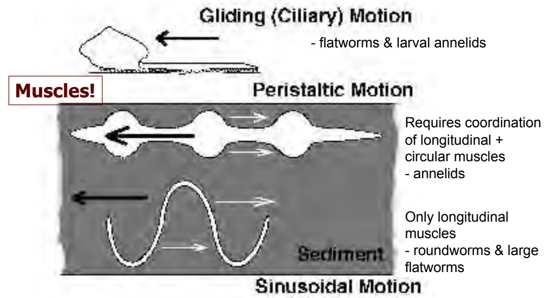
Animas: Locomotion

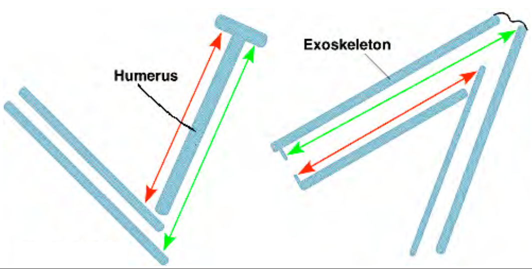
- **Cellular motility**

Organismal motility:



Muscles & Skeletons

- For much more power & versatility of movements:
- muscles attach to skeleton across hinge or joint



MUSCLES

- Muscle Function
- Muscle Structure & Action
- Muscle Types

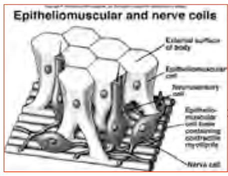
Muscle Functions

- Body movement
  - Locomotion & other behaviors
- Stabilizing body form and position
- Pumping & controlling areas of fluids
  - Within: blood, lymph, air, food
  - Without: secretion/excretion of exocrine products & wastes
- Generate heat

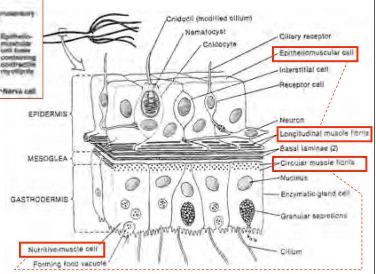
Got Mesoderm?

- Diploblastic organisms lack true muscle
- Other contractile tissues:
  - Sponges — myocytes
    - Close pores
  - Cnidaria — myoepithelia
    - Also found in epithelial exocrine glands of other taxa (including us!)

Myoepithelia (Epitheliomuscular cells)



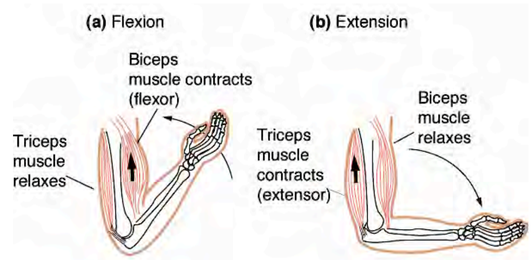
- Cnidarian body wall



Characteristics of muscle

- **Contractility**: shorten actively
- **Extensibility:** stretch passively
- **Elasticity:** recoil to resting length
- **Excitability:** respond to stimulation

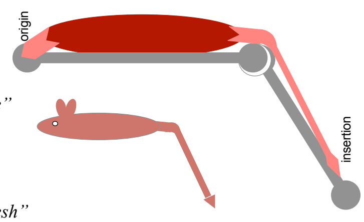
Contraction: shorten via internal force
Extension: muscle can be lengthened only by an external force



Biceps contracts, elbow bends

Triceps exerts force to lengthen biceps, straighten arm

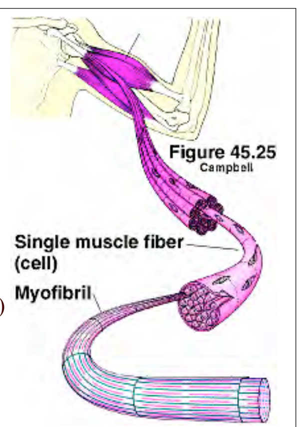
Muscle terms



Mus-, mys- = *"mouse"*
muscle, myofiber

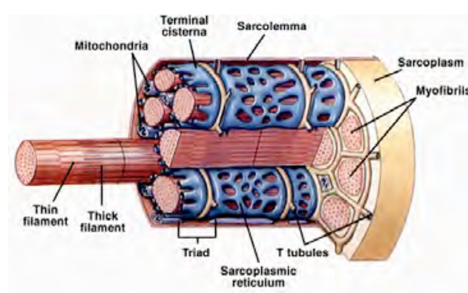
Sarco- = *"meat"*; *"flesh"*
Especially with respect to modified cell components of the mulinuclear myofiber:
- cytoplasm ➡ sarcoplasm
- plasmalemma (cell membrane) ➡ sarcolemma
- [smooth] endoplasmic reticulum ➡ sarcoplasmic reticulum

