The major problems of Locomotion

Support (generating force against gravity)

Movement (generating thrust = force in direction of movement)

Environment has a great influence on locomotor problems.

WATER is a high density media (viscous)

less need for support, but drag is bigger problem.

AIR is a low density media

the effect of gravity is strong, but drag is usually negligible.

Functional Considerations

- Fishes : Support is not a big problem.
- Terrestrial vertebrates: Needs support against gravity while allowing movement.
  - Body "hangs" off of the spinal column.
  - Legs support body weight
  - Rib cage helps support internal organs.

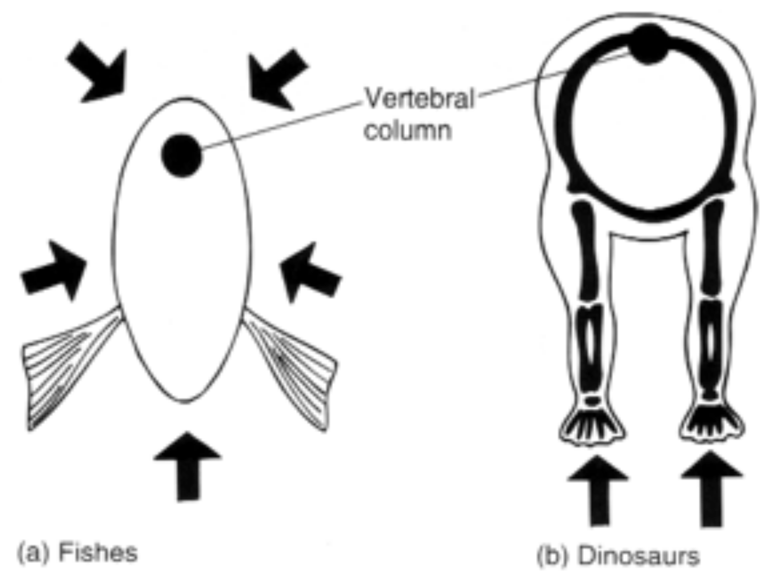


FIGURE 8.33 **Body support.** (a) In fishes, the surrounding water (arrows) supports and buoys the weight of the body. (b) In tetrapods, the limbs support and the vertebral column suspends the weight of the body.

Stress and Strain

Stress = applied force measured per cross sectional area

Strain = deformation of a material caused by applying force

Elastic region: deformation is not permanent, when stress is released, both stress and strain return to zero.

Elastic energy: energy stored in the elastic material that is stretched (recoverable energy).

Young's modulus: slope of elastic region (stress/strain) rubber band - low E, bone - high E.

Plastic region: beyond the yield point, material is permanently deformed. Will not return to original dimensions when stress is released.

Fracture Point: breaks if stressed beyond this point.

Stress-strain curve for bone

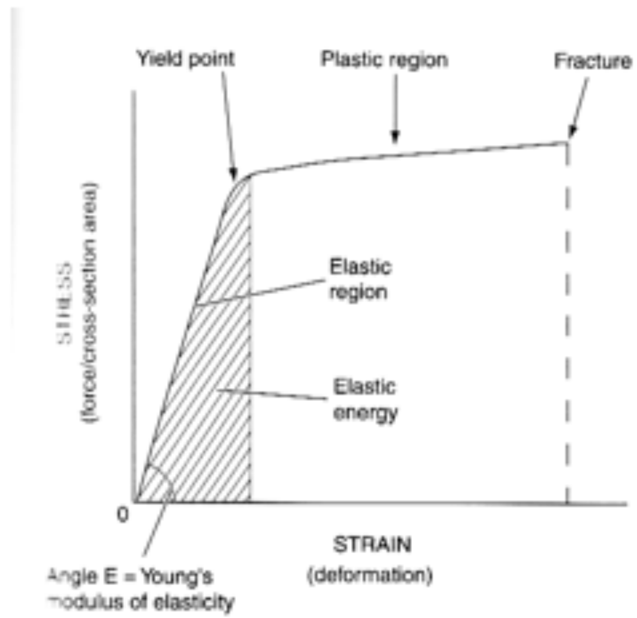
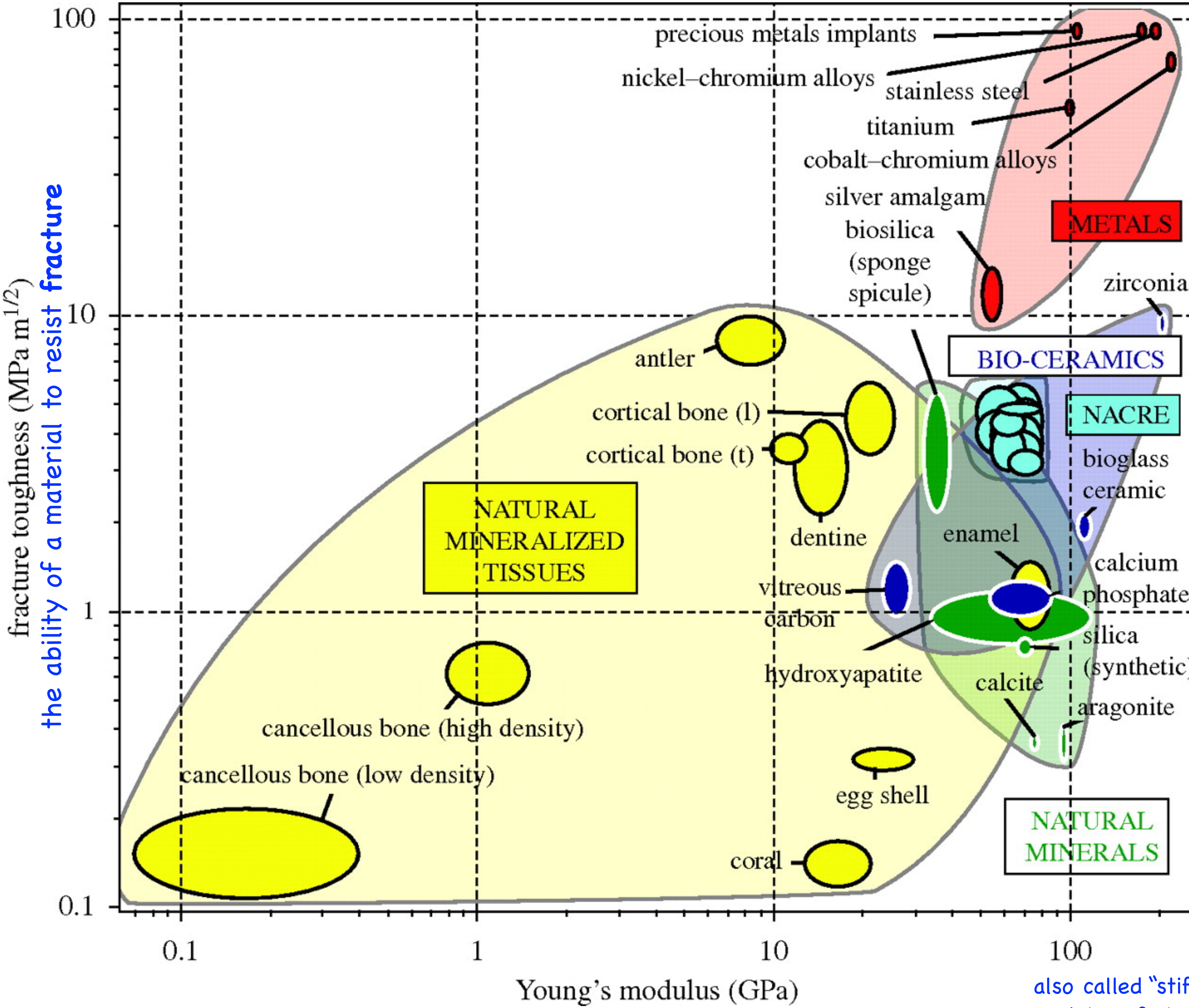


