Chapter 12 Outline

- Skeletal Muscles
- Mechanisms of Contraction
- Contractions of Skeletal Muscle
- Energy Requirements of Skeletal Muscle
- Neural Control of Skeletal Muscles
- Cardiac and Smooth Muscle

Skeletal Muscle Structure

- Most distinctive feature of skeletal muscle is its striations

Motor Units

- Motor unit: one nerve fiber and all the muscle fibers innervated by it
- All or none – all fibers contract
- Avg. ~ 200 muscle fibers per motor unit
- Small motor units - fine degree of control
- Large motor units – more strength than control
  - Powerful contractions supplied by large motor units

Neuromuscular Junction (NMJ)

- Synaptic ending of motor neuron that innervates a muscle fiber
- Motor end plate = right where junction occurs

Motor Unit

- If individual motor units fire "all-or-none," how do skeletal muscles perform smooth movements?
  - Recruitment!!!:
    - Brain estimates number of motor units required and stimulates them to contract
    - Keeps recruiting more units until desired movement is accomplished in smooth fashion
    - More and larger motor units are activated to produce greater strength
Recruitment and Stimulus Intensity

- Stimulating nerve with higher and higher voltages produces stronger contractions (more nerve cells excited = more motor units stimulated)
- Recruitment of multiple motor unit (MMU) summation – the process of bringing more motor units into play

Structure of Muscle Fiber

- Each fiber is packed with myofibrils
- Myofibrils: 1µm in diameter and extend length of fiber
- Packed with myofilaments
  - Actin & Myosin

Sarcomeres

- The Functional Units of Skeletal and Cardiac muscle
- Contractile units (actin & myosin) between 2 Z discs (Structural proteins)
  - M lines: structural proteins that anchor myosin
  - Titin: Structural proteins attaching myosin to Z disc
- Troponin & Tropomyosin (aka T-T Complex)

Excitation of a Muscle Fiber

- Arrival of nerve signal
- Acetylcholine (ACh) release
- Opening of voltage-regulated ion gates; creation of action potentials
- Sodium enters the fiber
- Release of calcium from the sarcoplasmic reticulum
- Binding of calcium to troponin
- Troponin-Tropomyosin complex moves, allowing actin and myosin to interact
- Muscle fibers shorten

Excitation-Contraction Coupling

- Initiation of muscle action potential
- Calcium causes the release of ATP from the sarcoplasmic reticulum
- ATP is used to power the contraction process
- Calcium is reabsorbed by the sarcoplasmic reticulum

Key:
- Actin
- Myosin
- Z disc
- Titin
- T tubule
- ACh receptors
- Calcium channels
- Sodium channels
- Calcium pumps
- Myosin thick filament
- Myosin head
- Myosin light chain
- Calcium ions
- Troponin
- Tropomyosin
- Myofibrils
- Myofilaments
Excitation-Contraction Coupling

Action potentials propagated down T tubules

Calcium released from terminal cisternae

Voltage-gated Ca²⁺ channels on T tubules – change shape and bind to Ca²⁺ release channels on S.R.

Voltage-gated Ca²⁺ channels on Transverse Tubules – change shape and bind to Ca²⁺ release channels on S.A.

Contraction

Hydrolysis of ATP to ADP + Pi; activation and cocking of myosin head

Formation of myosin – actin cross-bridge

Power stroke; sliding of thin filament over thick filament

Binding of new ATP; breaking of cross-bridge

Binding of ATP to myosin; formation of myosin – actin cross-bridge

Release of ADP and P

An action potential introduced at the neuromuscular junction is propagated along the sarcomeres of the skeletal muscle.
Relaxation

Cessation of nervous stimulation and ACh release

ACh breakdown by acetylcholinesterase (AChE)

Ca\(^{2+}\) pumped back into SR by active transport.
ATP is needed for muscle relaxation as well as muscle contraction!

Twitch & Summation

- **Twitch**: A single contraction/relaxation of a muscle fiber
- **Summation**: Occurs if 2nd stimulus occurs before muscle relaxes from 1st stimulus

Twitch Strength & Stimulus Frequency

- Incomplete tetanus: stimuli before muscle relaxes = summation of twitches = rapid cyclic of contr. & relax. Tension builds!
- Complete tetanus: freq so great there is no relaxation

Velocity of Contraction

- For muscle to shorten it must generate force greater than the load
- The lighter the load the faster the contraction and vice versa

Movement

- (a) Isometric contraction
- (b) Isotonic concentric contraction
- (c) Isotonic eccentric contraction
Length-Tension Relationship

- Strength of muscle contraction influenced by:
  - No. fibers in muscle that are stimulated
  - Frequency of stimulation
  - Thickness of each muscle fiber
  - Initial length of muscle fiber (how stretched or contracted it is when stimulated)
    - Ideal resting length is that which can generate maximum force

