Lecture 9a

Muscle structure

Topics

- Smooth, skeletal, and cardiac muscle tissues
- Structure and function of skeletal muscle cells.
- Sarcomeres structure and contraction
- Actin-myosin interaction and sliding filament theory

Muscle Similarities

- Muscle types: skeletal, cardiac, smooth
- Skeletal and smooth muscle cells are elongated and are called muscle fibers
- Muscle contraction depends on two kinds of myofilaments – actin and myosin
- Muscle terminology is similar
  - Sarcolemma – muscle plasma membrane
  - Sarcoplasm – cytoplasm of a muscle cell
  - Prefixes – myo, mys, and sarco all refer to muscle

Classification of Muscle Cells

- Striated (muscle cells with a banded appearance) or nonstriated (not banded)
- Muscle cells can have a single nucleus or be multinucleate
- Muscle cells can be controlled voluntarily (consciously) or involuntarily (automatically)

Skeletal Muscle

- Striated, “voluntary”, and multinucleated
- Cells can be very long
- Contracts rapidly but tires easily
- Is extremely adaptable and can exert forces ranging from a fraction of an ounce to over 70 pounds
- **Satellite cells**: Like a muscle “stem cell,” can divide to become new skeletal muscle cells (adult skeletal muscle cells do not divide).

Cardiac Muscle Cells

- Occurs only in the heart
- Is striated, not voluntary, uni- or bi- nucleate
- Contracts at a fairly steady rate set by the heart’s pacemaker cells
- Cells are called cardiac myocytes
- Form branching networks connected at intercalated disks
- Neural controls allow the heart to respond to changes in bodily needs

Limited capacity for repair

Smooth Muscle Cells

- Nonstriated, involuntary, and have a single nucleus
- Smooth muscle cells are small and tapered
- can divide and regenerate
- Found in walls of hollow organs and blood vessels
- Contract alone or under nervous system control
- Smooth muscle helps maintain blood pressure, and squeezes or propels substances (i.e., food, feces) through organs

Functional Characteristics of Muscle Tissue

- Excitability, or irritability – the ability to receive and respond to stimuli
- Contractility – the ability to shorten forcibly
- Extensibility – the ability to be stretched or extended
- Elasticity – the ability to recoil and resume the original resting length

Characteristics of Skeletal, Cardiac, and Smooth Muscle

TABLE 10–4 A Comparison of Skeletal, Cardiac, and Smooth Muscle Tissues

Property	Skeletal Muscle	Cardiac Muscle	Smooth Muscle
Fiber dimensions (diameter × length)	100 μm × up to 30 cm	10–20 μm × 50–100 μm	5–10 μm × 30–200 μm
Nuclei	Multiple, near sarcolemma	Generally single, centrally located	Single, centrally located
Filament organization	In sarcomeres along myofibrils	In sarcomeres along myofibrils	Scattered throughout sarcoplasm
SR	Terminal cisternae in triads at zones of overlap	SR tubules contact T tubules at Z lines	Dispersed throughout sarcoplasm, no T tubules
Control mechanism	Neural, at single neuromuscular junction	Automaticity (pacemaker cells)	Automaticity (pacesetter cells), neural or hormonal control
Ca^{2+} source	Release from SR	Extracellular fluid and release from SR	Extracellular fluid and release from SR
Contraction	Rapid onset; may be tetanized; rapid fatigue	Slower onset; cannot be tetanized; resistant to fatigue	Slow onset; may be tetanized; resistant to fatigue
Energy source	Aerobic metabolism at moderate levels of activity; glycolysis	Aerobic metabolism, usually lipid or carbohydrate substrates	Primarily aerobic metabolism (anaerobic during peak activity)

Table 10-4

The Muscular System

- Includes only skeletal muscles
  - attached to the skeletal system
  - allow us to move
- Muscle tissue (muscle cells or fibers)
- Connective tissues
- Nerves
- Blood vessels

Functions of Skeletal Muscles

1. Produce skeletal movement
2. Maintain body posture
3. Support soft tissues
4. Stabilize joints
5. Guard body openings
6. Generate heat

Skeletal Muscle

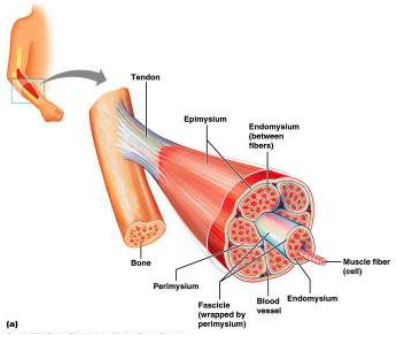
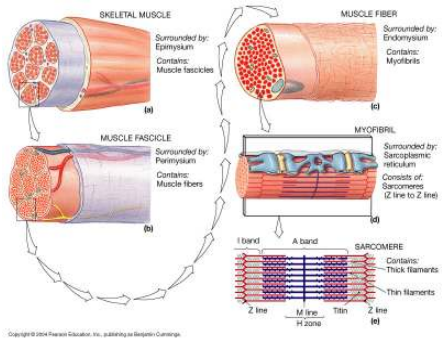


Figure 9.2a

Organization of Connective Tissues

- Muscles have 3 layers of connective tissues:
  - –Epimysium – an overcoat of dense regular and irregular connective tissue that surrounds the entire muscle; Separates muscle from surrounding tissues
  - –Perimysium – fibrous connective tissue that surrounds groups of muscle fibers called fascicles; Contains blood vessel and nerve supply to fascicles
  - –Endomysium – fine sheath of connective tissue composed of collagen and reticular fibers surrounding each muscle cell/fiber; Contains capillaries and nerve fibers contacting muscle cells; Contains satellite cells (stem cells) that repair damage

Levels of organization



Level 1: Skeletal Muscle

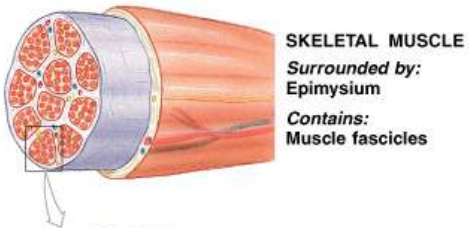


Figure 10-6 (1 of 5)

Level 2: Muscle Fascicle

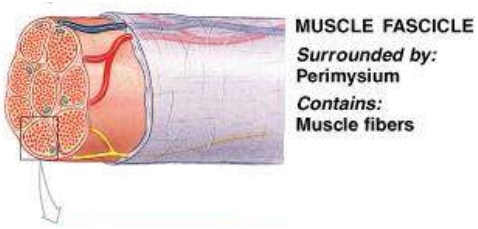


Figure 10-6 (2 of 5)

Level 3: Muscle Cell (Fiber)