FIGURE 5-4
A stress–strain curve for a fairly rigid material, such as bone. The material at first deforms only slightly as stress increases greatly. *(After Currey.)*



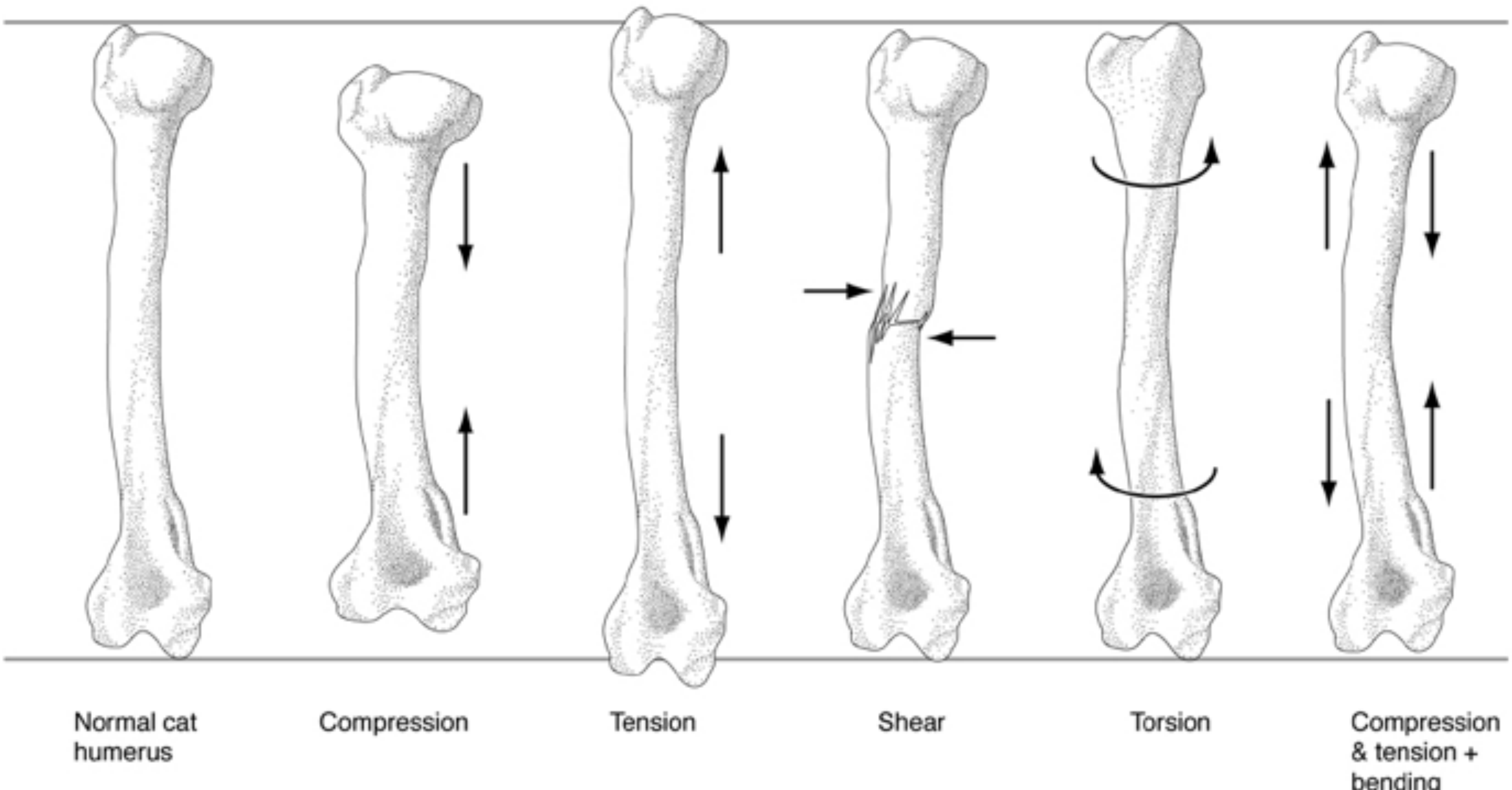
the ability of a material to resist **changes in length** under **tension or compression**

also called "stiffness" or modulus of elasticity

http://rsta.royalsocietypublishing.org/content/roypta/368/1917/2099/F1.large.jpg?width=800&height=600&carousel=1

Major Types of Stresses on Biomaterials

Stresses: shown by arrows
Strains: shown by deformations



Bones are generally designed with high safety factors

Biological Tissues and their Material Properties

In order to support a significant mass, we need to have some rigid materials. These are usually connected by soft tissues.

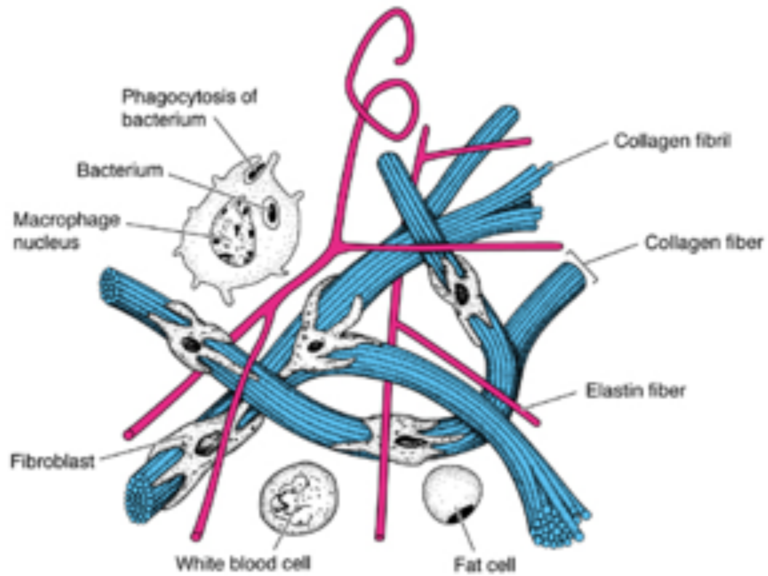
Biological tissues are subject to the same laws of physics as inanimate objects. “Material Properties” = parameters such as stiffness, breaking point, etc.