Muscle Metabolism

- All muscle contraction depends on ATP
- ATP supply depends on availability of:
  - Oxygen
  - Organic energy sources (e.g., glucose and fatty acids)
- Two main pathways of ATP synthesis
  - Anaerobic
  - Aerobic

Metabolism of Skeletal Muscles

- During light exercise, most energy is derived from aerobic respiration of fatty acids
- During moderate exercise, energy derived equally from fatty acids and glucose
- During heavy exercise, glucose supplies 2/3 of energy
- Liver increases glycolysis
- GLUT-4 carrier is moved to muscle cell’s plasma membrane

Modes of ATP Synthesis During Exercise

- Anaerobic respiration supported by cardiopulmonary bringing O₂ to muscles
- Repayment of oxygen debt

Physiological Classes of Muscle Fibers

- Slow oxidative (SO), slow-twitch, red, or type I fibers
  - Abundant mitochondria, myoglobin and capillaries - deep red color
  - Adapted for aerobic respiration and fatigue resistance
  - Relative long twitch lasting about 100 msec
- Fast glycolytic (FG), fast-twitch, white, or type II fibers
  - Well adapted for quick responses, but not fatigue resistant
  - Rich in enzymes of phosphagen and glycogen-lactic acid systems generate lactic acid causing fatigue
  - Few mitochondria, myoglobin, and blood caps = pale appearance
Fatigue

- Muscle fatigue - progressive weakness and loss of contractility from prolonged use of the muscles

- Causes of muscle fatigue
  - ATP synthesis declines as glycogen is consumed
  - ATP shortage slows down the Na⁺-K⁺ pumps
  - Lactic acid lowers pH of sarcoplasm
  - Inhibits enzymes involved in contraction, ATP synthesis
  - Released of K⁺ with each action potential causes the accumulation of extracellular K⁺
    - Hyperpolarizes the cell and makes the muscle fiber less excitable
  - Motor nerve fibers use up their Ach
  - Central nervous system fatigues, so there is less signal output to the skeletal muscles

Neural Control of Skeletal Muscles

- Motor neuron cell bodies are in spinal cord; axons leave via ventral root (aka lower motor neurons)
- Activity influenced by sensory feedback from muscles and tendons:
  1. Golgi tendon organs (tension on tendons)
  2. Muscle spindle apparatus (length of muscle detector)
- Excitatory and inhibitory activity from upper motor neurons & interneurons.

Muscle Spindle Apparatus (sensory)

- Consists of modified thin muscle cells:
  - Intrafusal fibers: (packaged w/in CT sheath)
    - No myofibrils in middle
  - Extrafusal fibers: regular cells outside of spindle app.
  - Both insert into tendons

Muscle Spindle Apparatus (sensory)

- Sensory Neurons:
  - Detect stretching of Spindle App.
- Motor Neurons:
  - α motor neurons stimulate extrafusal fibers (shorten muscle)
  - Gamma motor neurons cause intrafusal fibers (spindle to tighten only at ends)
  - Usually stimulated in concert
- Golgi Tendon organs:
  - Monitor tension on tendons
  - Synapse w interneurons (IPSP)

Somatic Motor Reflexes

- Polyneuronal reflexes - two or more synapses

Monosynaptic-Stretch Reflex

- Autonomic visceral reflexes - 2 efferent neurons

Figure 13-1b
Golgi Tendon Organ Reflex

- Involves 2 synapses in CNS
- Sensory axons from Golgi tendon organ synapse on interneurons
- Which make inhibitory synapses on motor neurons
- Prevents excessive muscle contraction or passive muscle stretching
  (disynaptic reflex)

Patellar Tendon (Knee Jerk) Reflex

Flexion Reflex and the Crossed Extensor Reflex

CNS Control of Voluntary Movement

Cardiac muscle

- Characteristics?
- Heart muscle = myocardium
- Gap junctions (intercalated discs)
- Sinoatrial node (pacemaker) – group of autorythmic cells
  i.e., heart cells don’t require outside stimulation
  But:
  - Frequency of HB can be influenced by epinephrine
  - Frequency of HB can be influenced by stretching chambers
Smooth Muscle

- Characteristics?
- Often circular/longitudinal arrangement
- No sarcomeres!
- Has no Troponin!!!!!!!!!
- Has gap junctions
- Contains more actin than myosin
- Allows greater stretching and contracting
- Actin filaments are anchored to dense bodies (like z-discs)
- Can have graded depolarizations (contractions)

Smooth Muscle Contraction

1. Intracellular Ca²⁺ concentration increases and is released from sarcoplasmic reticulum.
2. Ca²⁺ binds to calmodulin (CaM).
3. Ca²⁺–CaM activates myosin light chain kinase (MLCK).
4. MLCK phosphorylates light chains in myosin heads and increases myosin ATPase activity.
5. Active myosin crossbridges slide along actin and create muscle tension.

Depolarization can spread from cell to cell

Each cell must be innervated by a neuron