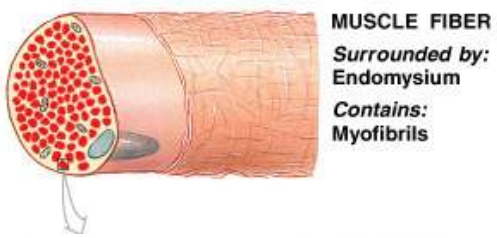


Figure 10-6 (3 of 5)

Level 4: Myofibril

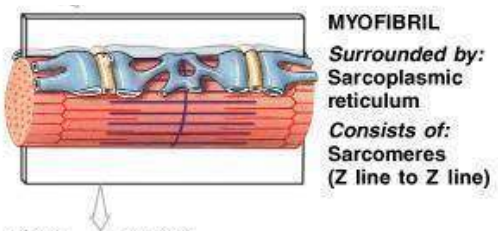


Figure 10-6 (4 of 5)

Level 5: Sarcomere

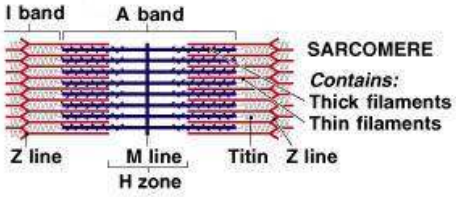
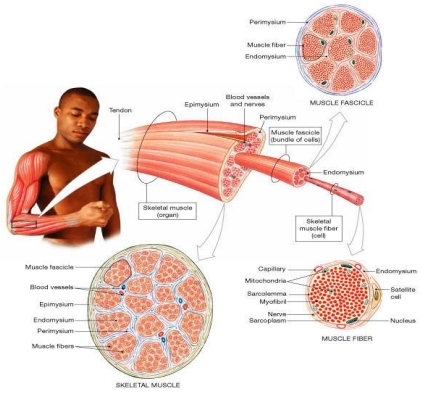


Figure 10-6 (5 of 5)



Summary – muscle orgnaization

- Epimysium surrounds muscle (which are bundles of fascicles)
- Perimysium surrounds fascicles (which are bundles are fibers/cells)
- Endomysium surrounds muscle fibers (which are filled with myofibrils)
- Myofibrils are long cylinders of sarcomeres
- Sarcomeres contract to shorten muscles. (Made up of myofilaments)

Muscle Attachments

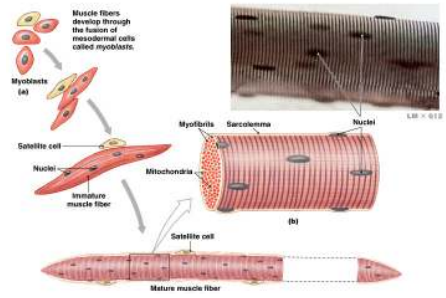
- Direct – epimysium of the muscle is fused to the periosteum of a bone
- Indirectly – connective tissue wrappings (endomysium, perimysium, and epimysium) come together at ends of muscles and extend beyond it as a tendon (bundle) or aponeurosis (sheet)

Innervation and Vascularization

- Nerves
  - Skeletal muscles are voluntary muscles, controlled by nerves of the somatic nervous system
- Muscles have extensive vascular systems:
  - supply large amounts of oxygen and nutrients
  - carry away wastes

Formation of Skeletal Muscle Fibers

- Skeletal muscle cells are called fibers
- Myoblasts join to form muscle fibers



igure 10-2

Skeletal Muscle Fibers

- Are very long cylindrical cell with hundreds of nuclei just beneath the sarcolemma
- Each cell is a syncytium produced by fusion of embryonic mesodermal cells (myoblasts)
- Fibers are 10 to 100 μm in diameter, and up to hundreds of centimeters long

Organization of Skeletal Muscle Fibers

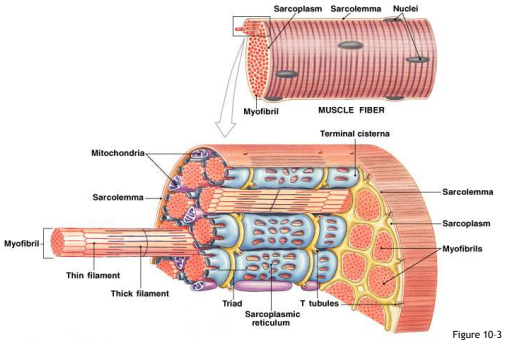
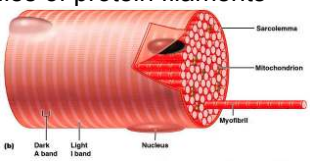


Figure 10-3

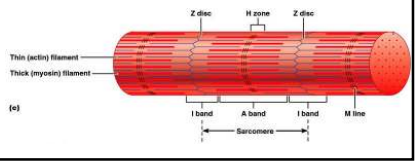
Myofibrils

- Myofibrils are densely packed, rodlike contractile elements
- Make up most of the muscle cell volume
- Made up sarcomeres, which are themselves bundles of protein filaments (myofilaments)



Sarcomeres

- The smallest contractile unit of a muscle
- The region of a myofibril between two successive Z discs
- Composed of myofilaments made up of contractile proteins
- The repeating pattern of myofibrils notice the presence of a repeating portion known as a **sarcomere**



Myofilaments

- Myofibrils and sarcomeres consist of **thick** and *thin* myofilaments
- These filaments are responsible for the striations of muscle, which are alternating **dark** and *light* bands
- Myofilaments are responsible for muscle contraction
  - Thin filaments:
    - made of the protein actin
  - Thick filaments:
    - made of the protein myosin

Sarcomeres

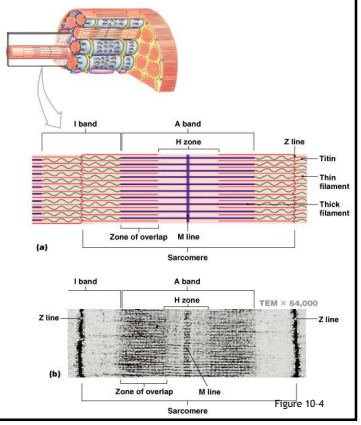
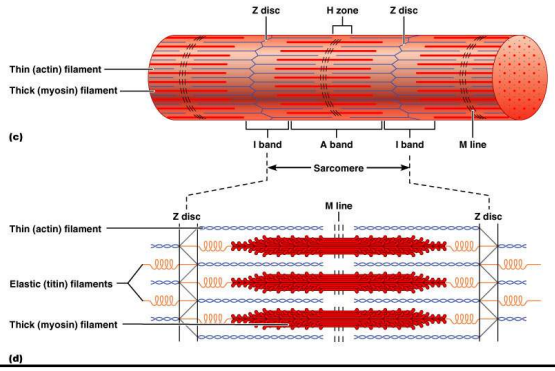