Soft Connective Tissues: Loose connective tissues

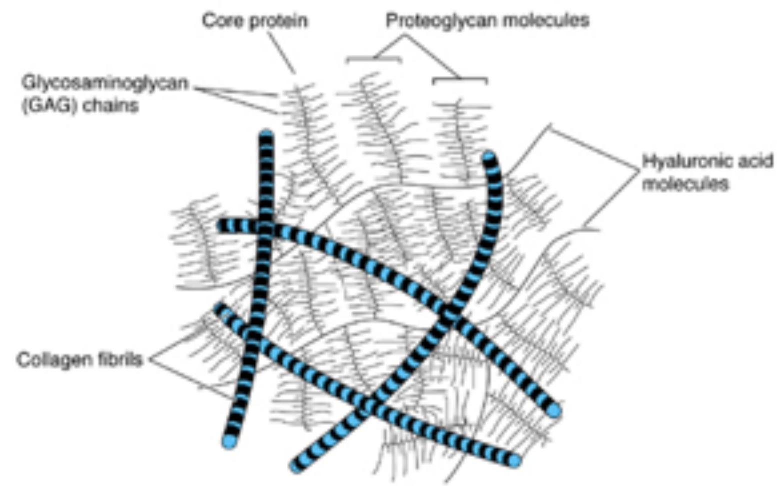
Rigid Tissues:

- Hydrostats
- Cartilage
- Bone

Loose connective tissue



A. Components of loose connective tissue



B. Ground substance of loose connective tissue

<u>Loose connective tissue</u>

- Fibroblasts - cells which produce loose connective tissue
- Collagen - a filamentous protein, bends, but does not stretch easily
- Elastin - stretchy protein. (like rubber band).

<u>Ground substance</u> of loose connective tissue: Matrix of proteoglycan, hyaluronic acid molecules, collagen

Also, macrophages, fat cells

Hydrostats

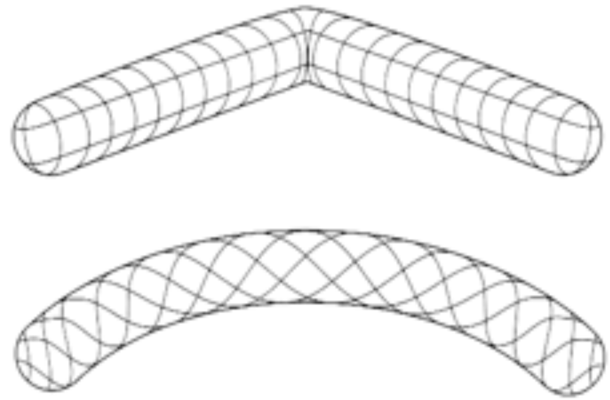


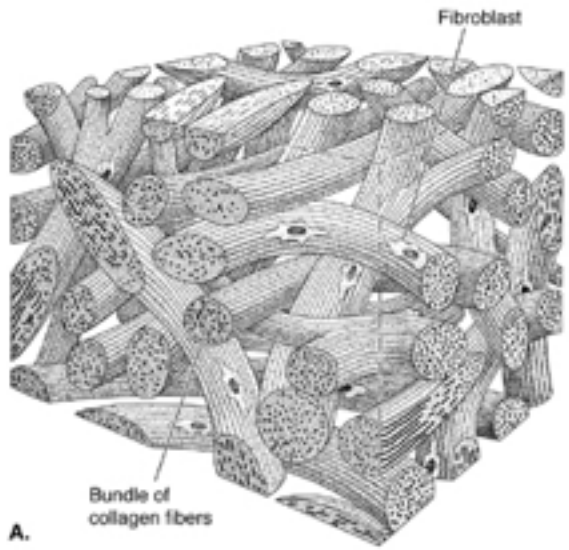
FIGURE 5-5
Two arrangements of reinforcing fibers in the wall of a pressurized cylinder. A helical arrangement permits the cylinder to bend without kinking. *(After Wainwright.)*

- Hydrostats are fluid-filled membranes that resist compression. (they may be designed to "give" in one direction but not another).

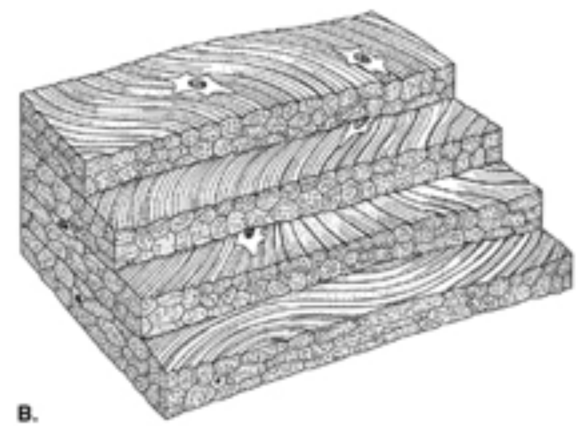
- Example: notochord (primitive spinal column for support).

- The arrangement of reinforcing fibers influences resistance to different deformations. Helical arrangement allows bending without kinking.

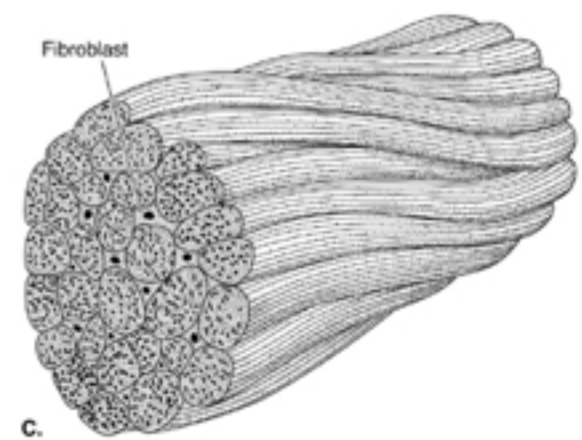
Arrangement of collagen in different connective tissues -- Density & Arrangement confer physical properties



Skin - Dense irregular connective tissue



Ligament - in sheets



Tendon - cable-like

Cartilage

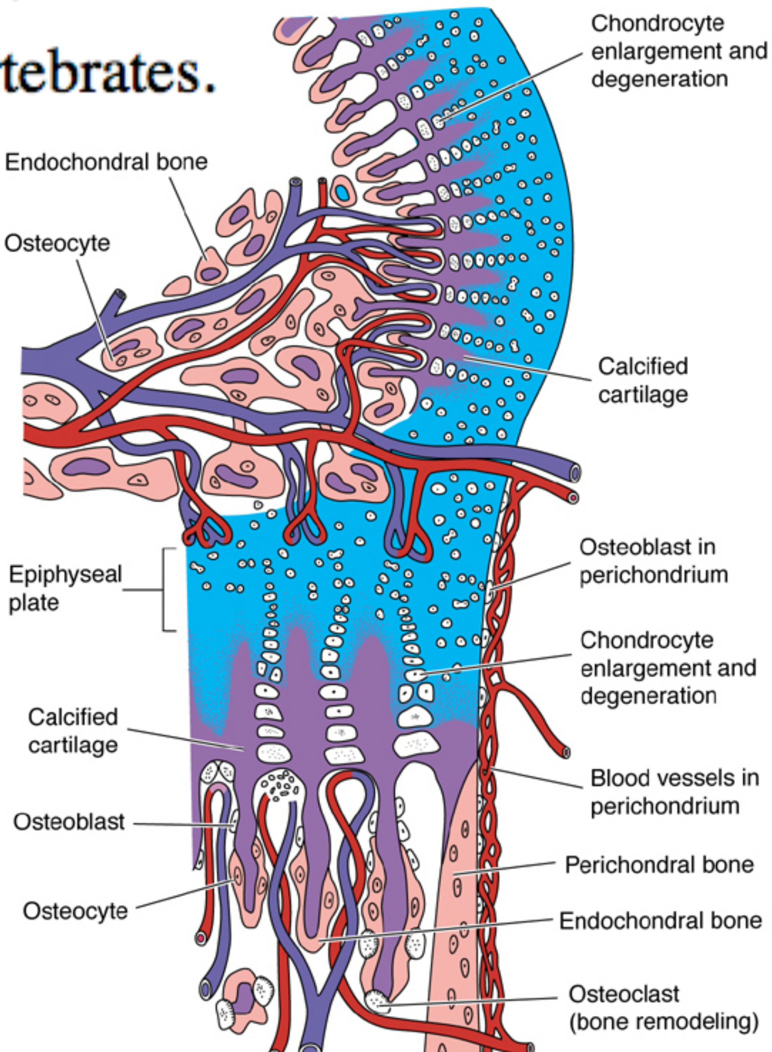
- Bone and cartilage are dense, rigid connective tissues. Both resist compression, thus provide **support**.
- Cartilage is nearly as strong as bone in resisting **compression**, but does not resist **tension** and **shear** as well.
- Cartilage and bone are **composite materials**, matrices containing several types of materials and spaces.
- Special cartilages:
  - Hyaline cartilage: mammals, ends of limb bones, ribs, cartilages of larynx and tracheal rings.
  - Elastic cartilage: mammalian ears
  - Fibrocartilage: intervertebral disks, mandibular and pubic sympheses.
  - Calcified cartilage: in chondrichthyes (sharks and rays)

