Chapter 12 Muscle Physiology

Outline

- Skeletal Muscle Structure
- The mechanism of Force Generation in Muscle
- The mechanics of Skeletal Muscle Contraction
- Skeletal Muscle Metabolism
- Control of Skeletal Muscle Activity
- Smooth and Cardiac Muscle

12.1 Structure of Skeletal Muscle

- Muscle = group of fascicles
- Muscle fibers extend length of muscle from tendon to tendon

Muscle Terminology

<table>
<thead>
<tr>
<th>General Term</th>
<th>Muscle Equivalent</th>
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<tbody>
<tr>
<td>Muscle cell</td>
<td>Muscle fiber</td>
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<tr>
<td>Plasma membrane</td>
<td>Sarcolemma</td>
</tr>
<tr>
<td>Cytoplasm</td>
<td>Sarcoplasm</td>
</tr>
<tr>
<td>Mitochondria</td>
<td>Sarcosome</td>
</tr>
<tr>
<td>Modified endoplasmic reticulum</td>
<td>Sarcoplasmic reticulum (SR)</td>
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Organization of Skeletal Muscle

- Connective tissue: Binding, support and insulation
- Epimysium: surround muscle
- Perimysium: surround fascicles
- Endomysium: Surround muscle fiber

Components and Function of a Skeletal Muscle Fiber

Match the functions of the components of a muscle fiber.

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
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<tbody>
<tr>
<td>T-tubules</td>
<td>1. Regulatory filament that binds to calcium ions</td>
</tr>
<tr>
<td>Scaroplasmic reticulum (SR)</td>
<td>2. Thin contractile filament that containing myosin binding site</td>
</tr>
<tr>
<td>terminal cisternae</td>
<td></td>
</tr>
<tr>
<td>Sarcosome</td>
<td>3. Regulatory filament that covers myosin binding site during muscle relaxation</td>
</tr>
<tr>
<td>Actin</td>
<td>4. Transmit AP</td>
</tr>
<tr>
<td>Troponin</td>
<td>5. Thick contractile filament contain myosin heads</td>
</tr>
<tr>
<td>Tropomyosin</td>
<td>6. Produce ATP</td>
</tr>
<tr>
<td>Myosin</td>
<td>7. Store Calcium</td>
</tr>
</tbody>
</table>
• **Thin Myofilament**
  o Contractile Protein: actin
    ▪ **Globular** (G) actins form **fibrous** (F) actin.
    ▪ Actins have myosin-binding sites
  o Regulatory proteins
    ▪ **Tropomyosins** cover myosin-binding sites when a muscle fiber is at rest
    ▪ **Troponin** complex has three proteins which attach: actin filament, tropomyosin, and calcium ions.

• **Thick Myofilament: Myosine**
  o Each myosin is a dimer.
  o Cross bridges (myosin heads) contain actin-binding and ATPase site

• **Sarcomere: Functional Unit of Myofibrils**
  o **Sarcomere** is boarded from Z line to Z line.
  o **Titin** anchors thick filaments. It provides structural support and elasticity
  o **Z line**: Link thin filaments
  o **M line**: Link thick filaments
  o **A band**: Dark band under microscope where thick filaments & thin filaments overlap
  o **H zone** contains thick filaments only and M line
  o **I band**: Light band. It has thin filaments only and Z line

12.2 The Mechanism of Force Generation in Muscle
• The **sliding-filament model** of muscle contraction (Figure 12.6)
  o Thin and thick filaments slide past each other to make sarcomere shorter, myofibrils are shorter therefore muscle shorter (contraction)
  o According to the sliding-filament model of muscle contraction, **circle the shortened** components: I band, A band, H zone, sarcomere

• **The Crossbridge Cycle: How Muscle Generate Force**
  o **Crossbridge cycle** is cyclical formation of links between actin and myosin resulting in the sliding of thin filaments toward the M line of a sarcomere
  o **Power stroke**—myosin head moves propelling thin filament toward center of muscle (movement of oar propelling boat)
  o Five steps of crossbridge cycle ((Figure 12.7)
    a. ____________________________
    b. ____________________________
    c. ____________________________
    d. ____________________________
    e. ____________________________

• **How Muscle Contractions Are Turned On and Off? Excitation-Contraction Coupling**
  o **Excitation-contraction coupling** is the sequence of events linking an action potential (excitation) in the sarcolemma to the contraction
  o The somatic nerve system controls the activity of skeletal muscle through motor neuron (Figure 11.13)

• **Excitation Contraction Coupling**
  o Write the correct seven events in excitation-contraction coupling (Figure 12.8).
1) The AP triggers the release of Ca++ from SR
2) Crossbridge cycles begin
3) ACh is released from a motor neuron and it binds to receptor to generate an end-plate potential, which generates an AP in a muscle cell
4) Ca++ is actively transported back to SR
5) AP propagates along sarcolemma and down T-tubule
6) Ca++ binds to troponin exposing myosin-binding site
7) Tropomyosin blocks myosin-binding site

• **Role of Regulatory Factors in Contraction (Figure 12.9)**
  o Calcium must leave troponin, allowing tropomyosin to cover myosin binding sites on actin
  o Ca^{2+} ATPase in sarcoplasmic reticulum transports calcium from cytosol into sarcoplasmic reticulum.