Figure 10-4

Sarcomeres

- The contractile units of muscle
- Structural units of myofibrils (that is, myofibrils are made up of many sarcomeres postioned end to end)
- Form visible striated patterns within myofibrils:
  - alternating dark, thick filaments (A bands) and light, thin filaments (I bands)

Sarcomere



M Lines and Z Lines

- M line:
  - the center of the A band
  - at midline of sarcomere
- Z lines/discs:
  - the centers of the I bands
  - at 2 ends of sarcomere (like z is at the end of the alphabet)
  - coin-shaped sheet of proteins (connectins) that anchors the thin filaments and connects myofibrils to one another

Zone of Overlap

- The densest, darkest area on a light micrograph
- Where thick and thin filaments overlap

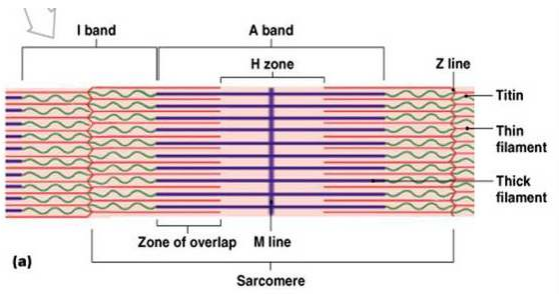
The H Zone

- The area around the M line
- Has only thick filaments but no thin filaments

Titin

- Strands of protein that reach from tips of thick filaments to the Z line
- Stabilize the filaments

Sarcomere



Sarcomere Structure

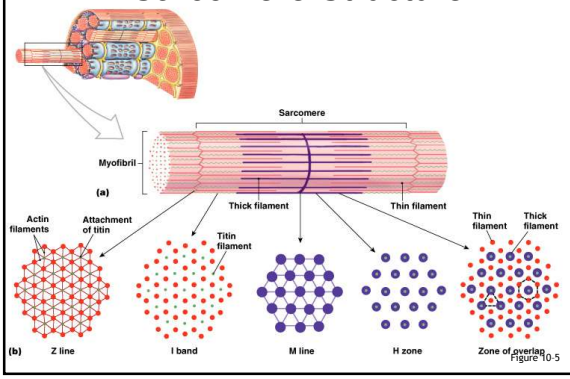


Figure 10-5

Special names for skeletal muscle cell structures

- Sarcolemma: plasma membrane
- Sarcoplasm: cytoplasm
- Sarcoplasmic reticulum (like smooth ER)

New to skeletal muscle cells:

- Transverse tubules (T tubules) are extensions of the sarcolemma that join with the SR at specialized regions

The Sarcolemma

- The cell membrane of a muscle cell
- Surrounds the sarcoplasm (cytoplasm of muscle fiber)
- Muscle contractions are started by a change in transmembrane potential (electrical charge on either side of the membrane)

Action potential

- A rapid, transitory reversal of the transmembrane potential that propagates quickly along the length of an electrically excitable cell.
- Huh? Basically, a portion of a cell goes from negative to positive charge very quickly and this spreads from one part of the cell to the next to the next and so on.

Transverse Tubules (T tubules)

- T tubules are continuous with the sarcolemma and have the same properties
- They conduct action potentials to the deepest regions of the muscle
- These impulses signal for the release of Ca^{2+} from adjacent terminal cisternae
- Allow entire muscle fiber to contract simultaneously

Zone of overlap and T tubules

- Transverse tubules encircle the sarcomere near zones of overlap (why?)
- Ca^{2+} released by SR causes thin and thick filaments to interact

Sarcoplasmic Reticulum

- An elaborate membranous structure that runs longitudinally, surrounding each myofibril
- Similar in structure to smooth endoplasmic reticulum
- Helps transmit action potential to myofibril
- Forms chambers (terminal cisternae) attached to T tubules that release calcium during muscle contraction

Terminal Cisternae

- Concentrate Ca^{2+} inside (*via* ion pumps)
- When stimulated by an action potential, they release Ca^{2+} into sarcomeres to begin muscle contraction

A Triad

- Structure formed by 1 T tubule and 2 terminal cisternae (thickenings of the SR)
- T tubules and SR provide tightly linked signals for muscle contraction
- T tubule proteins act as voltage sensors
- SR has receptors that regulate Ca^{2+} release from the terminal cisternae

Organization of Skeletal Muscle Fibers

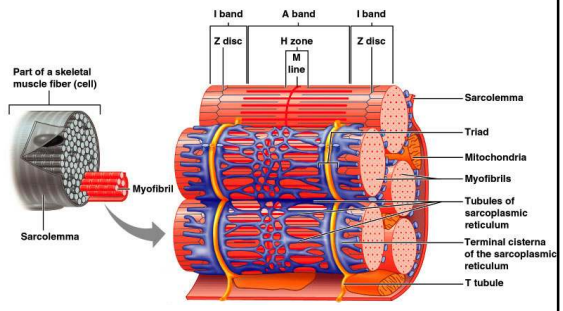
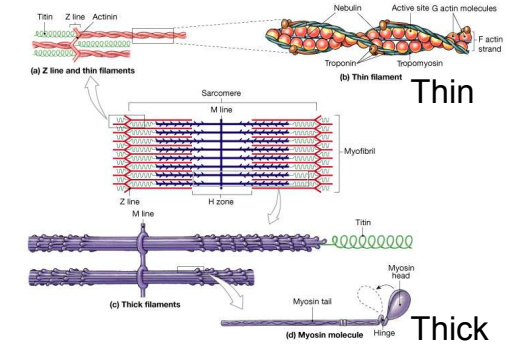


Figure 10-3

Muscle Contraction

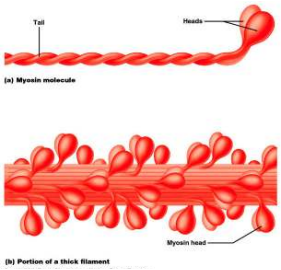
- Is caused by interactions of thick and thin filaments
- Structures of protein molecules detemine interactions

Thin and thick filaments



Myofilaments: Thick Filaments

- Composed of the protein myosin (approximately 500)
- Each myosin molecule has a rod-like tail and two globular heads
  - Tails – two interwoven, heavy polypeptide chains, bound together, pointing towards the M line
  - Heads – two smaller, light polypeptide chains that reach out and grab onto actin



The Myosin Molecule

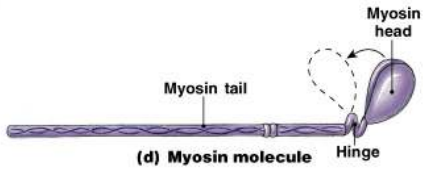
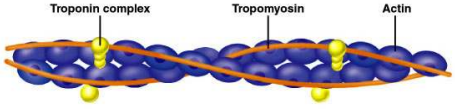