Bone

- Highly vascular.
- Mineralized and dense connective tissue.
- Primary skeletal tissue of most adult vertebrates.

Bone Remodelling

- Bone cannot expand. Therefore, to get larger, it must be removed and remodeled.
- **Osteoclasts** remove old bone.
- **Osteoblasts** make new bone.



B.

Mature Bone Structure

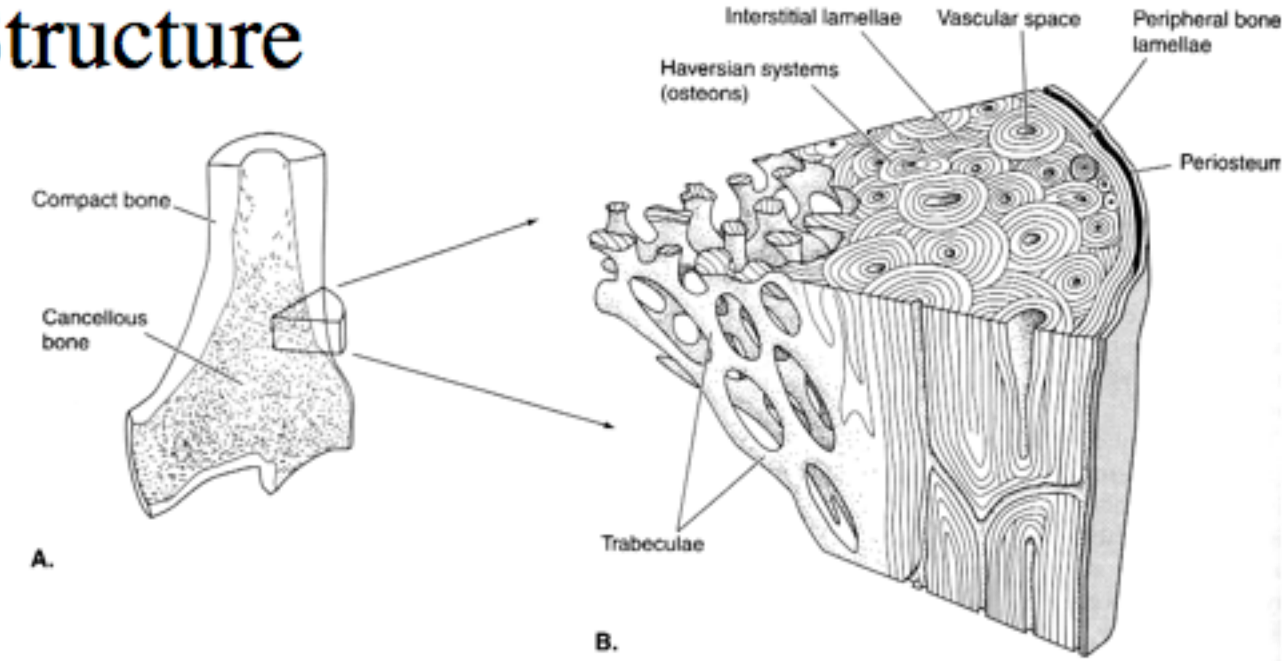


FIGURE 5-13
Mature bone structure. *A*, A longitudinal section near the end of a limb bone. *B*, An enlargement of a portion of it.

- **Compact bone** - dense, peripheral bone tissue
- **Cancellous bone** - bone tissue near ends of bone and adjacent to marrow cavity. Tends to retain trabecular structure.