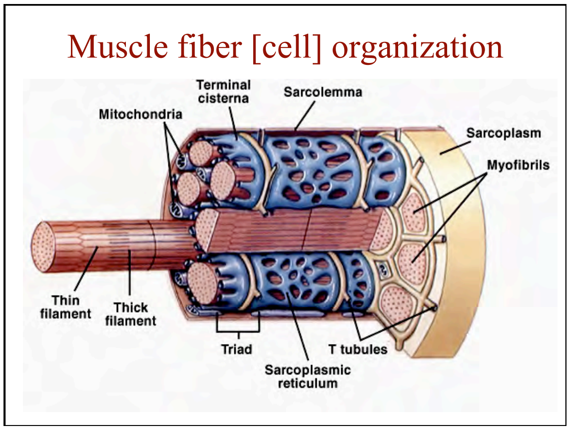
Vertebrate Skeletal Muscle Structure

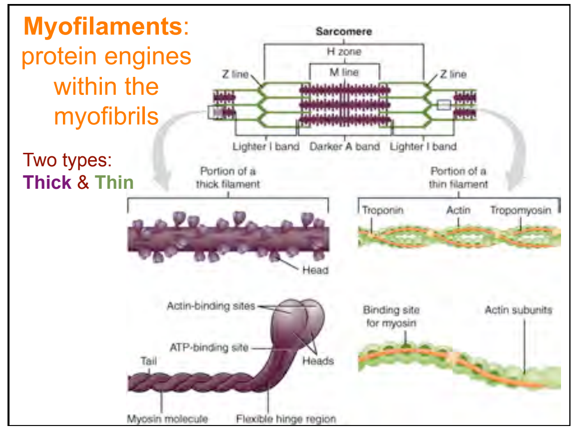


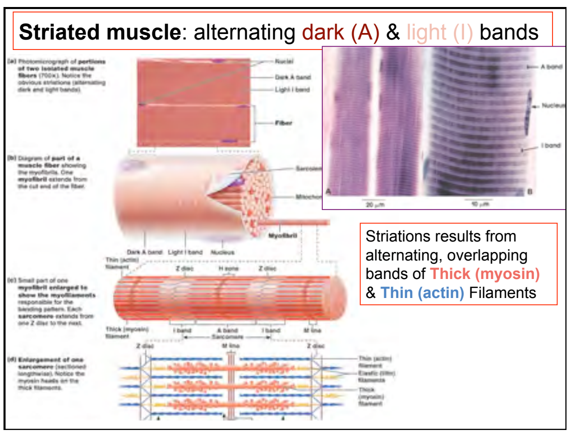
- Muscle fascicle (bundle)
- Muscle fiber (1-cell)
- Myofibril

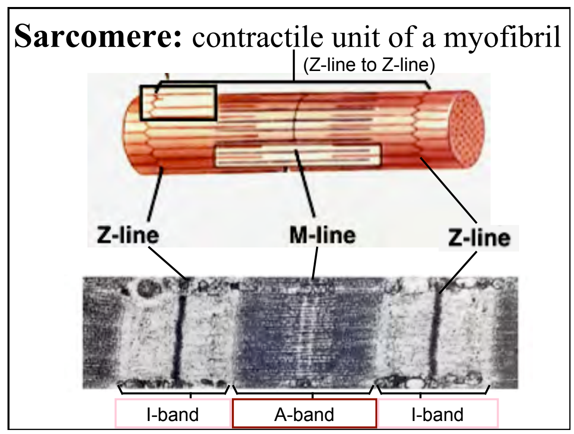
Muscle fiber organization

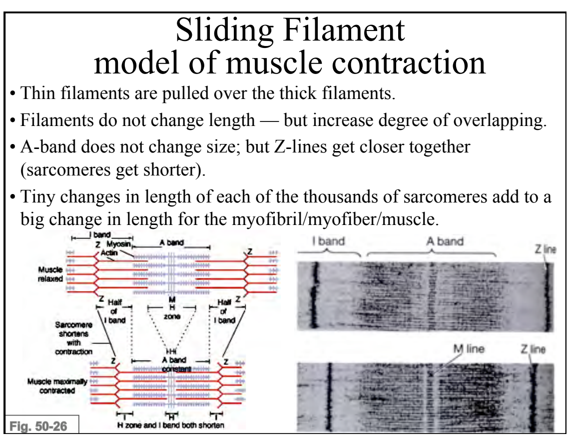


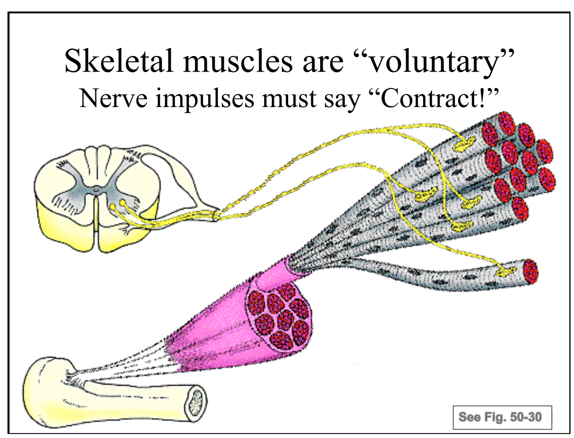

Muscle fiber [cell] organization
Terminal cisterna
Sarcolemma
Mitochondria
Sarcoplasm
Myofibrils
Thin filament
Thick filament
Triad
T tubules
Sarcoplasmic reticulum


