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
Most distinctive feature of skeletal muscle is its striations.

Skeletal Muscle Structure:
- Fibrous connective tissue from tendons forms sheaths (epimysium) that extend around and into skeletal muscle.
- Inside the muscle this connective tissue divides muscle into columns called fascicles.
- Connective tissue around fascicles is called perimysium.
- Muscle fibers are muscle cells.
  - Ensheathed by thin connective tissue layer called endomysium.
- Plasma membrane is called sarcolemma.
- Muscle fibers are similar to other cells except are multinucleate and striated.
Neuromuscular Junction (NMJ)

- Includes the single synaptic ending of the motor neuron innervating each muscle fiber and underlying specializations of sarcolemma
- Place on sarcolemma where NMJ occurs is the motor end plate
A motor unit is a single motor neuron and all muscle fibers it innervates.

Each motor neuron branches to innervate a variable number of muscle fibers.

When a motor neuron is activated, all muscle fibers in its motor unit contract.

Number of muscle fibers in motor unit varies according to the degree of fine control capability of the muscle.

- **Motor unit**
- **Innervation ratio** is # motor neurons : muscle fibers
- Vary from 1:100 to 1:2000
- Fine control occurs when motor units are small, i.e. 1 motor neuron innervates small # of fibers
Since individual motor units fire "all-or-none," how do skeletal muscles perform smooth movements?

- **Recruitment** is used:
  - Brain estimates number of motor units required and stimulates them to contract
  - It keeps recruiting more units until desired movement is accomplished in smooth fashion
  - More and larger motor units are activated to produce greater strength

**Motor Unit**

**Mechanisms of Contraction**

**Structure of Muscle Fiber**

- Each fiber is packed with **myofibrils**
- Myofibrils are 1μ in diameter and extend length of fiber
- Packed with **myofilaments**
  - Myofilaments are composed of thick and thin filaments that give rise to bands which underlie striations
Are contractile units of skeletal muscle consisting of components between Z-discs.

M-lines are structural proteins that anchor myosin during contraction.

Titin is elastic protein attaching myosin to Z-disc that contributes to elastic recoil of muscle.

**A band** is dark, contains thick filaments (mostly myosin).
- Light area at center of A-band is **H-band**.
- = area where actin and myosin don’t overlap.

**I band** is light, contains thin filaments (mostly actin).
- At center of I band is **Z line/disc** where actins attach.

Structure of Sarcomeres

Sarcomeres

- Are contractile units of skeletal muscle consisting of components between Z-discs.
- M-lines are structural proteins that anchor myosin during contraction.
- Titin is elastic protein attaching myosin to Z-disc that contributes to elastic recoil of muscle.
Sarcoplasmic Reticulum

- Ca\(^{2+}\) in SR is stored in terminal cisternae
- Running along terminal cisternae are T tubules
- Area where T tubules and terminal cisternae of SR is called the Triad

How Fiber Contracts

- Sliding Filament Theory of Contraction
  - Muscle contracts because myofibrils get shorter
  - Occurs because thin filaments slide over and between thick filaments towards center
    - Shortening distance from Z disc to Z disc
  - During contraction:
    - A bands (containing myosin) move closer together, do not shorten
    - I bands shorten because they define distance between A bands of successive sarcomeres
    - H bands (containing myosin) shorten
Table 12.2 Summary of the Sliding Filament Theory of Contraction

1. A myofiber, together with all its myofilaments, shortens by movement of the insertion toward the origin of the muscle.
2. Shortening of the myofilaments is caused by shortening of the sarcomeres—the distance between Z lines (or discs) is reduced.
3. Shortening of the sarcomeres is accomplished by sliding of the myofilaments—the length of each filament remains the same during contraction.
4. Sliding of the filaments is produced by asynchronous power strokes of myosin cross bridges, which pull the thin filaments (actin) over the thick filaments (myosin).
5. The A bands remain the same length during contraction, but are pulled toward the origin of the muscle.
6. Adjacent A bands are pulled closer together as the I bands between them shorten.
7. The H bands shorten during contraction as the thin filaments on the sides of the sarcomeres are pulled toward the middle.
Actin Filament

