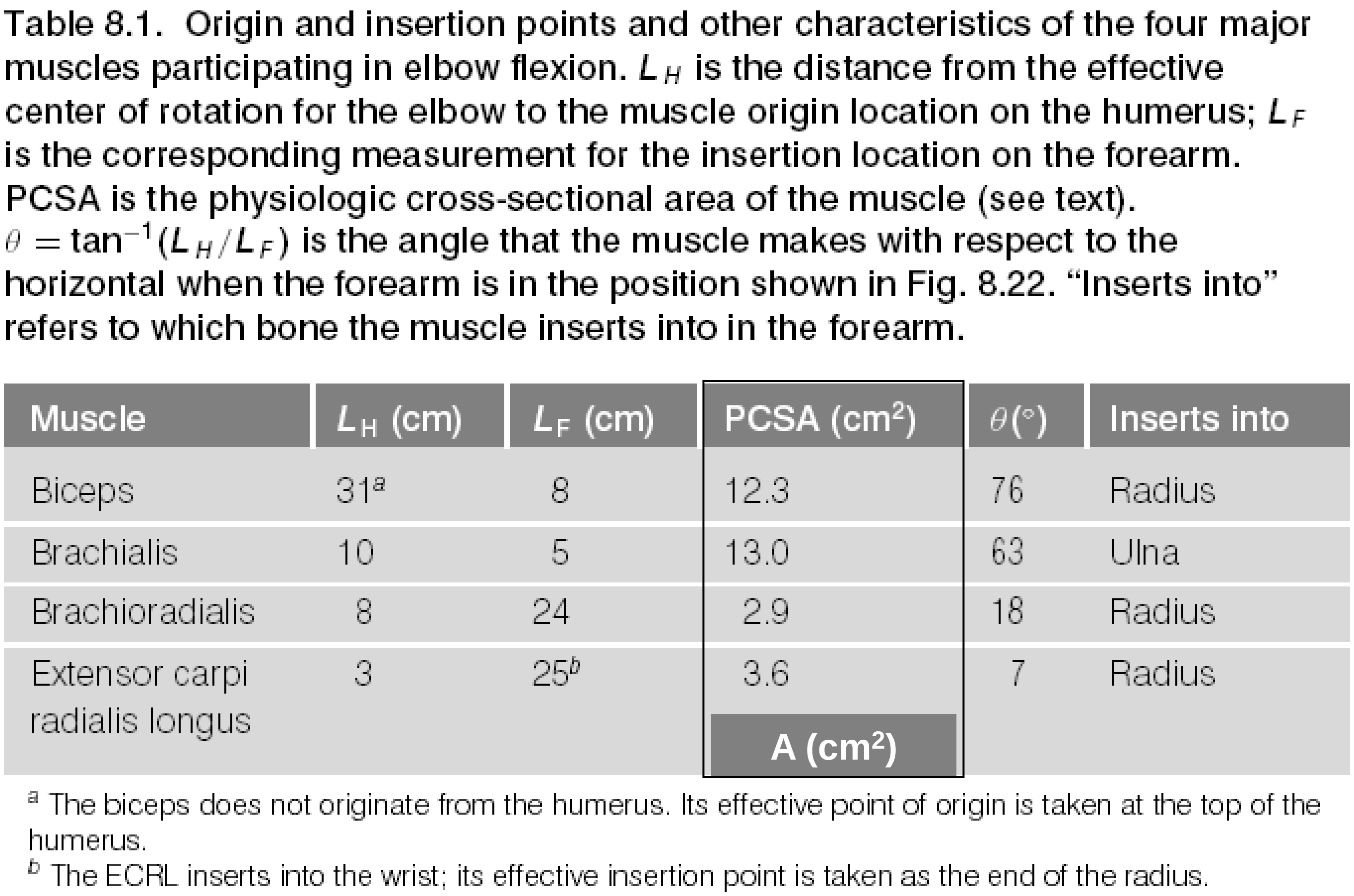


Table 8.1. Origin and insertion points and other characteristics of the four major muscles participating in elbow flexion. L_H is the distance from the effective center of rotation for the elbow to the muscle origin location on the humerus; L_F is the corresponding measurement for the insertion location 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.