Myofilaments: protein engines within the myofibrils
Two types: Thick & Thin
Sarcomere
H zone
M line
Z line
Z line
Lighter I band
Darker A band
Lighter I band
Portion of a thick filament
Portion of a thin filament
Troponin
Actin
Tropomyosin
Head
Actin-binding sites
ATP-binding site
Tail
Heads
Binding site for myosin
Actin subunits
Myosin molecule
Flexible hinge region


Striated muscle: alternating dark (A) & light (I) bands
Striations results from alternating, overlapping bands of Thick (myosin) & Thin (actin) Filaments


Sarcomere: contractile unit of a myofibril
(Z-line to Z-line)
Z-line
M-line
Z-line
I-band
A-band
I-band


Sliding Filament
model of muscle contraction
• Thin filaments are pulled over the thick filaments.
• Filaments do not change length — but increase degree of overlapping.
• A-band does not change size; but Z-lines get closer together (sarcomeres get shorter).
• Tiny changes in length of each of the thousands of sarcomeres add to a big change in length for the myofibril/myofiber/muscle.
I band
A band
Z line
M line
Z line
Muscle relaxed
Sarcomere shortens with contraction
Muscle maximally contracted
H zone and I band both shorten
Fig. 50-26


Skeletal muscles are "voluntary"
Nerve impulses must say "Contract!"
See Fig. 50-30

Conveying Contraction Signal

- Nerve impulses to **neuromuscular junction** opens Na^+ channels.
- Depolarization travels across membrane and conducted through the fiber by T-tubules.
- Voltage-gated Ca^{++} channels on **sarcoplasmic reticulum** open.
- Ca^{++} enters cytoplasm and starts contraction.

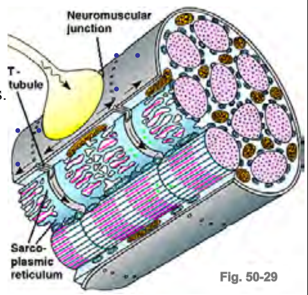
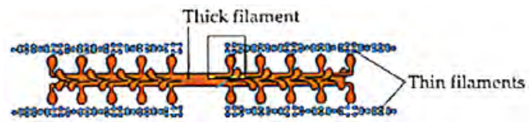
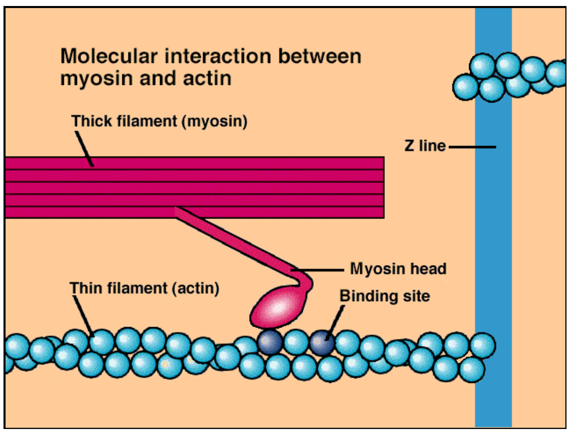


Fig. 50-29

Sliding Filaments

- Ca^{++} opens binding sites for myosin heads.
- Myosin heads swivel as they bind to actin.
- This requires ATP.





Sliding Filament Model

- Myosin-actin interactions underlying muscle fiber contraction

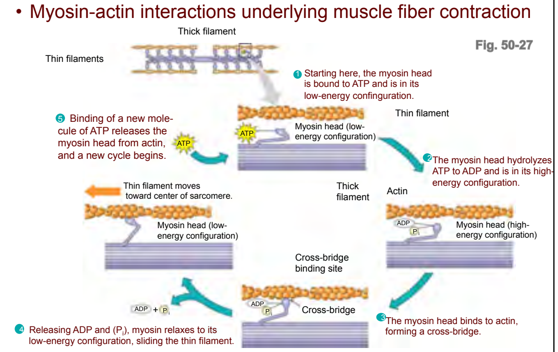
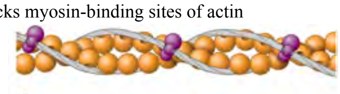


Fig. 50-27

Initiation of contraction by Ca^{++}

- Thin filament constructed of double chain of actin wrapped in fibers of troponin/tropomyosin
- Tropomyosin strand blocks myosin-binding sites of actin

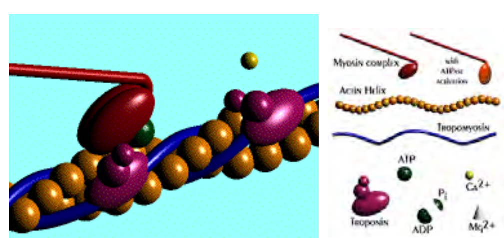


- Ca^{++} binds to troponin
  → tropomyosin moves aside
  → binding sites exposed
  → sliding filament cycle starts

Fig. 50-28

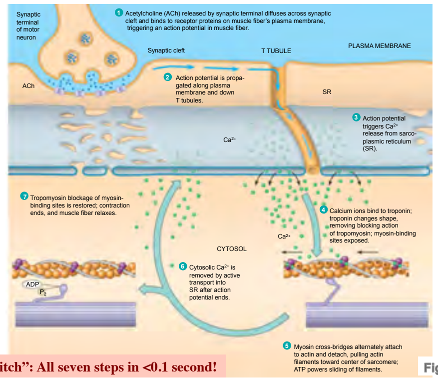
Review of contraction in a skeletal muscle fiber

- Myosin-Actin cross-bridges



http://www.sci.sdsu.edu/movies/actin_myosin_gif.html

Review of contraction in a skeletal muscle fiber



"Twitch": All seven steps in <0.1 second!