Bone Development follows Engineering Principles

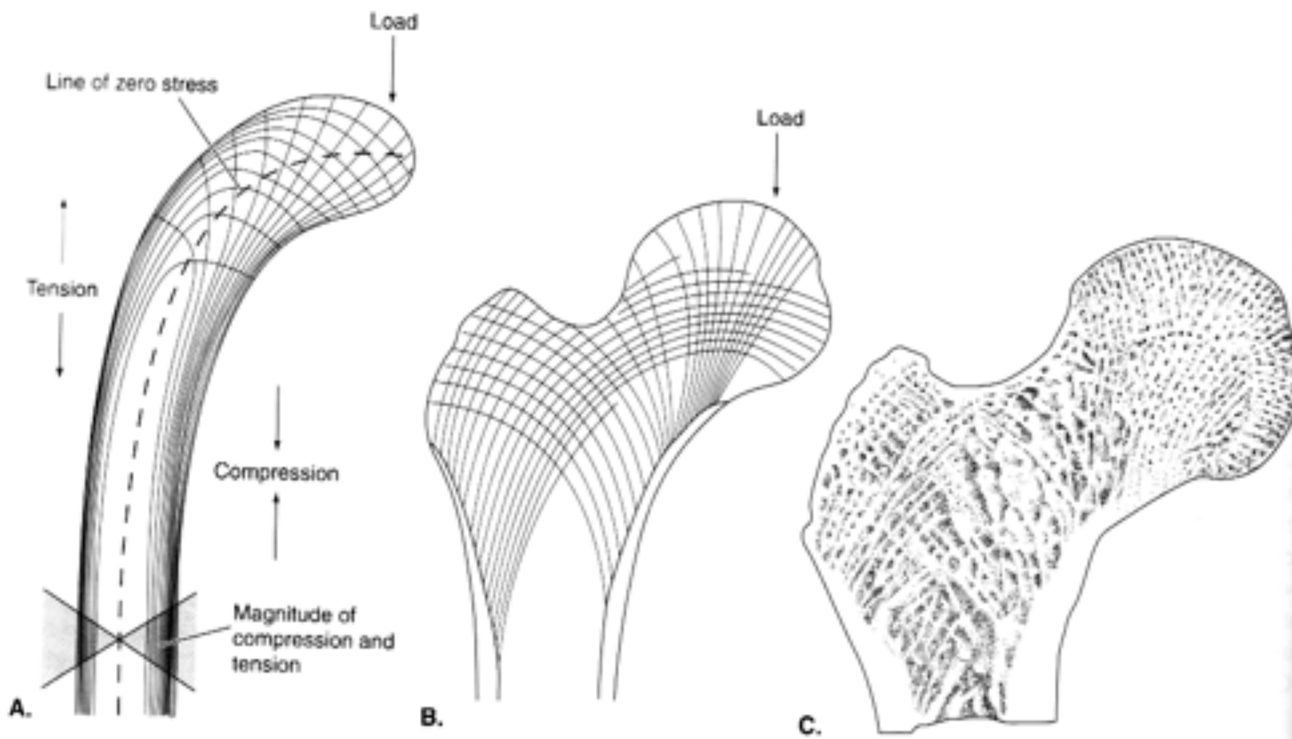
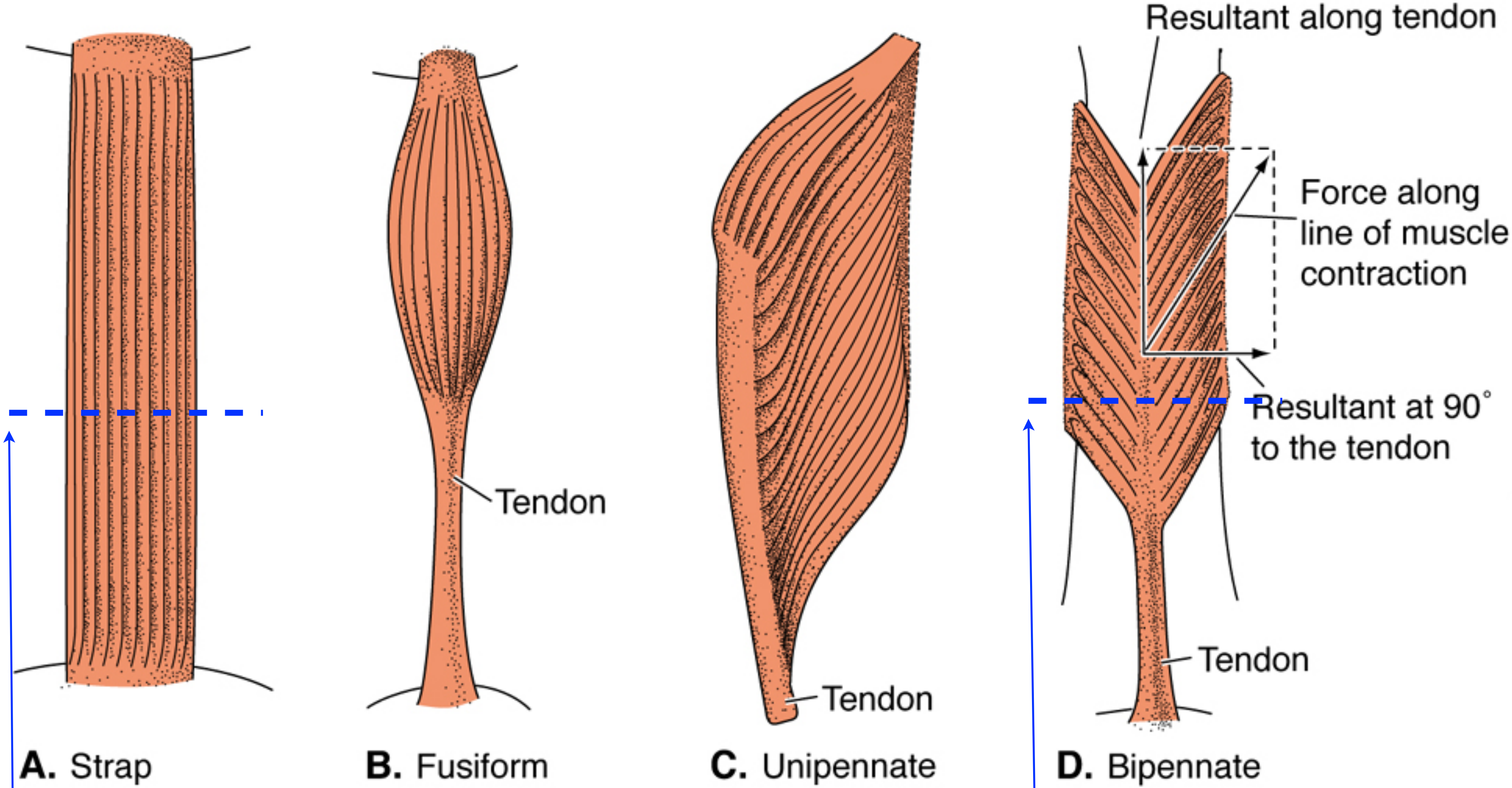


FIGURE 5-19
Stress trajectories in a simple Fairbairn crane (*A*) and the proximal end of a human femur (*B*) in response to a load applied to the medial side of the crane and to the head of the femur. Material on the load-bearing side is under compression; that on the opposite side is under tension. The magnitudes of both stresses decrease to zero at the neutral plane in the center. *C*, A drawing of an x-ray of the proximal end of the human femur showing that the orientation of the trabeculae approximates the expectation. *(A, after Murray.)*

Muscle Architecture: Force vs. Speed

Force produced is proportional to # cross-bridges involved



Lower Force: Fewer cross-bridges per cross-sectional area
Speed: Many Sarcomeres in series, Shortens a lot

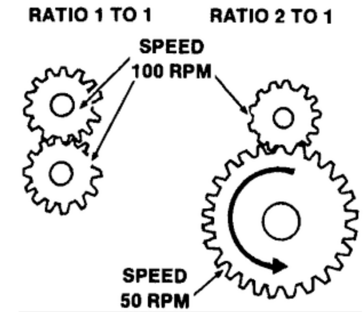
Higher Force: More cross-bridges per cross-sectional area
Low Speed: Doesn't shorten much