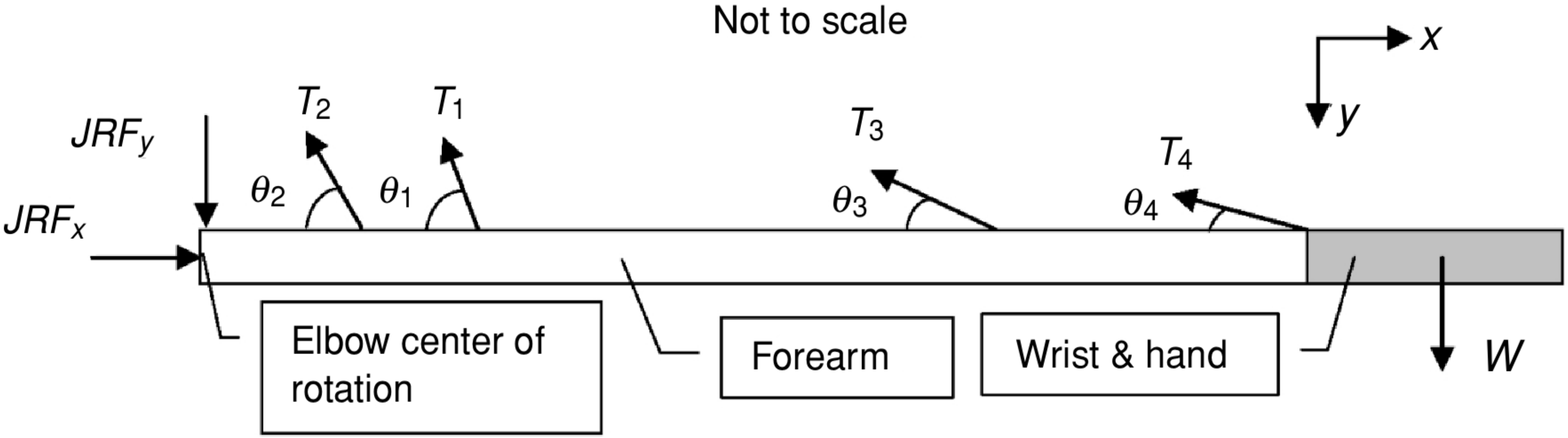
Simplifications:

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

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

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

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

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

Calculations

Bending Moment

	A (cm2)	w (N/cm2)	Lh (cm)	Lf (cm)	Theta	Fx (N)	Fy (N)	M (N m)
1. Bicep	12.3	20	31	8	1.318	61.5	238.2	1.906
2. Brachialis	13	20	10	5	1.107	116.3	232.6	1.163
3. Brachioradialis	2.9	20	8	24	0.322	55.0	18.3	0.440
4. ECRL	3.6	20	3	25	0.119	71.5	8.6	0.214
W							-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

Bending Stress

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

J (cm4)	Do (cm)	Di	Iz (cm4)	Abone (cm2)
0.35	1.40	0.70	0.175	1.15

Max Stress @ 8cm

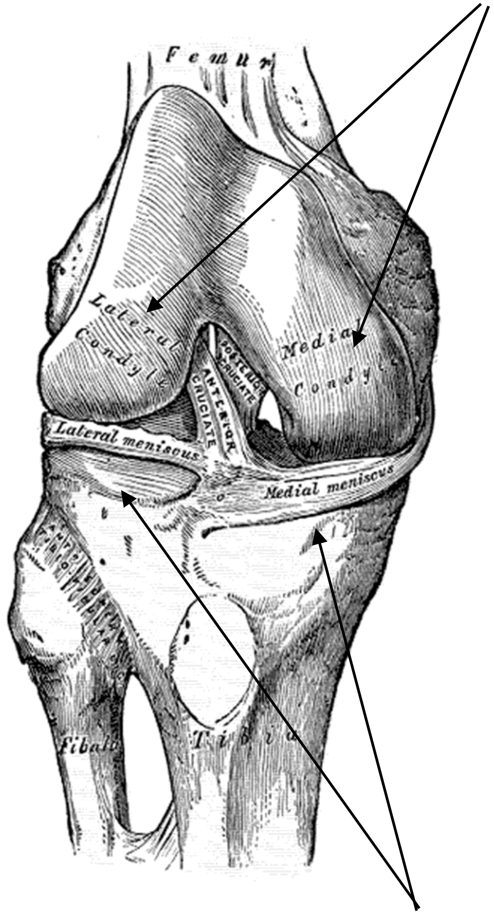
M (N m)	y (m)	Iz (m4)	Stress M
1.906	0.007	1.75E-09	7.60E+06