Fig. 50-29

Twitch Summation

one motor neuron signal ➔ one twitch

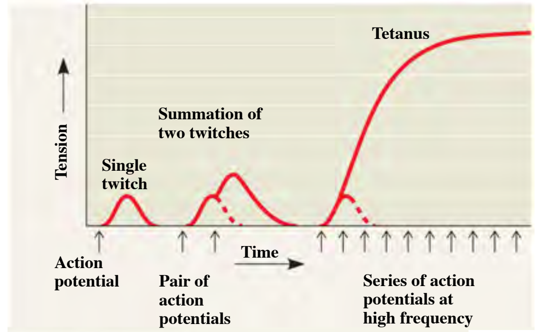


Fig. 50-31

- **Motor unit**: A single neuron and all the muscle fibers it controls
  - **Divergence**
- When motor neuron produces action potential ➔ <u>all</u> the muscle fibers in its motor unit contract as a group.

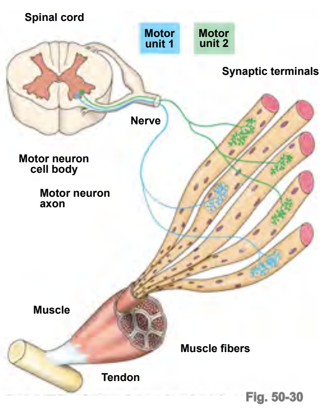
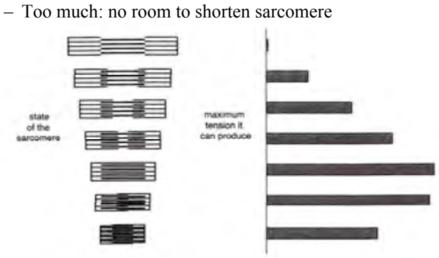


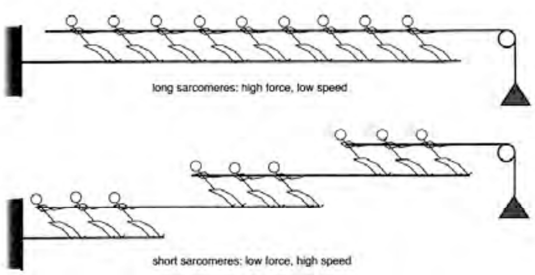
Fig. 50-30

Optimizing filament overlap

- Muscle force depend on the degree of overlap between thin & thick filaments
  - Too little: not many cross-bridges
  - Too much: no room to shorten sarcomere



Long sarcomere vs. short sarcomere



Skeletal Muscle

- Multi-nucleated / striated / "voluntary"
- **White**: short-term & mitochondria-poor
  - high power / fast twitch / low endurance
- **Red**: long-term & mitochondria-rich
  - high myoglobin content [red] for enhanced O_2
  - slow twitch (except in birds) / high endurance
    - swim muscles of oceanic fish
    - extra myoglobin in marine mammals

Types of skeletal muscle fibers

- Any muscle may have more than one type
- But only one muscle fiber type per motor unit
  (the motor neuron determines the muscle fiber type)

Table 49.1 Types of Skeletal Muscle Fibers

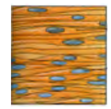
	Slow Oxidative	Fast Oxidative	Fast Glycolytic
Contraction speed	Slow	Fast	Fast
Myosin ATPase activity	Slow	Fast	Fast
Major pathway for ATP synthesis	Aerobic respiration	Aerobic respiration	Glycolysis
Rate of fatigue	Slow	Intermediate	Fast
Fiber diameter	Small	Intermediate	Large
Mitochondria	Many	Many	Few
Capillaries	Many	Many	Few
Myoglobin content	High	High	Low
Color	Red	Red to pink	White

Three types of vertebrate muscle tissue

- **Skeletal muscle**
  - Attached to bone (usually)
  - Striated: contractile proteins stacked in visible columns; contraction is linear
  - Voluntary: contract only in response to somatic motorneuron

- **Cardiac muscle**
  - Found only in heart
  - Striated
  - Involuntary: contract in response to intrinsic pacemaker; modifiable by autonomic motorneurons

- **Smooth muscle**
  - Found in lining of visceral organs, blood vessels, skin, etc.
  - Unstriated: contractile proteins aligned in 3-dimensional arrays; contraction may be multi-dimensional
  - Involuntary: contract either in response to intrinsic reflexes, or from extrinsic autonomic motorneuron stimulation