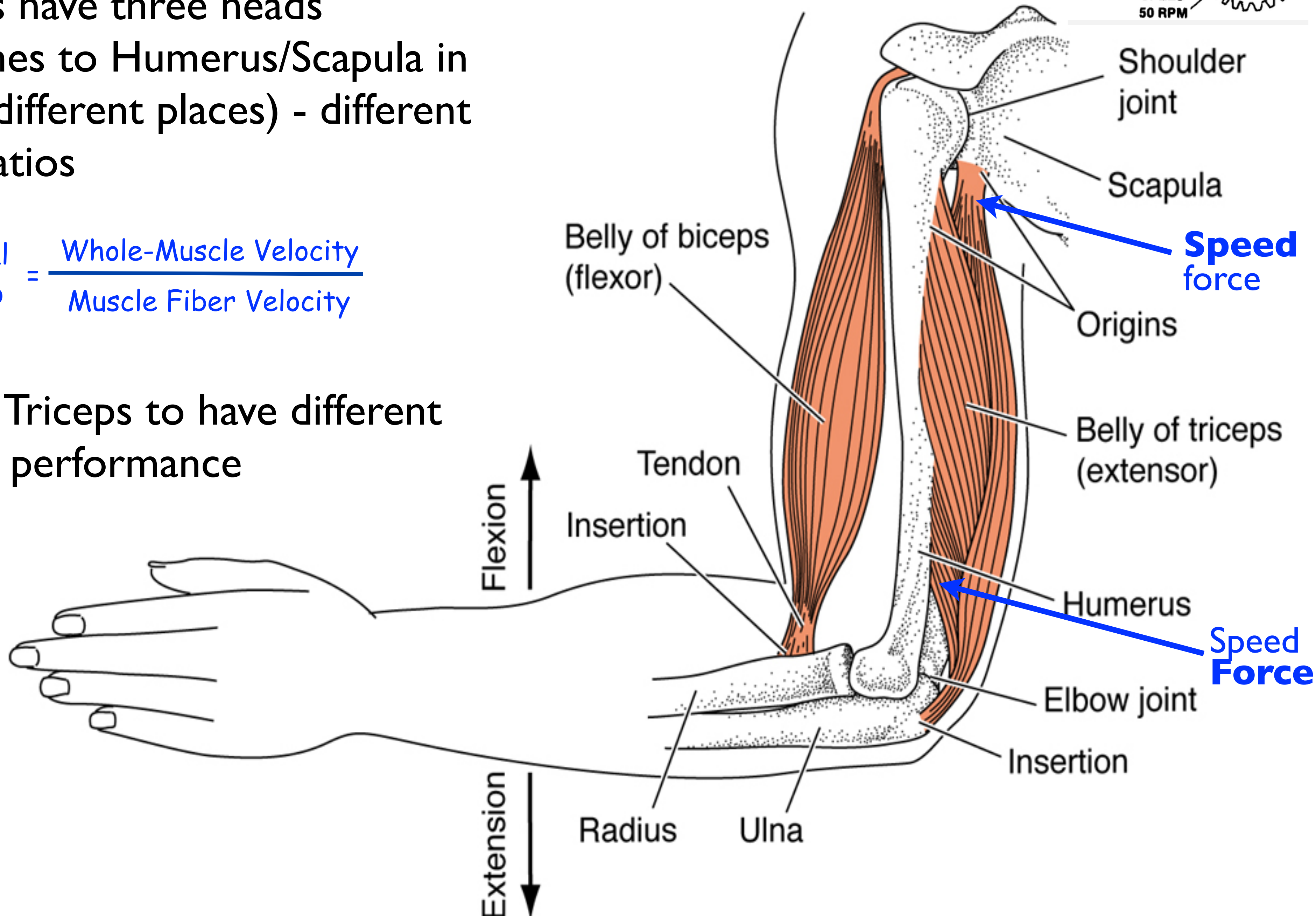
Biceps and Triceps

triceps have three heads (attaches to Humerus/Scapula in three different places) - different gear ratios

$$\text{Anatomical Gear Ratio} = \frac{\text{Whole-Muscle Velocity}}{\text{Muscle Fiber Velocity}}$$

Allows Triceps to have different muscle performance





Variable gearing in pennate muscles

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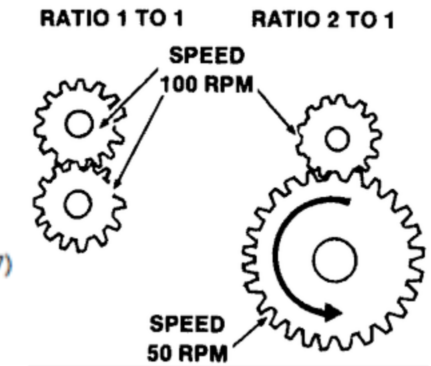
Edited by Ewald R. Weibel, University of Bern, Bern, Switzerland, and approved December 3, 2007 (received for review September 27, 2007)



http://blog.hemmings.com/index.php/2007/11/01/a-different-kind-of-brain-teaser/

Muscle fiber architecture, i.e., the physical arrangement of fibers within a muscle, is an important determinant of a muscle's mechanical function. In pennate muscles, fibers are oriented at an angle to the muscle's line of action and rotate as they shorten, becoming more oblique such that the fraction of force directed along the muscle's line of action decreases throughout a contraction. Fiber rotation decreases a muscle's output force but increases output velocity by allowing the muscle to function at a higher gear ratio (muscle velocity/fiber velocity). The magnitude of fiber rotation, and therefore gear ratio, depends on how the muscle changes shape in the dimensions orthogonal to the muscle's line of action. Here, we show that gear ratio is not fixed for a given muscle but decreases significantly with the force of contraction ($P < 0.0001$). We find that dynamic muscle-shape changes promote fiber rotation at low forces and resist fiber rotation at high forces. As a result, gearing varies automatically with the load, to favor velocity output during low-load contractions and force output for contractions against high loads. Therefore, muscle-shape changes act as an automatic transmission system allowing a pennate muscle to shift from a high gear during rapid contractions to low gear during forceful contractions. These results suggest that variable gearing in pennate muscles provides a mechanism to modulate muscle performance during mechanically diverse functions.

biomechanics | force–velocity tradeoff | gear ratio | muscle architecture

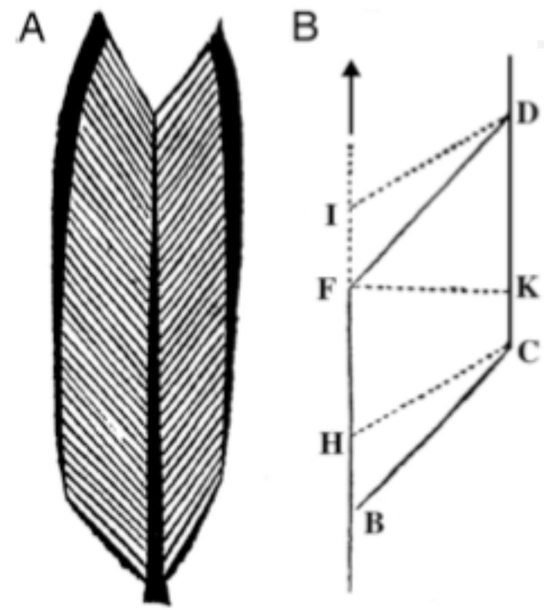
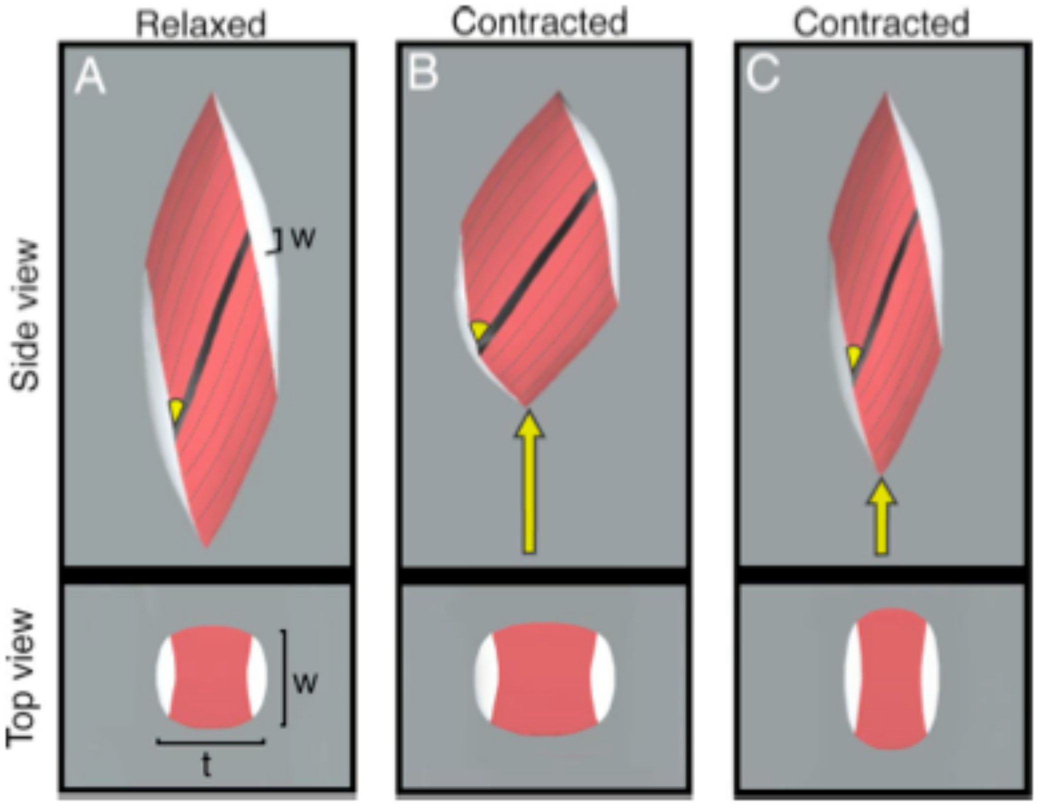