Fx (N)	A (m2)	Stress F
304	1.15E-04	2.65E+06

Total Stress (MPa)	10.25
E (MPa)	17000
strain (microstrain)	603

The Human Knee

“Bulbs” or condyles

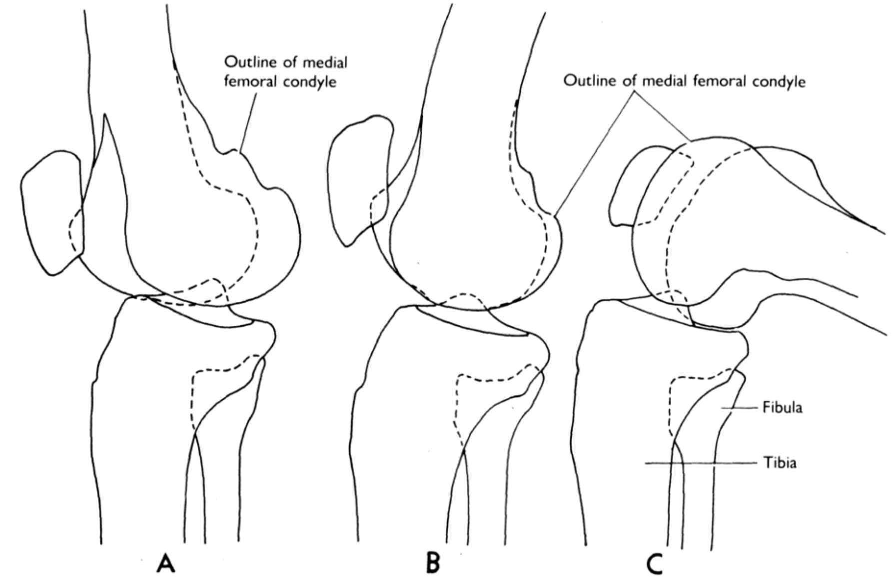


Tibial condyles are concave

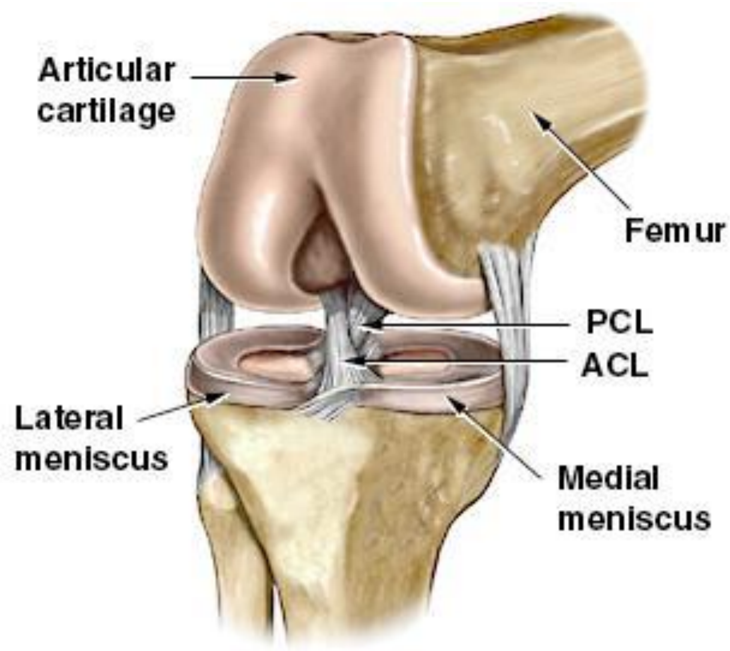
Femur
- lateral condyle
- medial condyle