Figure 10-7d

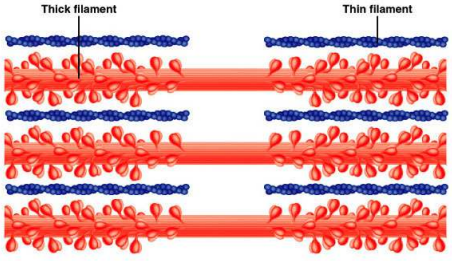
Myofilaments: Thin Filaments

- Thin filaments are chiefly composed of the protein actin held together by nebulin
- The subunits contain the active sites to which myosin heads attach during contraction
- Tropomyosin strands block active sites
- Troponin holds tropomyosin and actin together (at rest)



Arrangement of the Filaments in a Sarcomere

- Longitudinal section within one sarcomere

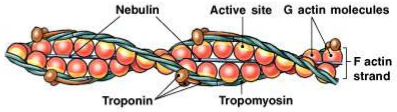


(d) Longitudinal section of filaments within one sarcomere of a myofibril

Figure 9.4d

Troponin and Tropomyosin

- Troponin binds tropomyosin to actin
  - consists of three subunits
    - TnI: binds to actin
    - TnT: bonds to tropomyosin
    - TnC: binds calcium
  - controlled by Ca^{2+}, kind of like the "lock" and Ca^{2+} is the "key"



Initiating Contraction

- Ca^{2+} binds to receptor on troponin molecule
- Troponin–tropomyosin complex changes shape, moves troponin out of the way
- Exposes the active site of each actin molecule (bead)

Myosin Action

- During contraction, myosin heads:
  - interact with actin filaments, forming cross-bridges
  - **pivot**, producing motion

  It is the pivoting of myosin heads that causes muscle contraction and therefore all movements

Sliding Filaments

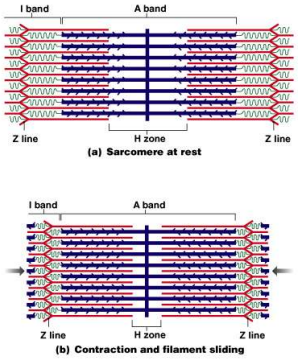
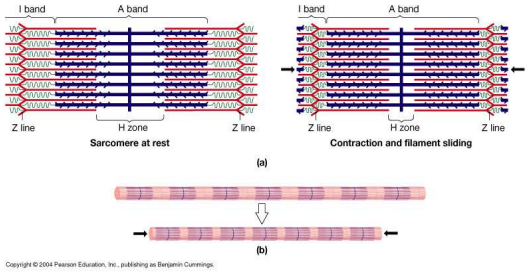


Figure 10-8

Notice that during contraction, the sarcomere shortens.



Sliding Filament Model of Contraction

- Thin filaments slide past the thick ones so that the actin and myosin filaments overlap to a greater degree
- In the relaxed state, thin and thick filaments overlap only slightly
- Upon stimulation, myosin heads bind to actin and sliding begins
- Myosin heads pull the actin thin filaments closer together, sliding them in between the thick filaments
- As this event occurs throughout the sarcomeres, the muscle shortens
  - Z lines move closer together
  - width of A band stays the same
  - width of the I band and the H zone both shrink

Movie

- contraction

Summary

- Smooth. Skeletal, and cardiac muscle tissues
- Structure and function of skeletal muscle cells.
- Sarcomere structure and contraction
- Actin-myosin interaction and sliding filament theory

Lecture 9b.

Muscle Contraction

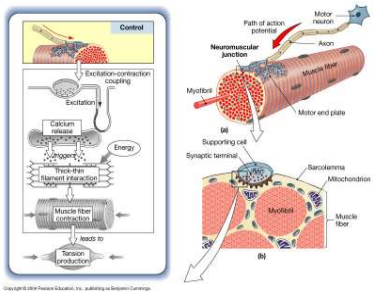
Topics

- The **excitation** part of excitation – contraction coupling: events at the neuromuscular junction
- The **contraction** part of excitation – contraction coupling: the contraction cycle and ATP
- Tension and motor units
- Muscle metabolism and fiber types

What needs to happen for a contraction to occur?

- In order to contract, a skeletal muscle must:
  - Be stimulated by a nerve ending
  - Propagate an electrical current, or action potential, along its sarcolemma, thorought the muscle cell via T tubules
  - Have a rise in intracellular Ca^{2+} levels, the final trigger for contraction
  - Thick and thin filaments need to interact
  - ATP is required
- Linking the electrical signal to the contraction is excitation-contraction coupling

Contraction begins at the neuromuscular junction



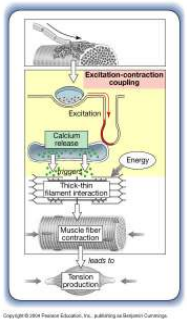
The Neuromuscular Junction

- Is the location of neural stimulation
- Action potential (electrical signal):
  - Travels along nerve axon
  - Axons of motor neurons branch profusely as they enter muscles
  - Each brance ends at synaptic terminal forming a neuromuscular junction with a single muscle fiber
  - Message is passed on through synapse to muscle and this causes contraction

Neuromuscular Junction

- The neuromuscular junction is formed from:
  - Axonal endings, which have small membranous sacs (synaptic vesicles) that contain the neurotransmitter acetylcholine (ACh)
  - The motor end plate of a muscle, which is a specific part of the sarcolemma that contains ACh receptors and helps form the neuromuscular junction
- Though exceedingly close, axonal ends and muscle fibers are always separated by a space called the synaptic cleft (a gap between synaptic terminal and motor end plate)

Excitation – contraction coupling



The muscle membrane sends the message to the SR through the T-tubules, leading to calcium release

Excitation–Contraction Coupling

- An action potential induced in the muscle by a nerve propagates from the site of nerve contact to a triad (through the T-tubules)
- SR releases Ca^{2+},which triggers the interaction of thick and thin filaments
- ATP is required to "cock" the myosin in the ready position, then Ca^{2+} allows contraction to begin producing tension