Fig. 1. A 17th century geometric examination of muscle architecture (5). (*A*) The adductor muscle in the claw of a lobster exemplifies bipennate architecture. (*B*) A geometric model of a unipennate muscle highlighting the orientation of fibers at rest (BC and DF) and contracted (HC and ID). This classic model predicts a change in pennation angle (i.e., fiber rotation) during contraction and assumes that muscle thickness (FK) remains constant. Arrow indicates the direction of the muscles' lines of action. Modified from reference 5.

Azizi, Brainerd, Roberts (2008) PNAS 105: 1745-50

www.pnas.org/cgi/content/full/ 0709212105/DC1.

$$\text{Anatomical Gear Ratio} = \frac{\text{Whole-Muscle Velocity}}{\text{Muscle Fiber Shortening Velocity}}$$



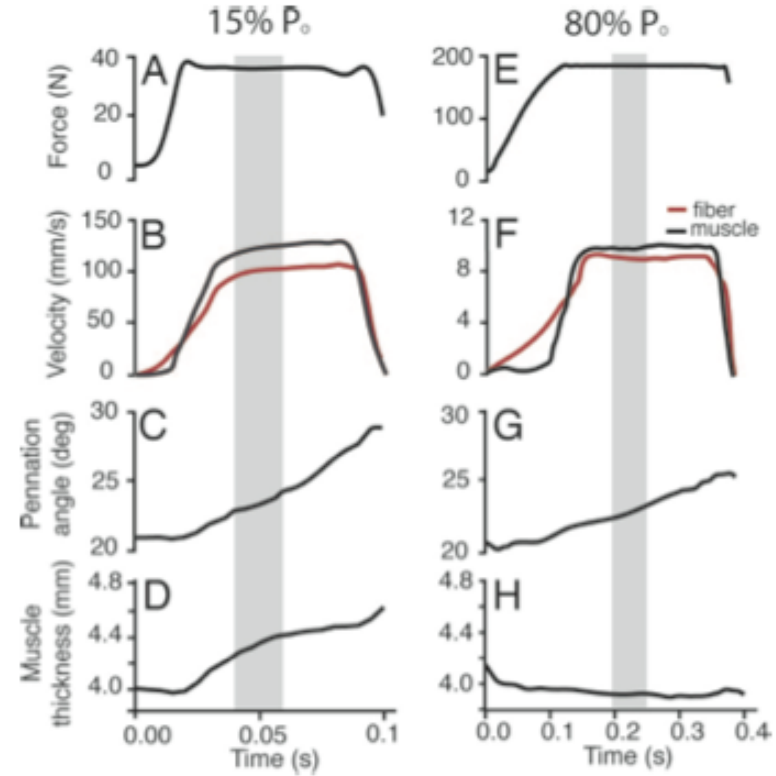
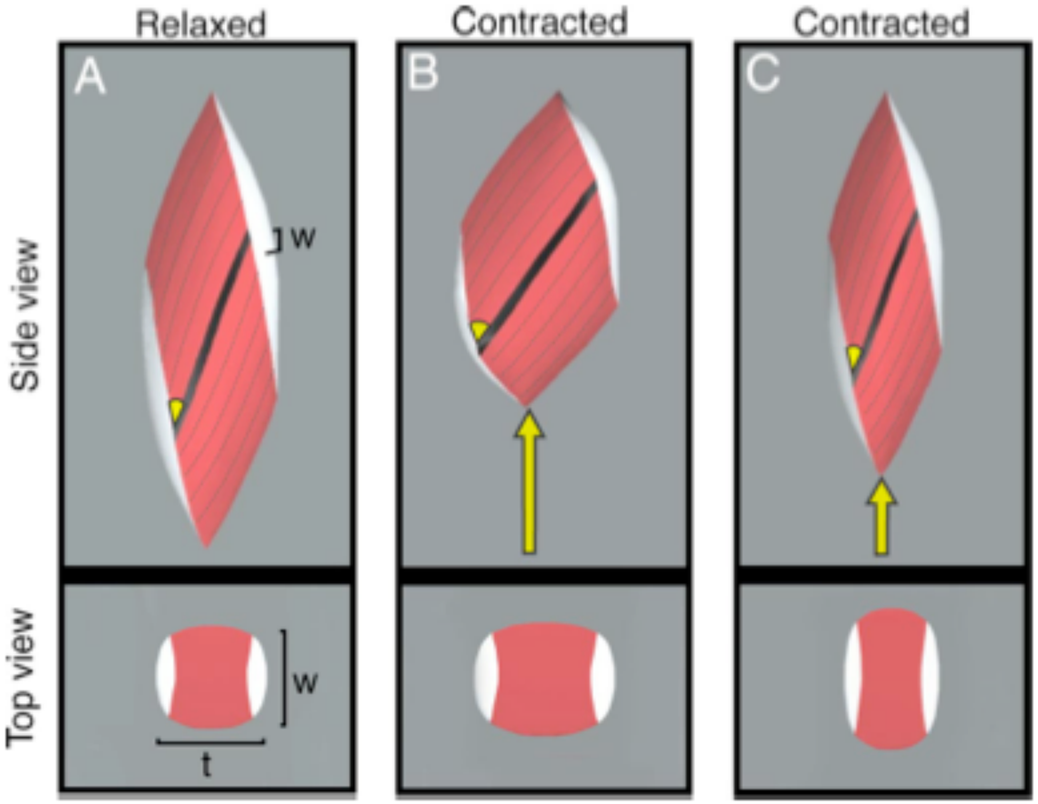


Fig. 3. Representative isotonic contractions in the lateral gastrocnemius of the wild turkey. The muscle was maximally stimulated in a branch of the sciatic nerve. Time-series plots from two sample contractions are shown. Muscle force was allowed to increase to a preset level (15% of maximum isometric force (P_0) in *A–D* and 80% P_0 in *E–H*) and was kept constant as the muscle fiber (red) and the muscle–tendon unit (black) shortened at a constant velocity. All measurements were taken during a period of constant force (gray bars) and at a similar initial pennation angle. Similar contractions were performed at varying levels of force for each muscle.