- Cross Bridges
  - Are formed by heads of myosin molecules that extend toward and interact with actin
  - Sliding of filaments is produced by actions of cross bridges

Control of Contraction

- Control of cross bridge attachment to actin is via troponin-tropomyosin system
  - Serves as a switch for muscle contraction and relaxation
  - The filament tropomyosin lies in grove between double row of G-actins (that make up actin thin filament)
  - Troponin complex is attached to tropomyosin at intervals of every 7 actins
  - In relaxed muscle, tropomyosin blocks binding sites on actin so crossbridges can't occur
    - This occurs when Ca** levels are low
  - Contraction can occur only when binding sites are exposed
Role of Ca++ in Muscle Contraction

- When Ca++ levels rise, Ca++ binds to troponin causing conformational change which moves tropomyosin and exposes binding sites
  - Allowing crossbridges and contraction to occur
  - Crossbridge cycles stop when Ca++ levels decrease
Excitation-Contraction Coupling

- Skeletal muscle sarcolemma is excitable
- Conducts Action Potentials
- Release of ACh at NMJ causes large depolarizing end-plate potentials and APs in muscle
- APs race over sarcolemma and down into muscle via T tubules

Excitation-Contraction Coupling continued

- T tubules are extensions of sarcolemma
- Ca++ channels in SR are mechanically linked to channels in T tubules
- APs in T tubules cause release of Ca++ from cisternae via V-gated and Ca++ release channels
  - Called electromechanical release
  - Channels are 10X larger than V-gated channels
Muscle Relaxation

- Ca++ from SR diffuses to troponin to initiate crossbridge cycling and contraction
- When APs cease, muscle relaxes
  - Because Ca++ channels close and Ca++ is pumped back into Sarcoplasmic Reticulum by Ca++-ATPase pumps.
  - Therefore, ATP is needed for relaxation as well as contraction.
Contractions of Skeletal Muscles

1. A single rapid contraction and relaxation of muscle fibers is a twitch.
2. If a second stimulus occurs before the muscle relaxes from the first, the second twitch will be greater (summation).
3. Contraction of varying strength (graded contractions) are obtained by stimulation of varying numbers of fibers.

Twitch, Summation, and Tetanus

- Twitch: A single rapid contraction and relaxation of muscle fibers.
- Summation: If a second stimulus occurs before the muscle relaxes from the first, the second twitch will be greater.
- Tetanus: Contractions of varying strength (graded contractions) are obtained by stimulation of varying numbers of fibers.

If muscle is stimulated by an increasing frequency of electrical shocks, its tension will increase to a maximum (incomplete tetanus).

If frequency is so fast that no relaxation occurs, a smooth sustained contraction results called complete tetanus or tetany.

If muscle is repeatedly stimulated with maximum voltage to produce individual twitches, successive twitches get larger.

This is Treppe or staircase effect.

Caused by accumulation of intracellular Ca++. 
Isotonic, Isometric, Eccentric, and Concentric Contractions

- During **isometric contraction**, exerted force does not cause load to move and length of fibers remains constant.
- During **isotonic contraction**, force remains constant throughout shortening process, length changes.
- During **eccentric contraction**, load is greater than exerted force and fibers lengthen despite its contraction.
- During **concentric contraction**, muscle tension is greater than the load and muscle shortens.

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.

![Velocity of Contraction Graph](image)

Length-Tension Relationship

- Strength of muscle contraction influenced by:
  - Frequency of stimulation
  - Thickness of each muscle fiber
  - Length of muscle fiber
  - Ideal resting length is that which can generate maximum force.
  - Too little overlap yields less tension because fewer cross bridges can form.
  - With no overlap force cannot be generated because cross bridges cannot form.
Energy Requirements of Skeletal Muscles

- Skeletal muscles respire anaerobically 1st 45-90 sec of moderate-to-heavy exercise
- Cardiopulmonary system requires this time to increase O₂ supply to exercising muscles
- If exercise is moderate, aerobic respiration contributes majority of muscle requirements after 1st 2 min
Maximum Oxygen Uptake

- **Maximum oxygen uptake (aerobic capacity)** is maximum rate of oxygen consumption ($\text{VO}_2\text{ max}$).
- Determined by age, gender, and size.
- **Lactate (anaerobic) threshold** is % of max $\text{O}_2$ uptake at which there is significant rise in blood lactate levels.
- In healthy individuals this is at 50–70% $\text{VO}_2\text{ max}$.

