CHAPTER 9
MUSCLES
MUSCLE TISSUE TYPES
SPECIAL CHARACTERISTICS OF MUSCLE
FUNCTIONS OF MUSCLE
The ability of muscle to be stretched is…

1) Excitability
2) Contractility
3) Extensibility
4) Elasticity
SKELETAL MUSCLE:
GROSS ANATOMY
Figure 9.1 Connective tissue sheaths of skeletal muscle: epimysium, perimysium, and endomysium.
The connective tissue sheath around a single muscle fiber is...

1) Endomysium
2) Epimysium
3) Perimysium
SKELETAL MUSCLE:
GROSS ANATOMY – ATTACHMENTS
SKELETAL MUSCLE: MICROSCOPIC ANATOMY
(a) Photomicrograph of portions of two isolated muscle fibers (700x). Notice the obvious striations (alternating dark and light bands).
(b) Diagram of part of a muscle fiber showing the myofibrils. One myofibril is extended from the cut end of the fiber.
Figure 9.2c Microscopic anatomy of a skeletal muscle fiber.

(c) Small part of one myofibril enlarged to show the myofilaments responsible for the banding pattern. Each sarcomere extends from one Z disc to the next.
The functional contractile unit of a muscle is the…

1) Fascicle
2) Muscle fiber
3) Sarcomere
4) Epimysium
(d) **Enlargement of one sarcomere** (sectioned lengthwise). Notice the myosin heads on the thick filaments.
Figure 9.2e Microscopic anatomy of a skeletal muscle fiber.

- **I band**: thin filaments only
- **H zone**: thick filaments only
- **M line**: thick filaments linked by accessory proteins
- **Outer edge of A band**: thick and thin filaments overlap

(e) Cross-sectional view of a sarcomere cut through in different locations.
Figure 9.3 Composition of thick and thin filaments.

Each thick filament consists of many myosin molecules whose heads protrude at opposite ends of the filament.

A thin filament consists of two strands of actin subunits twisted into a helix plus two types of regulatory proteins (troponin and tropomyosin).

In the center of the sarcomere, the thick filaments lack myosin heads. Myosin heads are present only in areas of myosin-actin overlap.
Figure 9.4 Transmission electron micrograph of part of a sarcomere clearly showing the myosin heads forming cross bridges that generate the contractile force.
SKELETAL MUSCLE: 
SLIDING FILAMENT MODEL OF MUSCLE CONTRACTION
Figure 9.6 Sliding filament model of contraction.

1. Fully relaxed sarcomere of a muscle fiber

2. Fully contracted sarcomere of a muscle fiber
Figure 9.12 Cross Bridge Cycle

1. Cross bridge formation.
2. The power (working) stroke.
3. Cross bridge detachment.

Mechanisms:
- Cross bridge formation
- Cocking of myosin head
- Cross bridge detachment
- Power stroke

Chemical Reactions:
- ATP hydrolysis
- ADP and Pi release
- ATP synthesis
Figure 9.5  Relationship of the sarcoplasmic reticulum and T tubules to myofibrils of skeletal muscle.

Part of a skeletal muscle fiber (cell)

Myofibril

I band

Z disc

A band

H zone

M line

Sarcolemma

Myofibrils

Mitochondria

Sarcolemma

Tubules of the SR

Triad:
- T tubule
- Terminal cisternae of the SR (2)

Tubules of the SR

Myofibrils

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Contraction of a sarcomere occurs because of sliding of ______ past ______.

1) Actin / myosin
2) Myosin / actin
3) Tropomyosin / myosin
4) Tropomyosin / actin
Before a cross-bridge cycle can occur, calcium ions must bind to...

1) actin
2) Myosin
3) Tropomyosin
4) Troponin
Once troponin binds calcium, it moves, exposing ______ binding sites on ______.

1) Actin / myosin
2) Myosin / actin
3) Tropomyosin / actin
4) Tropomyosin / myosin
SKELETAL MUSCLE: PHYSIOLOGY OF MUSCLE FIBERS

Or: How does the calcium get released?
Figure 9.8  Events at the Neuromuscular Junction (1 of 4)

Myelinated axon of motor neuron

Action potential (AP)

Nucleus

Axon terminal of neuromuscular junction

Sarcolemma of the muscle fiber
1. Action potential arrives at axon terminal of motor neuron.

2. Voltage-gated Ca\(^{2+}\) channels open and Ca\(^{2+}\) enters the axon terminal.

3. Ca\(^{2+}\) entry causes some synaptic vesicles to release their contents (acetylcholine) by exocytosis.

4. Acetylcholine, a neurotransmitter, diffuses across the synaptic cleft and binds to receptors in the sarcolemma.
Figure 9.9  Summary of events in the generation and propagation of an action potential in a skeletal muscle fiber.