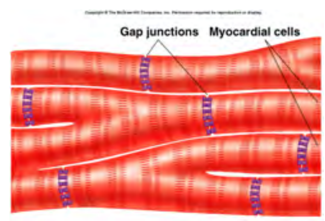


Skeletal muscle

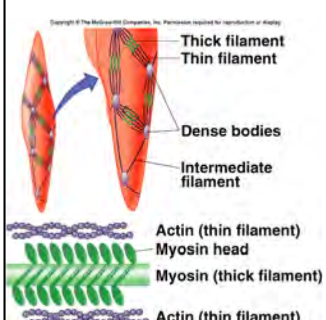
- Skeletal muscle cells are long, multi-nuclear **fibers**.
- Most of the cell's volume is taken up by stacks of protein **filaments**.
- Nuclei and mitochondria are displaced to the periphery.

Cardiac Muscle

- Striated: Contain actin and myosin arranged in sarcomeres.
- Contract via sliding-filament mechanism.
- Branched, mononuclear cells.
- Adjacent myocardial cells joined by gap junctions.
  - APs spread through cardiac muscle through gap junctions.
  - All cells contribute to contraction.
  - **Single-unit muscle**: entire muscle contracts as a single unit

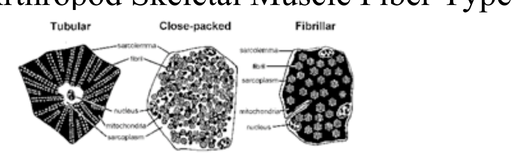


Smooth Muscle



- Filaments not arranged into sarcomeres.
- Contains > content of actin than myosin (ratio of 16:1).
- Myosin filaments attached at ends of the cell to dense bodies.
- Long, slow contractions

Arthropod Skeletal Muscle Fiber Types



Striated & aerobic

- Tubular: fibrils are arranged radially about a central column
  - Dragonfly flight muscles & legs of most insect species.
- Microfibrillar (close-packed): 1.5 to 2.0 µm diameter fibrils
  - Lepidoptera and Orthoptera flight muscles
- Fibrillar: large, 3–5 µm fibrils
  - Hymenoptera, Diptera, Coleoptera and Hemiptera flight muscles
  - Resonating: contract 20-30 times/impulse; contract 1000 times/sec

Vertebrate vs. Arthropod Muscles

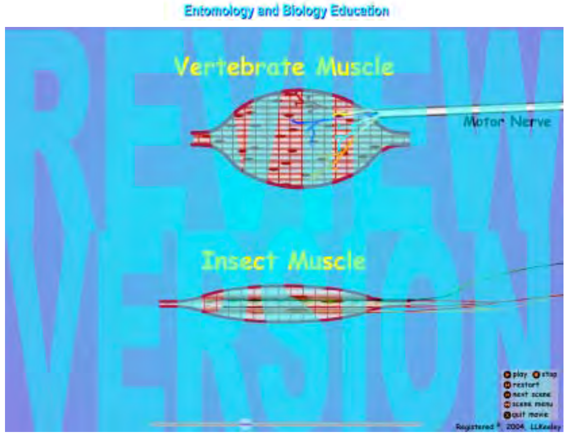
Small bodies cannot fit hundreds of fibers into each muscle

	Vertebrate Skeletal Muscle	Arthropod Skeletal Muscle
Fibers/Muscle	100–1000s	1–10s
Fiber innervation	1 motor end plate from 1 motor neuron/fiber	Multi-terminal & polyneuronal
Motor neuron action	Always excitatory	Some excitatory; some inhibitory
Neurotransmitter	Acetyl-choline	Glutamate [E]; GABA [I]
Fiber conduction of depolarization	Cell membrane & T-tubules of entire fiber	Localized T-tubules only
Fiber contraction	All-or-none twitch	Graded
⇧ Muscle strength/ speed	Recruit more fibers per muscle	Recruit more sarcomeres per fiber

Vertebrate vs. Arthropod Muscles

Small bodies cannot fit hundreds of fibers into each muscle

Physiology and Biochemistry Animations
for
Entomology and Biology Education

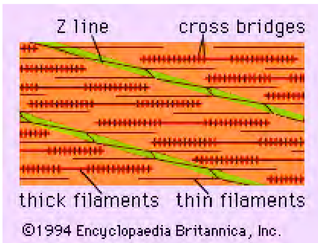


PhysioViva Educational Animations

http://www.physioviva.com/movies/insect_muscle_innervation/

Obliquely striated muscle

- found only in some invertebrate groups
  - nematodes, annelids, and mollusks



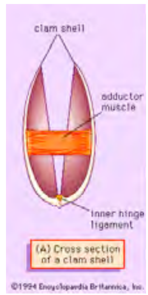
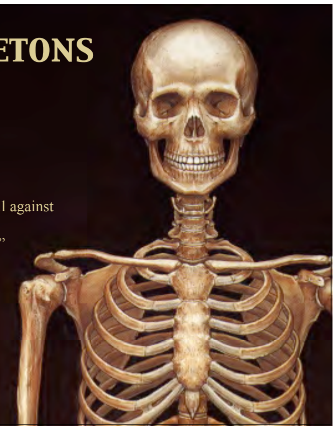


Figure 3: The arrangement of the myofilaments in obliquely striated muscle.