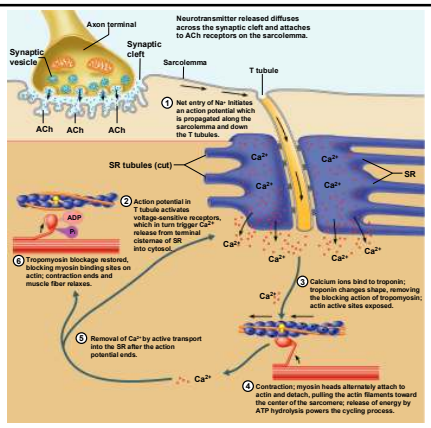
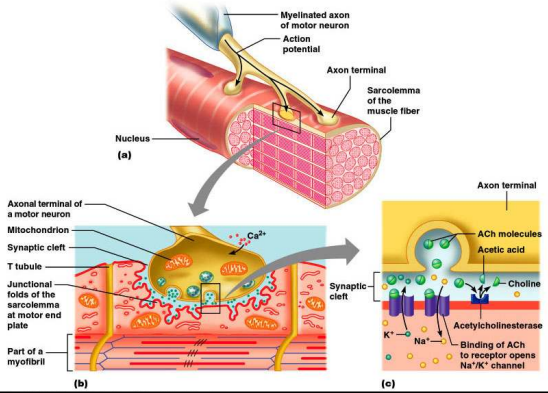
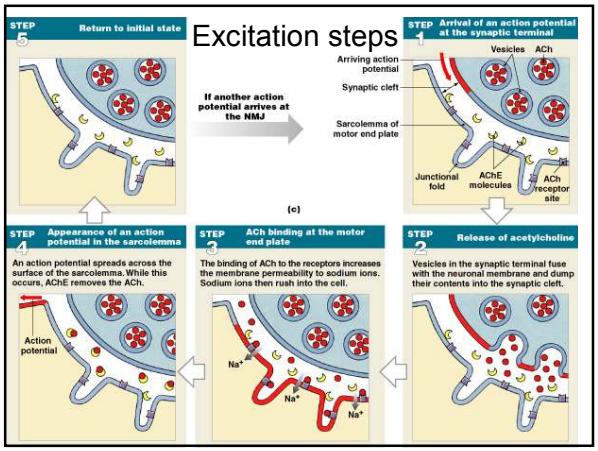


Figure 9.10

Close up of NMJ



Excitation steps



Excitation: Nerve Synaptic Terminal

- Arrival of action potential into terminal
- Voltage-regulated calcium channels open and allow Ca^{2+} to enter the axon
- Ca^{2+} inside the axon terminal causes axonal vesicles to fuse with the axonal membrane release vesicles full of neurotransmitter (acetylcholine or ACh) into the synaptic cleft

Excitation: The Neurotransmitter

- Acetylcholine or ACh:
  - travels across the synaptic cleft
  - binds to membrane receptors on sarcolemma (motor end plate)
  - causes sodium ions to rush into sarcoplasm through ACh receptors (that **are** Na+ channels)
  - is quickly broken down by enzyme (acetylcholinesterase or AChE)

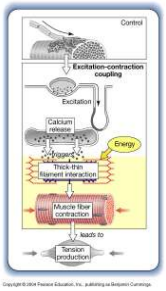
Excitation: Action Potential

- Generated by increase in sodium ions in the sarcolemma (coming in through ACh receptors)
- Travels along the T tubules
  - Note: T-tubules are just like the sacrolemma and are filled with extracellular fluid (hi Na+)
- Depolarization causes Calcium to be released from the SR terminal cisternae
- Next: contraction

Excitation: AChE stops the signal

- Acetylcholinesterase (AChE) present in the synaptic cleft breaks down the ACh and thus it is no longer present to bind to AChE receptors and cause an action potential in the muscle
- Signal ends, NO more calcium is released, contractions ceases

Contraction: Calcium ions are released….now what happens?



Contraction

- Myosin cross bridges alternately attach and detach
- Thin filaments move toward the center of the sarcomere
- Hydrolysis of ATP powers this cycling process
- Ca^{2+} is removed into the SR, tropomyosin blockage is restored, and the muscle fiber relaxes

5 Steps of the Contraction Cycle

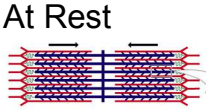
1. Exposure of active sites
2. Formation of cross-bridges
3. Pivoting of myosin heads
4. Detachment of cross-bridges
5. Reactivation of myosin

Movie

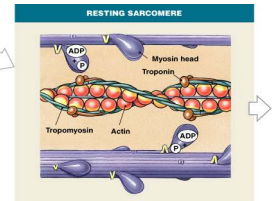
- Muscle contraction

The Contraction Cycle

At Rest



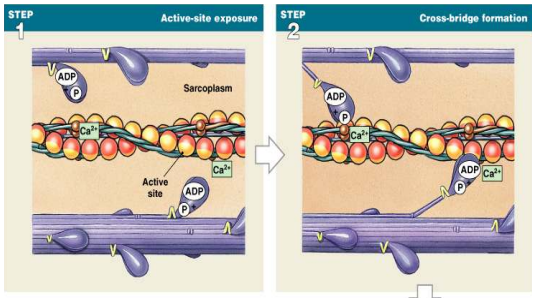
Myosin heads are cocked and ready (because ATP was already hydrolyzed to ADP)



But myosin can't bind to actin yet because tropomyosin blocks the active site

Figure 10-12 (1 of 4)

The Contraction Cycle



1. Heads are "cocked" & point **away from M line**

2. When active sites exposed, cocked heads can bind

Figure 10-12 (2 of 4)

Calcium exposes the Active Site

Calcium from SR cisternae binds to troponin, causes tropomyosin to move and allowing myosin to bind actin

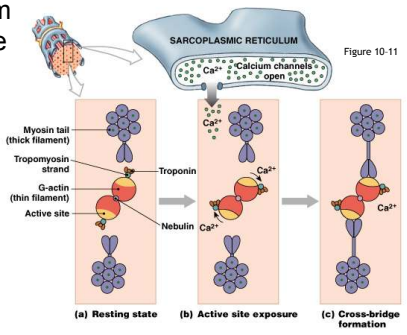
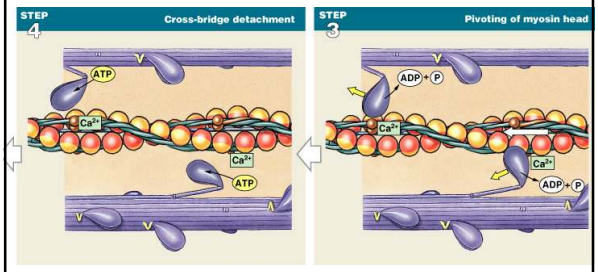


Figure 10-11

The Contraction Cycle

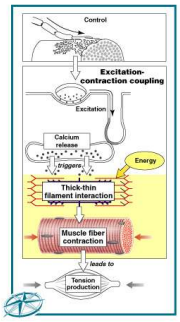


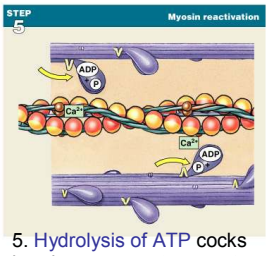
4. Binding of ATP causes heads to dissociate