1. Local depolarization: generation of the end plate potential on the sarcolemma

2. Generation and propagation of the action potential (AP)

3. Repolarization
The electrical signal from a neuron is carried to a muscle by the neurotransmitter called…

1) Epinephrine
2) Calcium
3) Acetylcholine
4) Action potential
Figure 9.11  Excitation-Contraction Coupling (1 of 4)

Setting the stage

Axon terminal of motor neuron

Synaptic cleft

Action potential is generated

Terminal cisterna of SR

ACh

Sarcolemma

Muscle fiber

Ca^{2+}

Triad

One sarcomere
Steps in E-C Coupling:

1. Action potential is propagated along the sarcolemma and down the T tubules.

2. Calcium ions are released.
Calcium binds to troponin and removes the blocking action of tropomyosin.

Active sites exposed and ready for myosin binding

Contraction begins

The aftermath
The depolarization of the membrane reaches the sarcoplasmic reticulum via…

1) T-tubules
2) Voltage-sensitive tubule proteins
3) SR calcium-release channels
4) All of the above
SKELETAL MUSCLE: CONTRACTION
Figure 9.13a A motor unit consists of a motor neuron and all the muscle fibers it innervates.

(a) Axons of motor neurons extend from the spinal cord to the muscle. There each axon divides into a number of axon terminals that form neuromuscular junctions with muscle fibers scattered throughout the muscle.
Figure 9.13b A motor unit consists of a motor neuron and all the muscle fibers it innervates.

(b) Branching axon terminals form neuromuscular junctions, one per muscle fiber (photomicrograph 330x).
Figure 9.14a The muscle twitch.

Latent period

Period of contraction

Period of relaxation

(a) Myogram showing the three phases of an isometric twitch
Figure 9.14b  The muscle twitch.

Latent period

Extraocular muscle (lateral rectus)

Gastrocnemius

Soleus

(b) Comparison of the relative duration of twitch responses of three muscles
During the period of relaxation, what is happening in the muscle fiber on a molecular level?

1) The membrane is depolarizing
2) Ca$^{2+}$ is being released from the SR
3) Ca$^{2+}$ is being taken up into the SR
4) The cross-bridge cycle is beginning
Figure 9.15a Muscle response to changes in stimulation frequency.

(a) A single stimulus is delivered. The muscle contracts and relaxes.
Figure 9.15b Muscle response to changes in stimulation frequency.

(b) If another stimulus is applied before the muscle relaxes completely, then more tension results. This is temporal (or wave) summation and results in unfused (or incomplete) tetanus.
Figure 9.15c  Muscle response to changes in stimulation frequency.

(c) At higher stimulus frequencies, there is no relaxation at all between stimuli. This is fused (complete) tetanus.
Figure 9.16 Relationship between stimulus intensity (graph at top) and muscle tension (tracing below).

- **Stimulus strength**
  - Threshold stimulus
  - Maximal stimulus

- **Stimulus voltage**
  - Stimuli to nerve

- **Proportion of motor units excited**

- **Strength of muscle contraction**
  - Maximal contraction

- **Time (ms)**
Figure 9.17 The size principle of recruitment.

- Motor unit 1 recruited (small fibers)
- Motor unit 2 recruited (medium fibers)
- Motor unit 3 recruited (large fibers)
(a) Concentric isotonic contraction

On stimulation, muscle develops enough tension (force) to lift the load (weight). Once the resistance is overcome, the muscle shortens, and the tension remains constant for the rest of the contraction.
Muscle is attached to a weight that exceeds the muscle’s peak tension-developing capabilities. When stimulated, the tension increases to the muscle’s peak tension-developing capability, but the muscle does not shorten.
When you perform a bicep curl with a barbell weight, your biceps brachii is doing a(n)…

1) Concentric isotonic contraction
2) Isometric contraction
3) All of the above
SKELETAL MUSCLE: METABOLISM
Figure 9.19a Pathways for regenerating ATP during muscle activity.

(a) Direct phosphorylation

**Coupled reaction of creatine phosphate (CP) and ADP**

**Energy source:** CP

**Oxygen use:** None

**Products:** 1 ATP per CP, creatine

**Duration of energy provision:** 15 seconds

Diagram:

- CP → ADP
- Creatine kinase
- Creatine
- ATP

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Figure 9.19b Pathways for regenerating ATP during muscle activity.

(b) Anaerobic pathway

Glycolysis and lactic acid formation

Energy source: glucose

Glucose (from glycogen breakdown or delivered from blood)

Glycolysis in cytosol

Pyruvic acid

Lactic acid

Oxygen use: None

Products: 2 ATP per glucose, lactic acid

Duration of energy provision: 60 seconds, or slightly more
Figure 9.19c Pathways for regenerating ATP during muscle activity.