12.3 The Mechanics of Skeletal Muscle Contraction
• Skeletal muscle can contract over a wide range of forces and velocities
• Force exerted by contracting muscle = tension
• Force opposing contraction (such as weight to be moved) = load

**Components of a Muscle**
• Contractile elements = the collection of sarcomeres
• Series elastic elements: Tendons and connective tissue are elastic and absorb tension as muscle contracts. They recoil as muscle relaxes and spring back to the resting length

**Twitch and Motor Unit**
  o **A motor unit** = A motor neuron and all muscles it innervates
  o **Twitch** = Contraction produced in a muscle fiber, a motor unit or a whole in response to a single action potential
  o Twitch is an all-or-nothing event for a given muscle fiber at rest and is reproducible.

**Phases of a Twitch (Figure 12.11)**
  o **Latent period** is the time from action potential in muscle cell to onset of contraction (few msec). This is when excitation-contraction coupling occurs.
  o **Contraction phase** is the time tension (or force) is increasing (10–100 msec) to the peak. Crossbridge cycling generates force.
  o **Relaxation phase** is time tension is decreasing back to zero (longer than contraction phase). Calcium reuptake increases and crossbridge decreases.

**Isotonic Twitch Contraction**
  o **Isotonic** (same strength) contraction
  o Tension > Load
    ▪ Tension remains constant, loads are moved as muscle shortens, muscle length changes
    ▪ Concentric contraction: Muscle shortens e.g. Weight lifting
    ▪ Eccentric contraction: Muscle lengthens

**Isometric Twitch Contraction**
  o **Isometric** (same length) contraction
    ▪ Contractile elements shortens to create tension
• Series elastic elements stretches
  o Load > Tension therefore muscle does NOT shorten, load not lifted
    ▪ e.g. Maintain body posture, and hold a book

**Effect of Load on Tension in an Isotonic twitch (Figure 12.13)**
  o Isotonic contraction at which loads? 5 g; 10 g, 15 g and 20 g

**Factors Affecting Force of Individual Muscle Fibers**
  o Frequency of stimulation
  o Fiber diameter
  o Changes in fiber length
  o Extent of fatigue

**Frequency of Stimulation**
  o Increases in frequency of action potentials in muscle fibers increases tension two ways: treppe and summation
  o **Treppe** is the Successive twitches get larger to trigger a treppe or staircase effect until reaching the plateau. Plateau may be caused by accumulation of intracellular Ca++
  o **Summation and Tetanus (Figure 12.16)**
    ▪ If 2nd stimulus occurs before muscle relaxes from 1st, the 2nd twitch will be greater than the 1st twitch. This is **summation**.
    ▪ If muscle is stimulated by an increasing frequency of electrical shocks, its tension will increase to a maximum called **incomplete tetanus**
    ▪ If frequency is so fast no relaxation occurs, a smooth sustained contraction results **complete tetanus**

**Cause of Summation and Tetanus**
  • Amount of tension developed depends on amount of calcium bound to troponin
  • At high frequencies, calcium release exceeds reuptake; as a result calcium increases in cytosol and eventually saturate system
  • All troponin has calcium bound to it
  • Crossbridge cycling maxed out
  • Maximum tetanic contraction

**Fiber Diameter**
  o Force-generating capacity= Inherent ability of muscle to generate force
    ▪ Depends on number of crossbridges in each sarcomere and geometrical arrangement of sarcomeres
      ➢ More crossbridges/sarcomere → more force
      ➢ More sarcomeres in parallel → more force
  o Is directly proportional related to the fiber diameter
    ▪ Larger diameter → more filaments → more force

**Fiber Length-Tension**
  o Optimum length (normal) is the ideal resting length. It can generate maximum tension due to the maximum crossbridge overlap

**Regulation of the Force Generated by Whole Muscle**
  o A motor unit = A motor neuron and all muscles it innervates
  o Innervation ratio is number of motor neurons: muscle fibers. It varies from 1:100 to 1:2000
    ▪ Small for delicate and weak movements
    ▪ Large for strength and strong movements
Factors Affecting Whole Muscle Contraction
  o Motor unit recruitment is the increase in the number of active motor units.
  o Motor unit stimulation frequency

Recruitment of Motor Units (Figure 12.18)
  o Increases in tension occur in steps that is direct proportional to size of motor unit

Size Principle (Figure 12.19)
  o Order of motor unit recruitment related to size of motor units
    o Which type motor unit is recruited first? small or large

Velocity of Shortening (Figure 12.20)
  o ↑load: ↑the latent period; _duration of shortening and _velocity of shortening

Load-Velocity Graph (Figure 12.21)
  o The shortening velocity is inversely proportional related to the load.