Tibia
- lateral condyle
- medial condyle

Patella



Cruciate Ligaments



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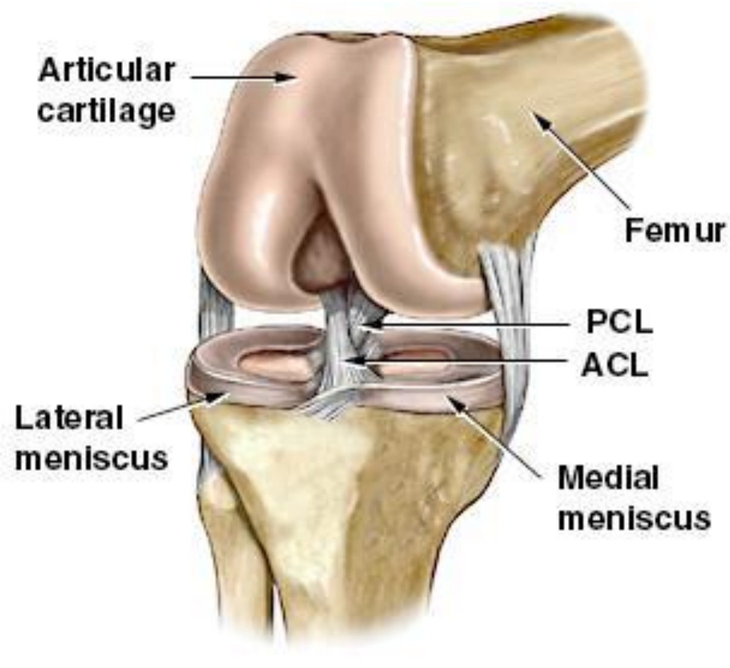
Named because "cross" over one another

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

Posterior cruciate ligament (PCL):
- connect tibia to lateral 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



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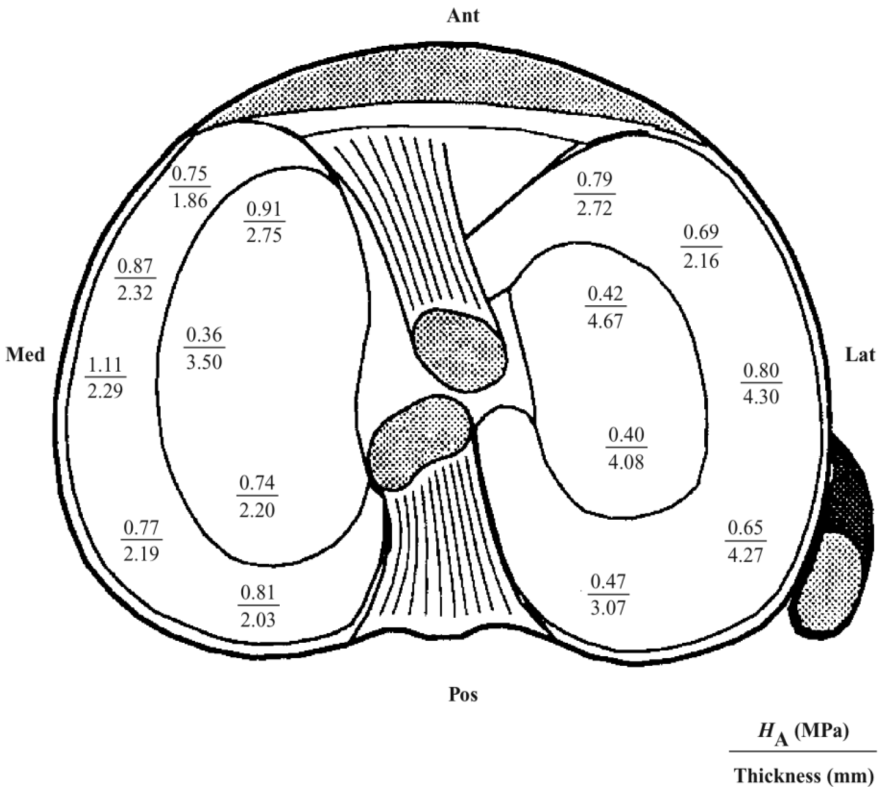


