Musculoskeletal systems

Animals: Locomotion

• Cellular motility

Organismal motility:

- Gliding (Ciliary) Motion
  - Flatworms & larval annelids

- Peristaltic Motion
  - Requires coordination of longitudinal + circular muscles
  - Annelids

- Sinusoidal Motion
  - Only longitudinal muscles
  - Roundworms & large flatworms

Muscles & Skeletons

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

Muscles & Skeletons

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
- **Muscle terms**
  - Mus-, mys- = “mouse”
  - muscle, myofiber
  - Sarco- = “meat”, “flesh”
  - Especially with respect to modified cell components of the multinucleate 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
Musculoskeletal systems

**Muscle fiber [cell] organization**

**Myofilaments:** protein engines within the myofibrils
- Two types: Thick & Thin

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

**Sarcomere:** contractile unit of a myofibril (Z-line to 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.

**Skeletal muscles are “voluntary”**
- Nerve impulses must say “Contract!”
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 Ca²⁺ channels on sarcoplasmic reticulum open.
- Ca²⁺ enters cytoplasm and starts contraction.

Sliding Filaments

- Ca²⁺ opens binding sites for myosin heads.
- Myosin heads swivel as they bind to actin.
- This requires ATP.

Molecular interaction between myosin and actin

- Thick filament (myosin)
- Thin filament (actin)
- Myosin head Binding site

Initiation of contraction by Ca²⁺

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

- Ca²⁺ binds to troponin
  → tropomyosin moves aside
  → binding sites exposed
  → sliding filament cycle starts

Sliding Filament Model

- Myosin-actin interactions underlying muscle fiber contraction

Review of contraction in a skeletal muscle fiber

- Myosin-Actin cross-bridges

http://www.sci.sdsu.edu/movies/actin_myosin_gif.html
**Musculoskeletal systems**

**Review of contraction in a skeletal muscle fiber**

- **ACh (Acetylcholine)** released by synaptic terminal diffuses across synaptic cleft and binds to receptor proteins on muscle fiber’s plasma membrane, triggering an action potential in muscle fiber.

- **Action potential** is propagated along plasma membrane and down **T tubules**.

- **Action potential** triggers **Ca**$^{2+}$ release from sarcoplasmic reticulum (SR).

- **Myosin cross-bridges** alternately attach to actin and detach, pulling actin filaments toward center of sarcomere; **ATP** powers sliding of filaments.

- **Calcium ions** bind to troponin; troponin changes shape, removing blocking action of tropomyosin; myosin-binding sites exposed.

- **Tropomyosin blockage** of myosin-binding sites is restored; contraction ends, and muscle fiber relaxes.

**Twitch Summation**

- **One motor neuron signal** → **one twitch**

**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**

- **Long sarcomere**: high force, low speed
- **Short sarcomere**: low force, high speed

**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>
<thead>
<tr>
<th>Table 49.1 Types of Skeletal Muscle Fibers</th>
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</thead>
<tbody>
<tr>
<td><strong>Slow Oxidative</strong></td>
</tr>
<tr>
<td>Fiber diameter</td>
</tr>
<tr>
<td>Nerve innervation</td>
</tr>
<tr>
<td>Fatigue resistance</td>
</tr>
<tr>
<td>Rate of fatigue</td>
</tr>
<tr>
<td>ATPase activity</td>
</tr>
<tr>
<td>Contraction speed</td>
</tr>
<tr>
<td>Myosin ATPase activity</td>
</tr>
<tr>
<td>Major pathway for ATP synthesis</td>
</tr>
<tr>
<td>Rate of fatigue</td>
</tr>
<tr>
<td>Fiber diameter</td>
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<td>Contraction speed</td>
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</tbody>
</table>

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 motorneurons

- **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

Heyer
### Vertebrate vs. Arthropod Muscles

Small bodies cannot fit hundreds of fibers into each muscle

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

Musculoskeletal systems

Obliquely striated muscle

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

Hydrostatic Skeletons

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

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.

Calcareous Shells

- Calcium carbonate (CaCO₃)
  - Tubes
    - Cnidarians
    - Polychaetes
- Globe-shaped test
  - Echinoderm ossicles w/ sutures
  - Foraminiferans spiral
- Molluse Shells
  - Spiral of snails
  - Bivalve shells
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 be 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

**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 muscles

- 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 insects 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.
Musculoskeletal systems

Endochondral Bone Growth

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

Bone Structure

- Extracellular matrix of collagen and other proteins
- Calcified: hydroxyapatite calcium phosphate (Ca_{10}[PO_4]_6(OH)_2)
- Spongy bone is at ends.
- Dense bone in mid-region.
  - Surrounds blood-forming marrow.
  - Nourished by osteonic canals with 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

- \( F_{in}L_{in} = F_{out}L_{out} \)
  - ↑ \( F_{out} \) for a given \( F_{in} \) (more power)
- But, \( V_{in}L_{in} = V_{out}L_{out} \)
  - ↑ \( V_{out} \) 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

The human skeleton

Figure 49.26

Bone Growth
### 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**

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.

**CONCLUSION**

Comparing Costs of Locomotion

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

**Graph**

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.

### 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