SKELETONS

Functions:
- Support
- Protection
- Mineral storage
- Movement
  - Structure for muscle to pull against
  - True skeleton vs. "shell", "test", or "cuticle"
- Types
  - Hydrostatic skeletons
  - Exoskeletons
  - Endoskeletons



Hydrostatic Skeletons

- Flexibility
  - cnidarians
  - annelids
  - nematodes
  - echinoderms
- **Peristalsis**
  - longitudinal & circular muscles
- Best developed in **annelids.**
  - septa let segments work independently

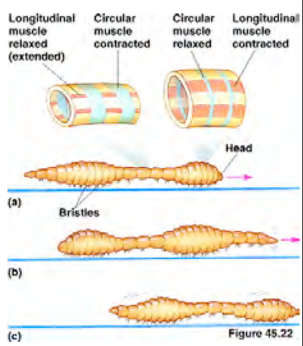


Figure 45.22

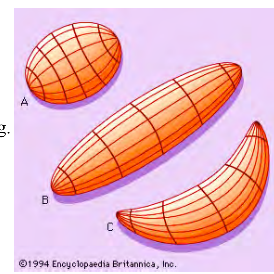
Muscle action with a hydrostatic skeleton

Changes in body form in wormlike soft-bodied animals.

A. The longitudinal muscle contracting.

B. The circular muscle contracting.

C. The longitudinal muscle above contracting while the circular muscles maintain a constant length, stretching the longitudinal muscles below.



Muscle action with a hydrostatic skeleton

- Echinoderm tube feet

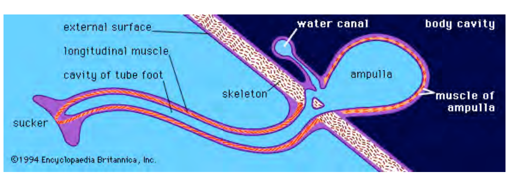
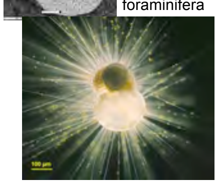


Figure 6: Tube foot of the sea urchin.

Calcareous Shells

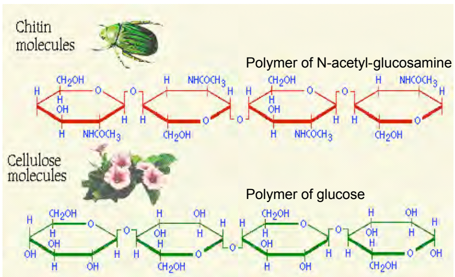
Calcium carbonate ($CaCO_3$)
- Tubes
  - Cnidarians
  - Polychaetes
- Globe-shaped **test**
  - Echinoderm **ossicles** w/ **sutures**
  - Foraminiferans spiral
- Mollusc Shells
  - Spiral of snails
  - Bivalve shells

foraminifera



Ecdysozoans: **Chitinous Cuticles**

Chitin & Cellulose: polymers similar in structure & function.



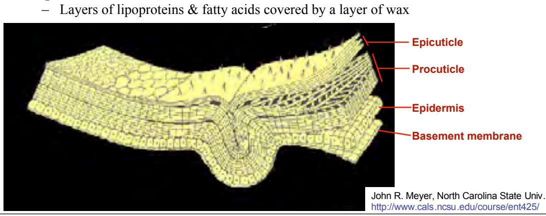
The two most abundant polysaccharides in nature.

Arthropod Chitinous **Exoskeleton**

- Terrestrial: waterproof waxy layer
- Marine: calcified
- Chitin fibers layered like plywood for strength
- 30–50% of arthropod exoskeleton

Arthropod **Exoskeleton**

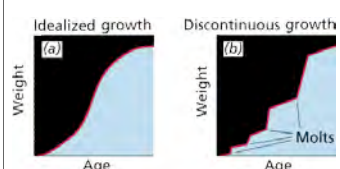
- **Epidermis & basement membrane**
  - Simple epithelia on a layer of collagen & polysaccharides
- **Procuticle**
  - Layers of chitin fibers in a protein matrix
  - Proteins may may elastic — membranes & joints
  - Or, outer layers may cross-link (sclerotization) to form hardened plates (sclerites)
- **Epicuticle**
  - Layers of lipoproteins & fatty acids covered by a layer of wax



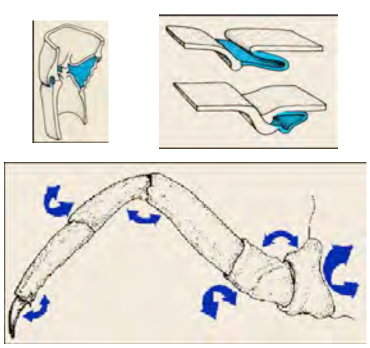
John R. Meyer, North Carolina State Univ.
http://www.cals.ncsu.edu/course/ent425/