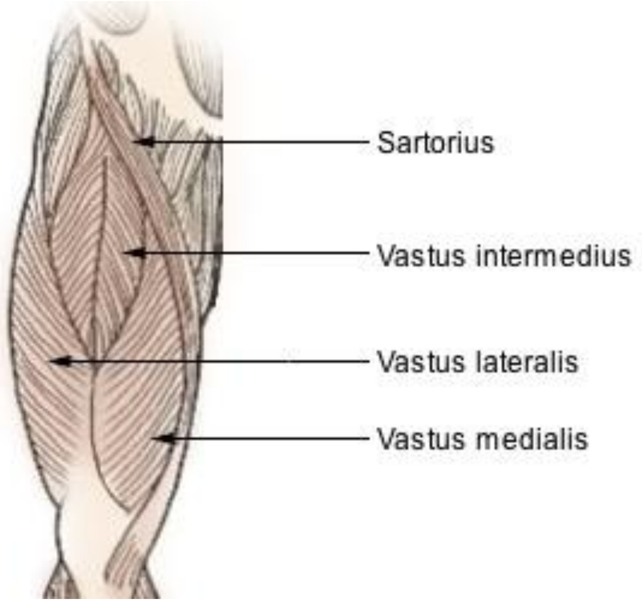
Layer of cartilage between femur and tibia

Entire knee enclosed in fluid-filled capsule
- Thin fluid for reduced friction and wear
- Allows knee to flex $>10^6$ over lifetime

H_A = aggregate compressive modulus

Thickness = cartilage thickness

Muscles

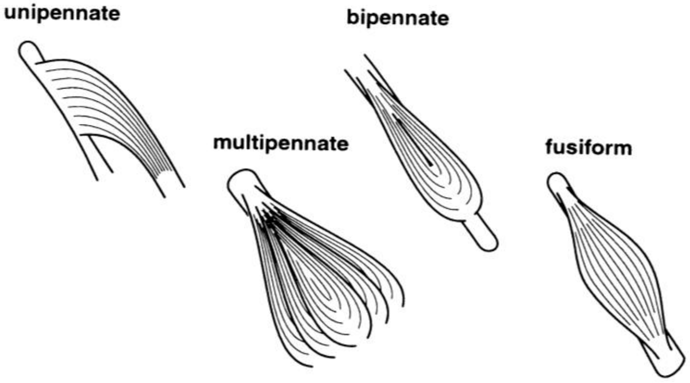


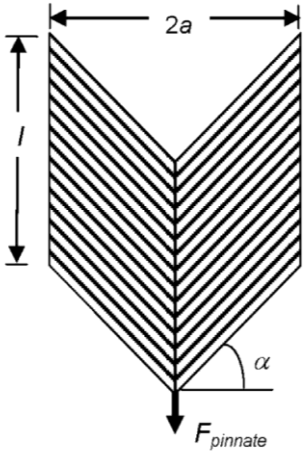
Quadriceps

- Large set of four muscles on anterior surface of thigh
- Tendons join (anastomose) to form *quadricep tendon*
- Connects to patella

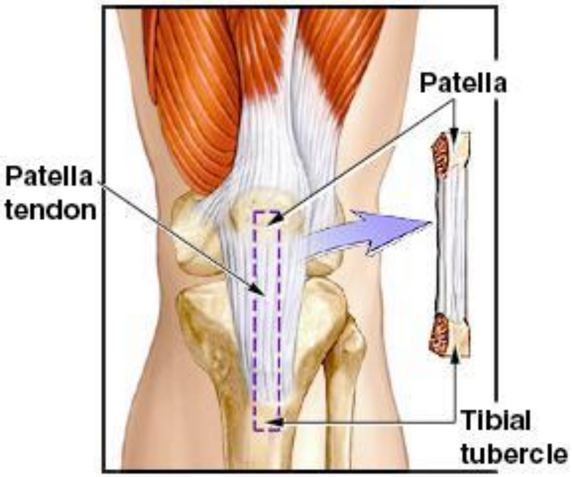
Pinnate vs Parallel (a/k/a fusiform) Muscle