3. Loss of ADP causes heads to **pivot**

Figure 10-12 (3 of 4)

The Contraction Cycle





5. Hydrolysis of ATP cocks heads, prepares to repeat

Figure 10-12 (Navigator) (4 of 4)

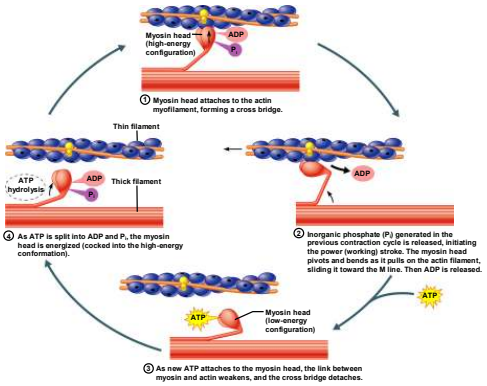


Figure 9.12

Fiber Shortening

- As sarcomeres shorten, muscle pulls together, producing *tension*

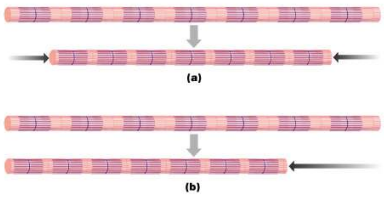


Figure 10-13

Contraction

- Contraction – refers to the activation of myosin's cross bridges (force-generating sites)
- Shortening occurs when the tension generated by the cross bridge exceeds forces opposing shortening
- Contraction ends when cross bridges become inactive, the tension generated declines, and relaxation is induced
- Duration depends on:
  - duration of neural stimulus
  - number of free calcium ions in sarcoplasm
  - availability of ATP

Relaxation

- Ca^{2+} concentrations fall
- Ca^{2+} detaches from troponin
- Active sites are recovered by tropomyosin
- Sarcomeres remain contracted
- Passive relaxation (**not** an active process of the muscle)

Muscle Relaxation

- After contraction, a muscle fiber returns to resting length by:
  - elastic forces (tendons, ligaments)
  - opposing muscle contractions
  - gravity

Rigor Mortis

- A fixed muscular contraction after death
- Caused when:
  - ion pumps cease to function
  - calcium builds up in the sarcoplasm
  - no ATP to remove myosin heads from actin
  - only ends during autolysis ~36 hrs

A Review of Muscle Contraction

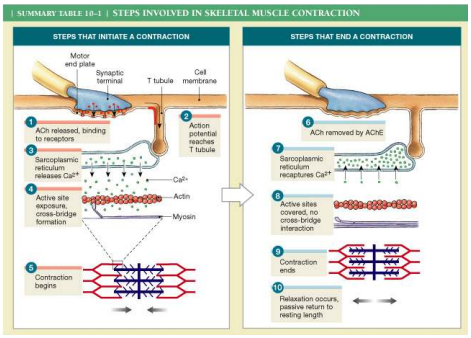


Table 10-1 (1 of 2)

A Review of Muscle Contraction

SUMMARY TABLE 10–1 | STEPS INVOLVED IN SKELETAL MUSCLE CONTRACTION

STEPS THAT INITIATE A CONTRACTION:

1. At the neuromuscular junction (NMJ), ACh released by the synaptic terminal binds to receptors on the sarcolemma.
2. The resulting change in the transmembrane potential of the muscle fiber leads to the production of an action potential that spreads across the entire surface of the muscle fiber and along the T tubules.
3. The sarcoplasmic reticulum (SR) releases stored calcium ions, increasing the calcium concentration of the sarcoplasm in and around the sarcomeres.
4. Calcium ions bind to troponin, producing a change in the orientation of the troponin–tropomyosin complex that exposes active sites on the thin (actin) filaments. Cross-bridges form when myosin heads bind to active sites on F actin.
5. The contraction begins as repeated cycles of cross-bridge binding, pivoting, and detachment occur, powered by the hydrolysis of ATP. These events produce filament sliding, and the muscle fiber shortens.

STEPS THAT END A CONTRACTION:

6. Action potential generation ceases as ACh is broken down by acetylcholinesterase (AChE).
7. The SR reabsorbs calcium ions, and the concentration of calcium ions in the sarcoplasm declines.
8. When calcium ion concentrations approach normal resting levels, the troponin–tropomyosin complex returns to its normal position. This change re-covers the active sites and prevents further cross-bridge interaction.
9. Without cross-bridge interactions, further sliding cannot take place, and the contraction ends.
10. Muscle relaxation occurs, and the muscle returns passively to its resting length.

Table 10-1 (2 of 2)

What happens when you get botulism?

Muscles and Tension

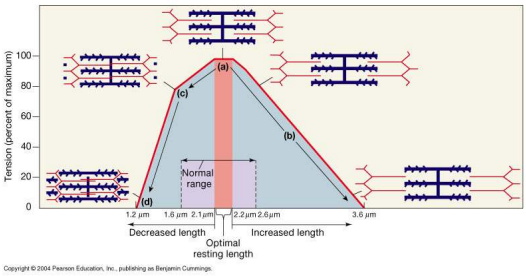
We will look at the following

- What two factors affect the tension produced by a muscle fiber?
- What is a twitch?
- What is a motor unit?
- What is the difference between isotonic and isometric contractions?

Tension Production

- Tension = pulling force
- The all–or–none principal: as a whole, a muscle fiber is either contracted or relaxed
- Amount of tension in a muscle is determined by the following:
  1. Resting length of the sarcomere at the time of stimulation
  2. Frequency of stimulation….which impacts the concentration of calcium ions

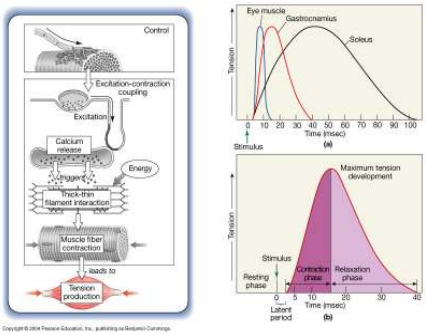
1. Resting length of Sarcomere determines the amount of tension



2. Frequency of Stimulation

- A single neural stimulation produces:
  - a single contraction or twitch
  - which lasts about 7–100 msec
  - Does NOT generate any action on its own
- Sustained muscular contractions:
  - require many repeated stimuli

Twitch Contraction



Muscle Response to Varying Stimuli

- A single stimulus results in a single contractile response – a muscle twitch
- Frequently delivered stimuli (muscle does not have time to completely relax) increases contractile force – wave summation