Angle changes,
Thickness ++,
More rotation
Muscle shortens
High AGR
speed ++

Angle preserved,
Thickness --,
No rotation,
little muscle shortening
Low AGR
More Force



Angle changes,
Thickness ++,
More rotation
Muscle shortens
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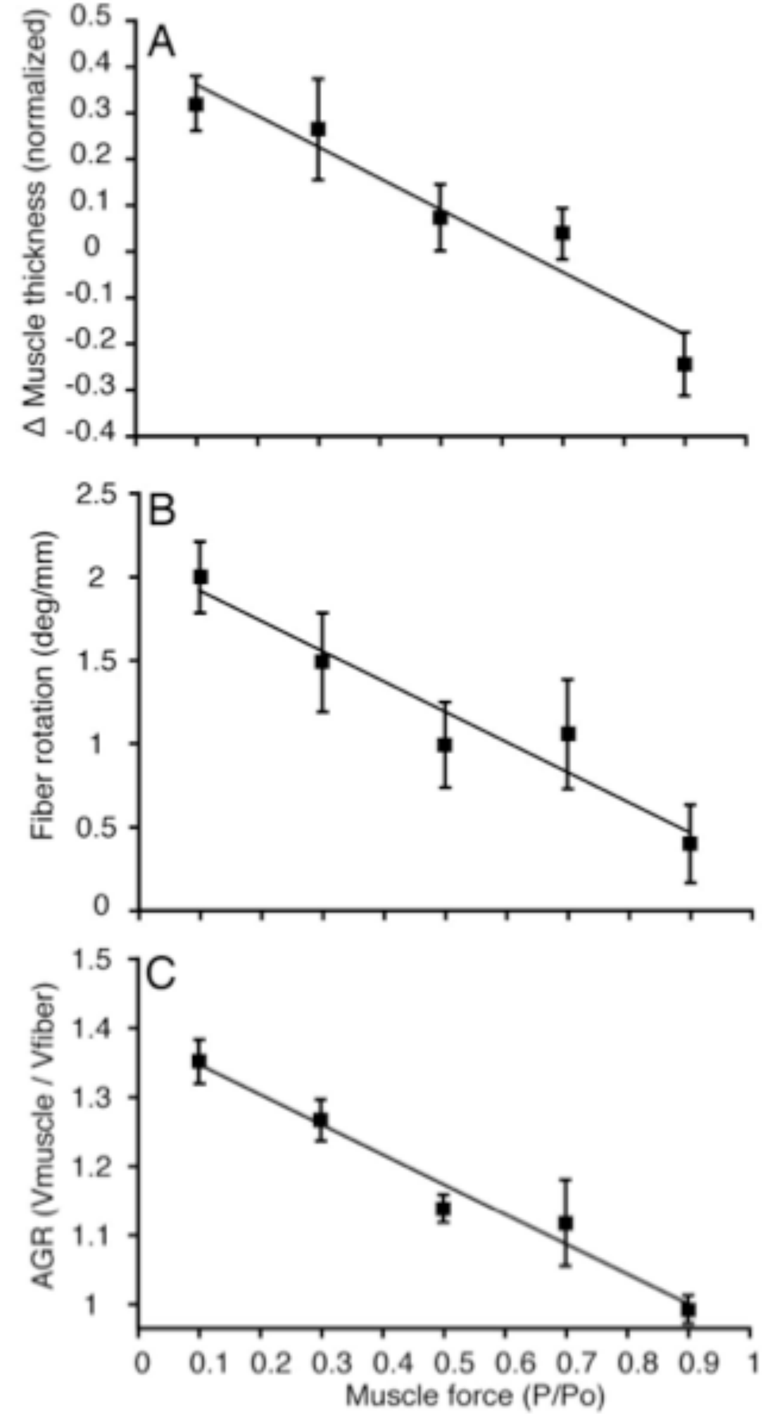
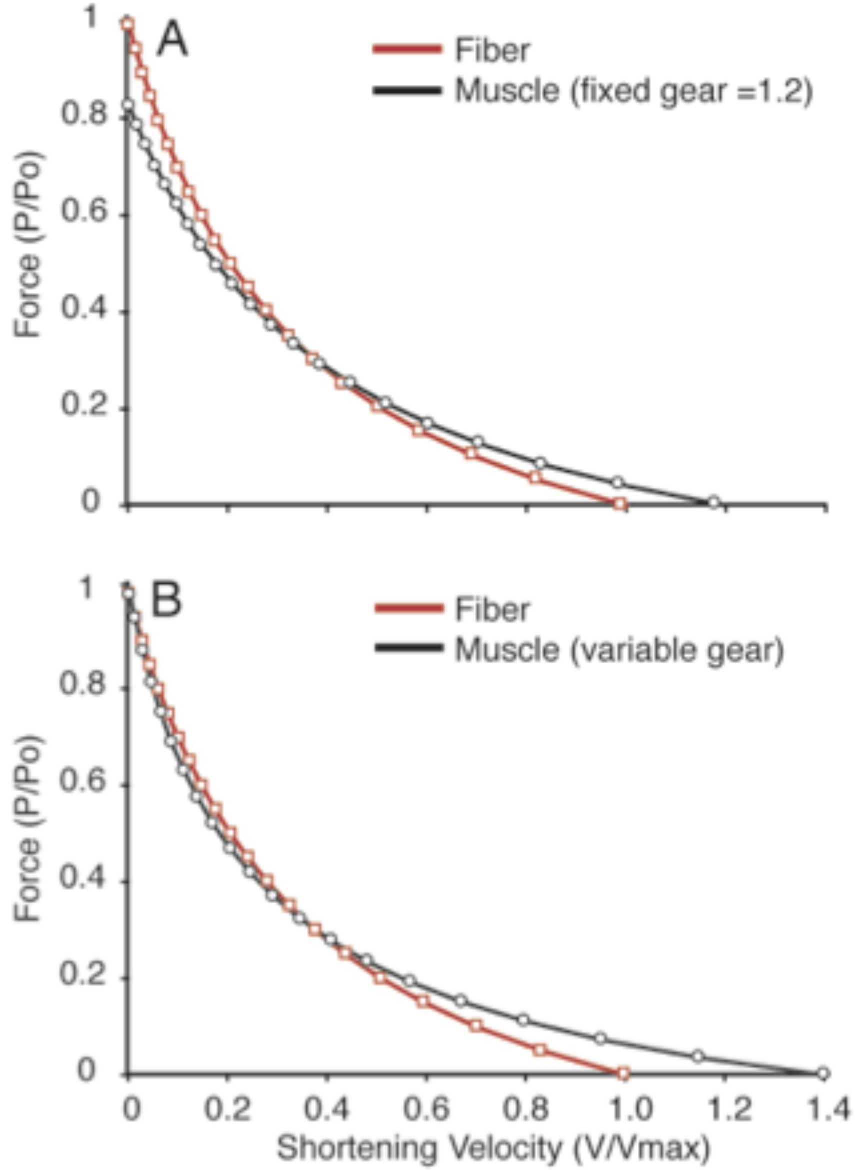
speed ++

Angle preserved,
Thickness --,
No rotation,
little muscle shortening
Low AGR
More Force




A
Fiber
Muscle (fixed gear =1.2)
Force (P/Po)
1
0.8
0.6
0.4
0.2
0
B
Fiber
Muscle (variable gear)
Force (P/Po)
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Shortening Velocity (V/Vmax)