- Bipinnate force larger than parallel





Tendons



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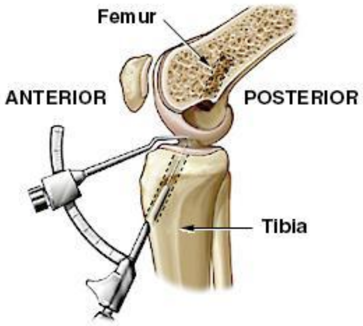

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Patellar Ligament (a/k/a Patellar Tendon)
- emanates from lower patella
- connects to tibia

ACL reconstruction
- Harvest central 1/3 of patellar tendon
- Keep bone block at each end
- Drill holes into the tibia & femur
- Pull tendon graft through the holes
- Hold graft with bioabsorbable screws or metallic screws
- Allows new blood vessels to grow into the graft for healing
- Begin physical therapy

Bone-bone reactions

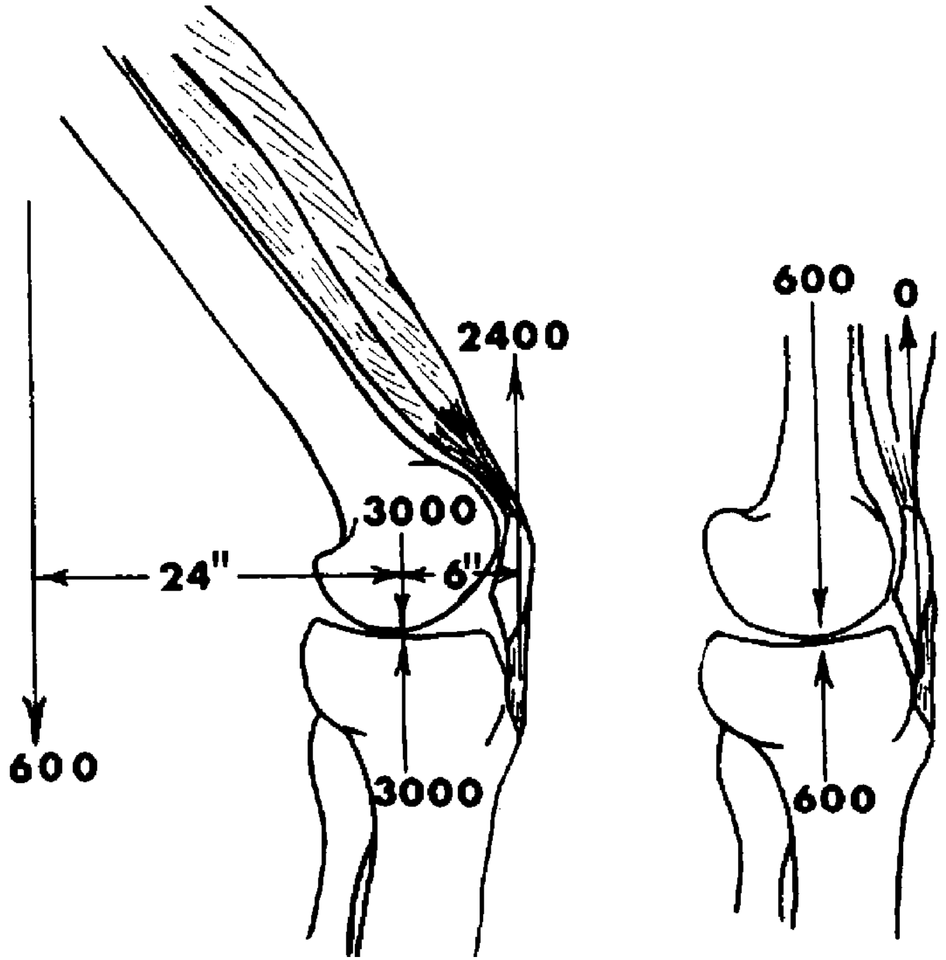
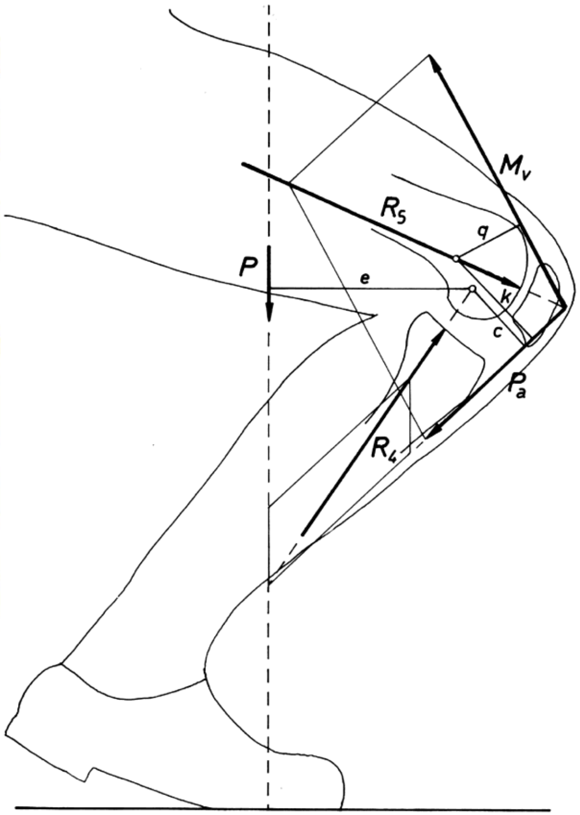
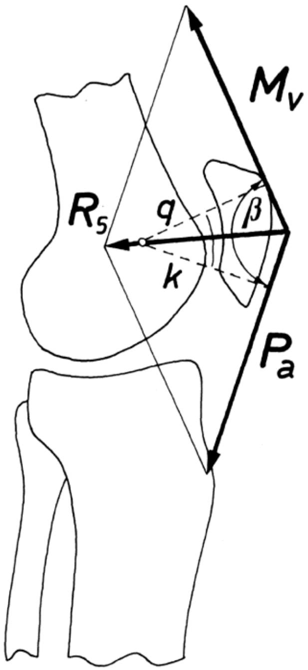
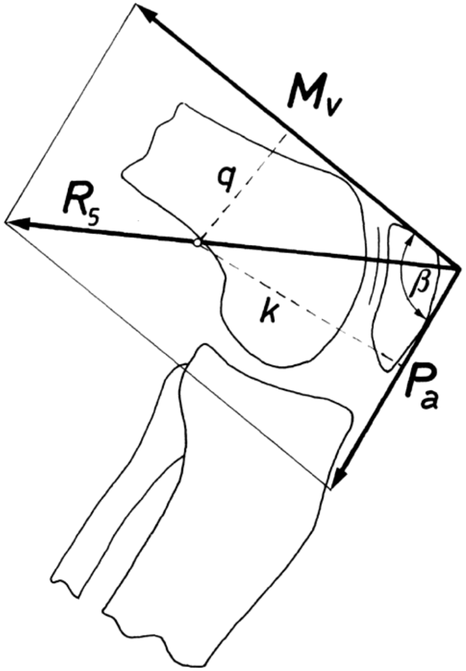