Growth, Molt, & Exoskeletons

- Recycle materials
- Vulnerable to predation during molt
- Growth is step-like

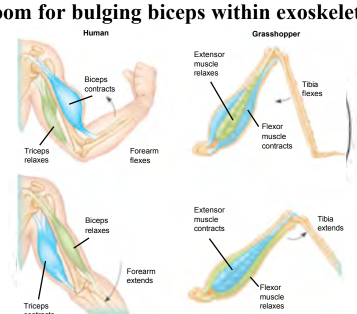


Arthropod joints



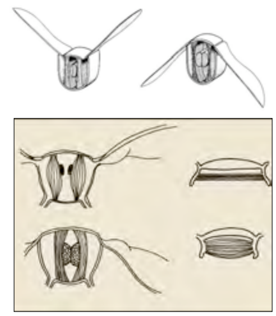
Parallel vs. pinnate muscle fibers

- muscles attach to skeleton across hinge or joint
- **No room for bulging biceps within exoskeleton**



Insect flight

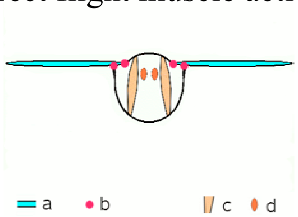
Insect flight muscles



Indirect flight musculature

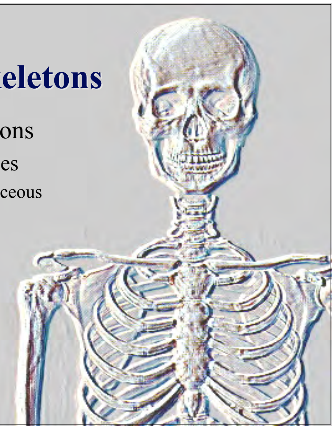
- Double-hinge attachment of wings to thoracic segment
- Dorsoventral muscles, running from the tergum to the bottom of the thorax, contract to raise the wings.
- Longitudinal muscles, running along the length of the thorax, contract to lower the wings.
- Synchronous systems: tubular or microfibrillar muscles; neurogenic; slow beat frequency: 4–20/sec
  - Butterflies & dragonflies
- Asynchronous systems: fibrillar muscles; myogenic; fast beat frequency:100–1000/sec
  - Bees, flies, mosquitoes

Indirect flight muscle action



Basic motion of the insect wing in insect with an indirect flight mechanism
Scheme of dorsoventral cut through a thorax segment with:
- –a: wings
- –b: joints
- –c: dorsoventral muscles
- –d: longitudinal muscles

Endoskeletons



- Minor endoskeletons
  - spicules of sponges
    - calcareous or siliceous
- Vertebrates
  - cartilage & bone

Not-so-Endo-skeletons

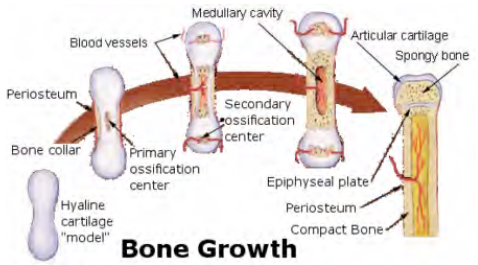
- Imbedded armor — **endodermal bone**
  - Armored fish dermal bone
  - Turtle carapace
  - Vertebrate skull
- **Intramembranous ossification**
  - Within dermal connective tissue
  - Sutures allow growth w/out shedding it.

Cartilage & Endoskeletons

- Flexible endoskeletons
  - Agnathans & Chondrichthyes
- Embryonic skeleton of all vertebrates
  - Cartilage later replaced by **endochondral bone**
- Forms articulating surfaces of bones.
- Supports trachea, nose, pinnae.

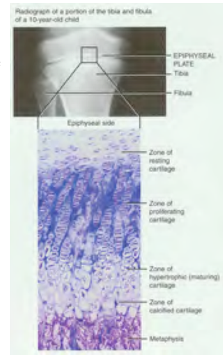
Endochondral Bone Growth

- Cartilagenous skeleton derived from embryo mesoderm.
- Ossification centers form within cartilage grow/replace cartilage w/ bone



Endochondral Bone Growth

- Epiphyseal plate
  - Cartilage cells are produced by mitosis on the epiphyseal side of the plate.
  - Cartilage cells are destroyed and replaced by bone on the diaphyseal side of plate.
- As reproductive maturation approaches, the epiphyseal plates close.
  - Cartilage cells in the plate stop dividing and bone replaces the cartilage.