12.4 Muscle Metabolism: How Muscle Cells Provide ATP to Drive the Crossbridge Cycle

Four sources of energy
  o _______ in muscle
  o _______
  o _______ respiration: phosphorylation
  o _______ respiration: glycolysis

Creatine/Creatine Phosphate
  o Creatine phosphate = first source of ATP. It can provide 4–5 times the amount of ATP present in cells at rest in one step process—very rapid: Creatine phosphate + ADP ↔ Creatine + ATP

Oxidative Phosphorylation
  o Primary energy source during light to moderate exercise
  o Example: aerobic exercises
  o To maintain adequate oxygen: Increase ventilation; Increase heart rate and contraction; Dilate vessels to muscle

Anaerobic Glycolysis
  o When oxygen supply to muscle is limited (during intense exercise), anaerobic glycolysis = primary source of ATP
  o Rapid source of ATP: Only two ATP/glucose and build up lactic acid (burning sensation)

Types of Skeletal Muscle Fibers
  o Differences in the speed of contraction:
    ▪ fast-twitch fibers
    ▪ slow-twitch fibers
  o Differences in the primary mode of ATP production:
    ▪ glycolytic fibers
    ▪ oxidative fibers
  o Myoglobin: oxygen-binding protein

Fatigue is the decline in a muscle’s ability to maintain a constant force of contraction during repetitive stimulation
  o Peripheral fatigue is the fatigue in muscles
  o Central fatigue occurs as brain is less able to activate muscles even when muscle is not fatigued

Causes of Muscle Fatigue
  o During high intensity exercises: Buildup of lactic acid; compression of blood vessels and
depletion of acetylcholine (neuromuscular fatigue)
  o During low intensity exercises, the depletion of energy reserves occurs and other possibilities could cause muscle fatigue include: buildup of inorganic phosphates, and changes in ion distribution
- **Muscle Fatigue:** Higher stimulation frequency causes fatigue more easily.

### 12.5 Control of Skeletal Muscle Activity

- To control skeletal muscle movements, central nerve system must receive continuous sensory feedback from
  o Muscle spindle apparatus: information about ______________
  o Golgi tendon organs: information on ____________

#### Properties of Smooth Muscle
- No troponin
- Dense bodies analogous to Z line
- Thin and thick filaments are oblique to each other

#### Excitation-Contraction Coupling in Smooth Muscle (Figure 12.35)

#### Relaxation of Smooth Muscle
- Termination requires phosphatase in smooth muscle not in skeletal muscle
- Phosphatase removes phosphate from myosin
- Calcium removed from cytoplasm by Ca-ATPase and Ca-Na counter transport

#### Neural Regulation of Smooth Muscle Contraction
- Innervated by autonomic nervous system
- Sympathetic and/or parasympathetic
- May be excitatory or inhibitory
- Target cell response depends on receptor type

#### Non-Neural Regulation of Contraction
- Intracellular [Ca++] determines tension
- Intracellular [Ca++] influenced by
  - Neural control—autonomic nervous system
  - Hormonal control
  - Paracines (local controls)

#### Properties of Multi-unit Smooth Muscle
- Located in large airways and arteries, eye (ciliary muscle and iris)
- Few if any gap junctions
- Each fiber acts individually and receives own innervation
- No tone
- Recruitment

#### Single-Unit Smooth Muscle
- Most common type
- Location: Intestinal tract, Blood vessels and respiratory tract

#### Properties of Single-Unit Smooth Muscle
- Muscle fibers activated synchronously
  - Fibers connected by gap junctions
  - Contract together as a single unit
- Pacemaker cells with spontaneous depolarizations
- Innervation to few cells
• Tone = level of contraction without stimulation
  • Increases/decreases in tension

• Spontaneous Changes in Membrane Potential
  o Pacemaker potentials: Spontaneous depolarizations to threshold
  o Slow-wave potentials: Cycles in resting Vm

• Cardiac and Skeletal Muscle Electrical Activity Compared
  o Long duration of action potential = 250–300 msec (1–2 msec in skeletal muscle)
  o The refractory period of cardiac muscle is also longer than that of the skeletal muscle
  o This prevents summation and tetanus of cardiac muscle, hence allows the heart to relax completely and fill with blood

http://humanphysiology.tuars.com/program/section2/2ch7/memprop.htm