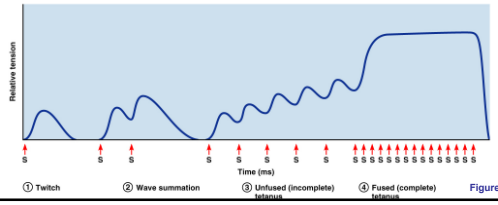
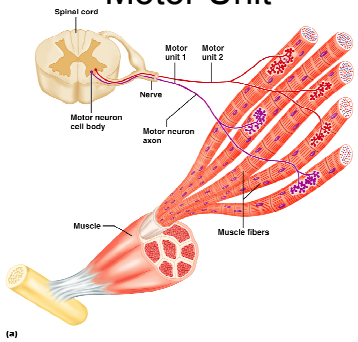


Figure 9.15

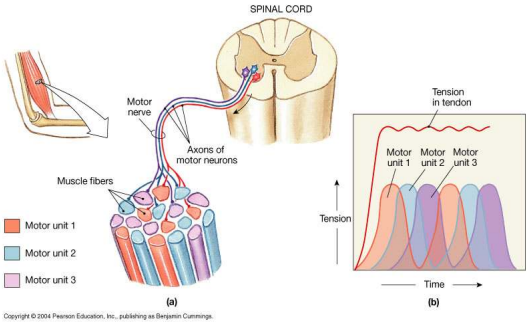
Motor Unit



Motor unit

- Consists of a motor neuron and all the muscle fibers it supplies
- All fibers activated at the same time
- Size varies greatly, from four to perhaps thousands of muscle fibers per motor unit
- Muscle fibers from a motor unit are spread throughout the muscle; therefore, contraction of a single motor unit causes weak contraction of the entire muscle

Motor Units in a skeletal muscle



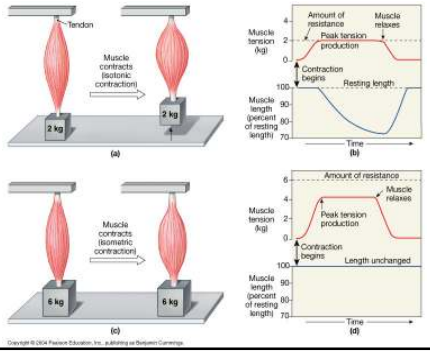
Size of motor unit

- Determines how finely you can control a muscle
- Fine control requires small motor units
  - Small: 1 nerve controls few fibers (2-6), e.g. fingers, eye
- Large weight-bearing muscles (thighs, hips) have large motor units
  - Large: 1 nerve controls many fibers (2000), e.g. thigh

Contractions vary based on the pattern of tension produced

- Isotonic
  - Tension rises **and** the skeletal muscle length changes
- Isometric
  - Tension rises but the muscle does not change length because the tension never exceeds the resistance

Isometric and Isotonic Contractions



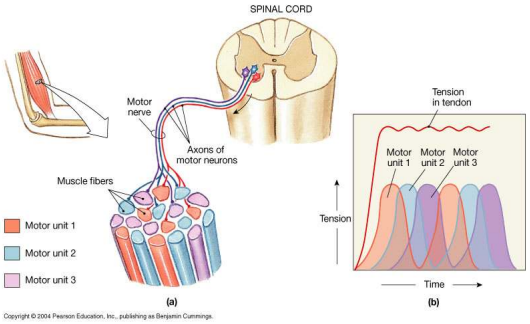
Recruitment (Motor Unit Summation)

- In a whole muscle or group of muscles, smooth motion and increasing tension is produced by slowly increasing number of motor units stimulated
- Often, the smaller fibers are recruited first, then larger fibers

Rotation

- Sustained Tension = less than maximum tension
- Allows motor units to rest in rotation: units cycle through periods of activity and inactivity

Rotation



KEY CONCEPT

- Force is increased by increasing the number of stimulated motor units (recruitment)
- Force is maintained by cycling the activity of motor units within a muscle (rotation)

Muscle Tone

- Is the constant, slightly contracted state of all muscles, which does not produce active movements
- Keeps the muscles firm, healthy, and ready to respond to stimulus
- Motor units actively maintain body position, without motion
- Spinal reflexes account for muscle tone by:
  - Activating one motor unit and then another
  - Responding to activation of stretch receptors in muscles and tendons
- Increasing muscle tone increases metabolic energy used, even at rest!

Muscle Metabolism

Contractions require lots of ATP

- If one muscle fiber contains 15 billion thick filaments, and you need 2500 ATP/thick filament, then how much ATP do you need?

→ Lots

- Muscle fibers must continuously manufacture ATP as needed

Three ways to make ATP

- Creatine phosphate is stored energy that can quickly be made into ATP
- Aerobic respiration with oxygen (generates 36 ATP/glucose)
- Anaerobic glycolysis (generates 2 ATP/glucose)
  - Stores of glucose or fatty acids are needed to do the latter two

Muscle Metabolism: Energy for

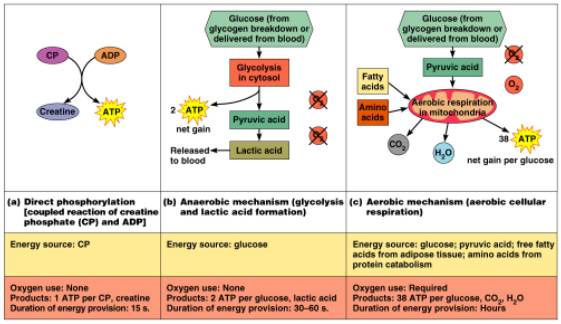


Figure 9.20

Energy Storage in Muscle Fiber

TABLE 10–2 Sources of Energy Stored in a Typical Muscle Fiber

Energy Stored as	Utilized through	Initial Quantity	Number of Twitches Supported by Each Energy Source Alone	Duration of Isometric Tetanic Contraction Supported by Each Energy Source Alone
ATP	ATP ⟶ ADP + P	3 mmol	10	2 sec
CP	ADP + CP ⟶ ATP + C	20 mmol	70	15 sec
Glycogen	Glycolysis (anaerobic) Aerobic metabolism	100 mmol	670 12,000	130 sec 2400 sec (40 min)

Table 10-2

Creatine

- Made by muscle cells from amino acids
- It is phosphorylated by the enzyme creatine phosphokinase (CPK) and becomes creatine phosphate
- Damaged muscle cells leak CPK and it is detected in the bloodstream
- Can quickly regenerate ATP from ADP by transferring a phosphate group to it

Aerobic Metabolism

- Is the primary energy source of most resting muscles
- Requires oxygen and a source of energy glucose (stored glycogen, fatty acids)
- Produces 30-36 ATP molecules per glucose molecule

But there's a problem:

- During peak muscle activity oxygen demands are too great
- When muscle contractile activity reaches 70% of maximum:
  - Bulging muscles compress blood vessels
  - Oxygen delivery is impaired
- Oxygen cannot enter the cell fast enough, metabolism switches to anaerobic, generating lactic acid

Anaerobic Glycolysis

- Is often the primary energy source for peak muscular activity
- Breaks down glucose from glycogen stored in skeletal muscles
- Produces 2 ATP molecules per molecule of glucose (inefficient) without requiring oxygen

Energy Use and Muscle Activity

- At rest
  - Fatty acids from fats are the primary energy source
  - Because oxygen is abundant, aerobic respiration is used
  - Glucose taken in is stored as glycogen for late use
  - Creatine phosphate reserves are built up

Energy Use and Muscle Activity

- At during light or normal exertion:
  - Creatine phosphate reserves are used first but are quickly exhausted
  - Muscles use aerobic respiration of fatty acids and glucose released from glycogen stores to make more ATP

Energy Use and Muscle Activity

- At peak exertion:
  - muscles lack oxygen to support mitochondria
  - muscles rely on glycolysis for ATP
  - pyruvic acid builds up, is converted to lactic acid

The Cori Cycle

- The removal and recycling of lactic acid by the liver
- Liver converts lactic acid to pyruvic acid
- Glucose is released to recharge muscle glycogen reserves

Muscle Fatigue

- When muscles can no longer perform a required activity, they are fatigued
- Caused by:
  - ATP production fails to keep pace with ATP use
  - There is a relative deficit of ATP, causing contractures
  - Lactic acid accumulates in the muscle
  - Ionic imbalances are present

Oxygen Debt

- After exercise:
  - the body needs more oxygen than usual to normalize metabolic activities
  - results in heavy breathing
  - Oxygen reserves must be replenished
  - Lactic acid must be converted to pyruvic acid
  - Glycogen stores must be replaced
  - ATP and CP reserves must be resynthesized

The Recovery Period

- The time required after exertion for muscles to return to normal
- Oxygen becomes available
- Mitochondrial activity resumes

Heat Production and Loss

- Active muscles produce heat
  - The vast majority of the heat generated by your body comes from muscle activity. What reaction occurs repeatedly in muscles?
- Up to 70% of muscle energy can be lost as heat, raising body temperature

KEY CONCEPT

- Skeletal muscles at rest metabolize fatty acids and store glycogen
- During light activity, muscles generate ATP through **aerobic** breakdown of carbohydrates, lipids or amino acids
- At peak activity, energy is provided by **anaerobic** reactions that generate lactic acid as a byproduct

Are all muscle fibers the same?

- No
- Why can you stand all day on your feet yet get tired during the 100 meter dash?

Muscle fibers vary in the body

- Fast fibers (white, fast twitch, fast glycolytic)
- Slow fibers (red, slow twitch, slow oxidative)
- Intermediate fibers (fast twitch, fast oxidative)

Fast Fibers

- Contract very quickly
- Have large diameter, large glycogen reserves, few mitochondria
- Have strong contractions, fatigue quickly
- Mostly anerobic (glycolytic)

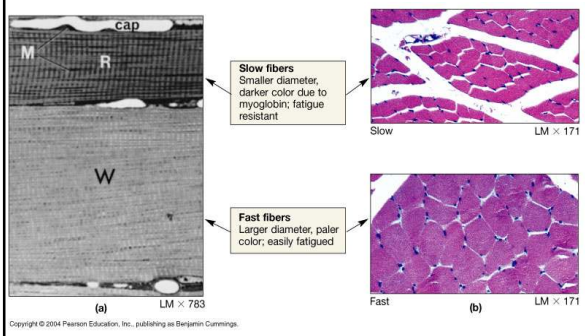
Slow Fibers

- Are slow to contract, but also slow to fatigue
- Have small diameter, more mitochondria
- Have high oxygen supply
- Contain myoglobin (red pigment) to bind and store extra oxygen
- Mostly aerobic

Intermediate Fibers

- Also: fast oxidative fibers
- Are mid-sized
- Have low myoglobin
- Have more capillaries than fast fibers, slower to fatigue
- Both aerobic and anerobic

Slow fibers vs. Fast fibers



Comparing Skeletal Muscle Fibers

TABLE 10–3 Properties of Skeletal Muscle Fiber Types

Property	Slow	Intermediate	Fast
Cross-sectional diameter	Small	Intermediate	Large
Tension	Low	Intermediate	High
Contraction speed	Slow	Fast	Fast
Fatigue resistance	High	Intermediate	Low
Color	Red	Pink	White
Myoglobin content	High	Low	Low
Capillary supply	Dense	Intermediate	Scarce
Mitochondria	Many	Intermediate	Few
Glycolytic enzyme concentration in sarcoplasm	Low	High	High
Substrates used for ATP generation during contraction	Lipids, carbohydrates, amino acids (aerobic)	Primarily carbohydrates (anaerobic)	Carbohydrates (anaerobic)
Alternative names	Type I, S (slow), red, SO (slow oxidizing), slow-twitch oxidative	Type II-A, FR (fast resistant), fast-twitch oxidative	Type II-B, FF (fast fatigue), white, fast-twitch glycolytic

Table 10-3

Muscles and Fiber Types

- White muscle:
  - mostly fast fibers
  - pale (*e.g.,* chicken breast, "white meat")
- Red muscle:
  - mostly slow fibers
  - dark (*e.g.,* chicken legs, "dark meat")
- Most human muscles are a mix of fiber types and therefore appear pink

Muscle Hypertrophy

- Muscle growth from weight training:
  - increases diameter of muscle fibers
  - increases number of myofibrils (but not number of muscle fibers)
  - increases numbers of mitochondria, glycogen reserves

Anaerobic activity

- Anaerobic activities (*e.g.,* 100-meter dash, competitive weightlifting):
  - use fast fibers
  - fatigue quickly with strenuous activity
- Performance improved by:
  - resistance exercise
  - frequent, brief, intensive workouts
  - hypertrophy
  - increased glycogen stores

Aerobic activity

- Aerobic activities (prolonged activity):
  - supported by mitochondria
  - require oxygen and nutrients
- Improved by:
  - repetitive training (muscle memory)
  - cardiovascular training leading to improved delivery of oxygen and nutrients, increase mitochondria and myoglobin synthesis

Fiber type "switching"

- Most fibers in human muscles are fast, and the relative amount of fast versus slow is genetic
- However, endurance training can cause some fast fibers to take on the appearance and properties of **intermediate fibers**, improving **aerobic** performance

Summary

- **Excitation**: events at the neuromuscular junction (5 steps)
- **Contraction:** the contraction cycle and ATP (5 steps)
- Tension and motor units
- Muscle metabolism and fiber types