The human skeleton

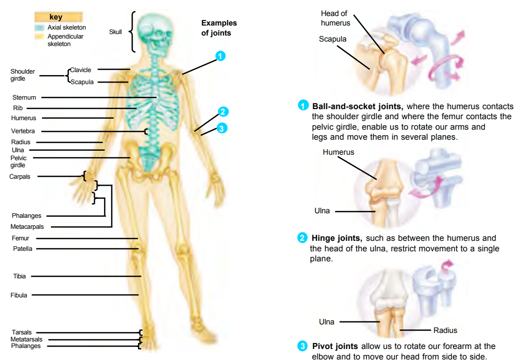
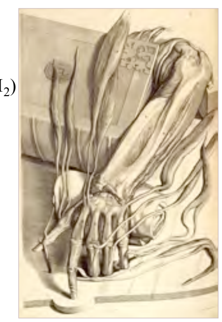


Figure 49.26

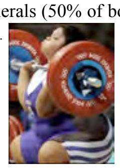
Bone Structure

- **Extracellular matrix** of
  - **collagen** and other **proteins**
  - **calcified**: hydroxyapatite calcium phosphate ($Ca_{10}[PO_4]_6OH_2$)
- **Spongy** bone is at ends.
- **Dense** bone in mid-region.
  - surrounds blood-forming marrow
  - nourished by **osteonic** canals w/ capillaries
- **Ligaments** join bone to bone.
- **Tendons** join bone to muscle.

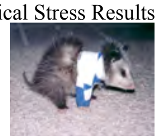


Exercise and Bone Tissue

- Mechanical Stress- the pull on bone by skeletal muscle and gravity.
  - Mechanical stress increases deposition of minerals (50% of bone) and the production of collagen (25% of bone).

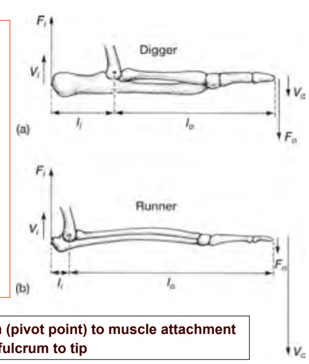


- Lack of Mechanical Stress Results in Bone Loss.



Levers & Fulcrums

- $F_{in}L_{in} = F_{out}L_{out}$
  -   **L_{in}/L_{out}**
  - ↑ **F_{out}** for a given **F_{in}**
  - (more power)
- But, $V_{in}/L_{in} = V_{out}/L_{out}$
  -   **L_{in}/L_{out}**
  - ↑ **V_{out}** for a given **V_{in}**
  - (faster)



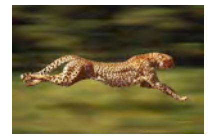
L_{in} = length of bone from fulcrum (pivot point) to muscle attachment
L_{out} = length of appendage from fulcrum to tip

Levers & Fulcrums

□□□ L_{out} □ □□□ V_{out}

Modes of Locomotion:

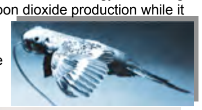
- Each has its costs & benefits



Comparing Costs of Locomotion

- The energy cost of locomotion
  - Depends on the mode of locomotion and the environment

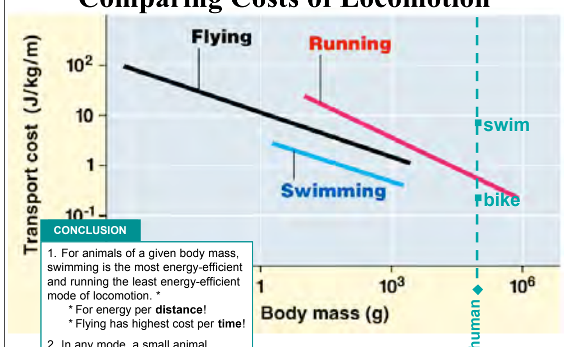
EXPERIMENT Physiologists typically determine an animal's rate of energy use during locomotion by measuring its oxygen consumption or carbon dioxide production while it swims in a water flume, runs on a treadmill, or flies in a wind tunnel. For example, the trained parakeet shown below is wearing a plastic face mask connected to a tube that collects the air the bird exhales as it flies.



RESULTS This graph compares the energy cost, in joules per kilogram of body mass per meter traveled, for animals specialized for running, flying, and swimming (1 J = 0.24 cal). Notice that both axes are plotted on logarithmic scales.

Fig. 50-37

Comparing Costs of Locomotion

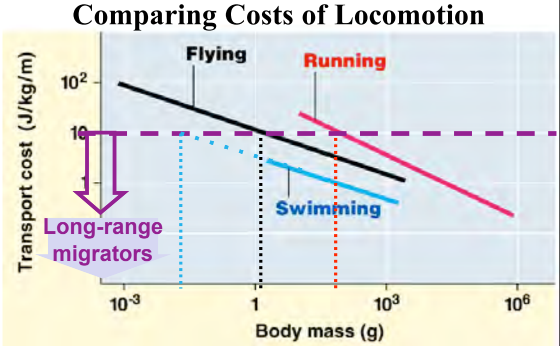


CONCLUSION

1. For animals of a given body mass, swimming is the most energy-efficient and running the least energy-efficient mode of locomotion. *
   - * For energy per **distance**!
   - * Flying has highest cost per **time**!
2. In any mode, a small animal expends more energy per kilogram of body mass than a large animal.

Fig. 50-37

Comparing Costs of Locomotion



- Do they have enough energy stores to sustain locomotion?

Comparing Costs of Locomotion

- Bigger animals have lower transport costs
  - Another reason smaller animals have higher metabolic rates per body mass
- Small animals work much harder to move faster
- But bigger animals have more cost for working against gravity
  - E.g., moving uphill