Table 8.2. Measured femoro-patellar contact loads during squatting, for physiological joint angles. Values in the last column are femoro-patellar contact forces, and should be multiplied by three to get in vivo loads. Values are mean for n = 12 knees (±95% confidence intervals). Reprinted from Huberti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



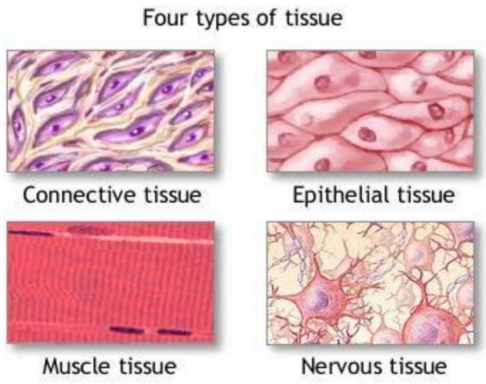




Musculoskeletal System

“Large” Considerations:

- Arrangement of muscle fibers muscle
- Arrangement of tendons w.r.t. bone,
- Skeletal anatomy
- Ligament connections
- Cartilage mechanics
- Neuronal activation



“Small” Considerations:

- External Forces on Cells & ECM elasticity
- ECM secretion / remodeling
- Cell Migration
- Mutations
- Any others?

Questions?