(c) Aerobic pathway

Aerobic cellular respiration

Energy source: glucose; pyruvic acid; free fatty acids from adipose tissue; amino acids from protein catabolism

Glucose (from glycogen breakdown or delivered from blood)

Pyruvic acid

Aerobic respiration in mitochondria

Oxygen use: Required
Products: 32 ATP per glucose, CO₂, H₂O
Duration of energy provision: Hours

Fatty acids
Amino acids

CO₂
H₂O

32 ATP

net gain per glucose
Figure 9.20  Comparison of energy sources used during short-duration exercise and prolonged-duration exercise.

**Short-duration exercise**

- **6 seconds:** ATP stored in muscles is used first.
- **10 seconds:** ATP is formed from creatine phosphate and ADP.
- **30–40 seconds:** Glycogen stored in muscles is broken down to glucose, which is oxidized to generate ATP.
- **End of exercise:**

**Prolonged-duration exercise**

- **Hours:** ATP is generated by breakdown of several nutrient energy fuels by aerobic pathway. This pathway uses oxygen released from myoglobin or delivered in the blood by hemoglobin. When it ends, the oxygen deficit is paid back.
The end result of all three types of muscle metabolism is…

1) Recharging creatine phosphate
2) Burning fat
3) ATP hydrolysis
4) ATP synthesis
SKELETAL MUSCLE: FORCE OF CONTRACTION
Figure 9.21 Factors influencing force of skeletal muscle contraction.

- Large number of muscle fibers activated
- Large muscle fibers
- High frequency of stimulation
- Muscle and sarcomere stretched to slightly over 100% of resting length

↑ Contractile force
Figure 9.22 Length-tension relationships of sarcomeres in skeletal muscles.

- **Sarcomeres greatly shortened**
  - 75% 

- **Sarcomeres at resting length**
  - 100%

- **Sarcomeres excessively stretched**
  - 170%

Optimal sarcomere operating length (80%–120% of resting length)
SKELETAL MUSCLE: VELOCITY & DURATION OF CONTRACTION
Figure 9.24 Cross section of the three types of fibers in skeletal muscle.
Figure 9.23  Factors influencing velocity and duration of skeletal muscle contraction.

- Predominance of fast glycolytic (fatigable) fibers → ↑ Contractile velocity
- Small load
- Predominance of slow oxidative (fatigue-resistant) fibers → ↑ Contractile duration
The greater the load, the less the muscle shortens and the shorter the duration of contraction.

The greater the load, the slower the contraction.
(a) The greater the load, the less the muscle shortens and the shorter the duration of contraction.
Figure 9.25b Influence of load on contraction duration and velocity.

(b) The greater the load, the slower the contraction
SKELETAL MUSCLE: EFFECT OF EXERCISE
SMOOTH MUSCLE: MICROSCOPIC STRUCTURE
Figure 9.26b Arrangement of smooth muscle in the walls of hollow organs.

(b) Cross section of the intestine showing the smooth muscle layers (one circular and the other longitudinal) running at right angles to each other.

Longitudinal layer of smooth muscle (shows smooth muscle fibers in cross section)

Circular layer of smooth muscle (shows longitudinal views of smooth muscle fibers)
Figure 9.27  Innervation of smooth muscle.

Varicosities release their neurotransmitters into a wide synaptic cleft (a diffuse junction).
Figure 9.28 Intermediate filaments and dense bodies of smooth muscle fibers harness the pull generated by myosin cross bridges.

(a) Relaxed smooth muscle fiber (note that adjacent fibers are connected by gap junctions)

(b) Contracted smooth muscle fiber
In smooth muscle, instead of neurotransmitters being released from axon terminals, they are released from…

1) Caveolae
2) Varicosities
3) Gap junctions
4) All of the above
SMOOTH MUSCLE: CONTRACTION
Figure 9.29 Sequence of events in excitation-contraction coupling of smooth muscle.

1. Calcium ions (Ca\(^{2+}\)) enter the cytosol from the ECF via voltage-dependent or voltage-independent Ca\(^{2+}\) channels, or from the scant SR.
2. Ca\(^{2+}\) binds to and activates calmodulin.
3. Activated calmodulin activates the myosin light chain kinase enzymes.
4. The activated kinase enzymes catalyze transfer of phosphate to myosin, activating the myosin ATPases.
5. Activated myosin forms cross bridges with actin of the thin filaments and shortening begins.
True or false: in smooth muscle, calcium ions bind to tropomyosin to allow myosin to bind to actin.

1) True
2) False
Figure 9.30 Formation of a multinucleate skeletal muscle fiber by fusion of myoblasts.

1. Embryonic mesoderm cells undergo cell division (to increase number) and enlarge.
2. Several myoblasts fuse together to form a myotube.
3. Myotube matures into skeletal muscle fiber.
A Closer Look 9.1  Athletes Looking Good and Doing Better with Anabolic Steroids?