Metabolism of Skeletal Muscles

- **Light exercise**, most energy is derived from aerobic respiration of fatty acids (25% $\text{VO}_2\text{ max}$).
- **Moderate exercise**, energy derived equally from fatty acids and glucose (50–70% $\text{VO}_2\text{ max}$).
- **Heavy exercise**, glucose supplies 2/3 of energy.
- Liver increases glycogenolysis.
- GLUT-4 carrier is moved to muscle cell’s plasma membrane.
Oxygen Debt

- When exercise stops, rate of oxygen uptake does not immediately return to pre-exercise levels
- Because of oxygen debt accumulated during exercise
  - When oxygen is withdrawn from hemoglobin and myoglobin
  - And because of \( \text{O}_2 \) needed for metabolism of lactic acid produced by anaerobic respiration

Phosphocreatinine

- During exercise ATP can be used faster than can be generated by respiration
  - Phosphocreatine (creatine phosphate) is source of high energy phosphate to regenerate ATP from ADP
  - So efficient that muscle ATP concentration decreases only slightly from rest to heavy exercise
Types of Skeletal Muscle Fibers

- Skeletal muscle fibers are categorized according to:
  - How they manufacture energy (ATP)
    - Oxidative fibers—produce ATP aerobically
    - Glycolytic fibers—produce ATP anaerobically
  - How quickly they contract
    - Slow-Twitch
    - Fast-Twitch
Skeletal muscle fibers can be divided on basis of contraction speed and resistance to fatigue:

- **Slow-twitch**, slow fatigue (Type I fibers)
- **Fast-twitch**, fast fatigue (Type IIA and IIX fibers)

*Note:* a=fast twitch extraocular, b=gastrocnemius muscle, and c=slow-twitch soleus

Also called **red** slow oxidative

- Adapted to contract slowly without fatigue
- Uses mostly aerobic respiration
- Has rich capillary supply, many mitochondria, and aerobic enzymes
- Has lots of myoglobin (O₂ storage molecule)
  - Gives fibers red color
- Have small motor neurons with small motor units

Type II Fibers

- **Type II(b) fibers** (fast) also called white **fast glycolytic**
  - Adapted to contract fast using anaerobic metabolism
  - Has large stores of glycogen, few capillaries and mitochondria, little myoglobin
- **Type II A (intermediate)** fibers also called white **fast oxidative**
  - Adapted to contract fast using aerobic metabolism
  - Intermediate to Type I and Type IIX
  - Have large motor neurons with large motor units
Muscle Fatigue

- Is exercise-induced reduction in ability of muscle to generate force
  - Sustained muscle contraction fatigue is due to accumulation of extracellular K⁺
    - From K⁺ efflux during AP
  - Occurs in moderate exercise as slow-twitch fibers deplete glycogen stores
    - Fast twitch fibers are then recruited, converting glucose to lactic acid which interferes with Ca²⁺ transport
  - Central fatigue caused by changes in CNS rather than by fatigue in muscles themselves

Adaptations of Muscles to Exercise Training

- **Endurance training** improves aerobic capacity (by 20%) and lactate threshold (by 30%)
- **Resistance training** increases muscle size by increasing # of myofibrils/fiber (hypertrophy)
  - Once a myofibril has attained a certain thickness, it may split into two myofibrils.
Table 12.4 Effects of Endurance Training on Skeletal Muscles

1. Improved ability to obtain ATP from oxidative phosphorylation
2. Increased size and number of mitochondria
3. Less lactic acid produced per given amount of exercise
4. Increased myoglobin content
5. Increased intramuscular triglyceride content
6. Increased lipoprotein lipase (enzyme needed to utilize lipids from blood)
7. Increased proportion of energy derived from fat; less from carbohydrates
8. Lower rate of glycogen depletion during exercise
9. Improved efficiency in extracting oxygen from blood
10. Decreased number of type IIx (fast glycolytic) fibers; increased number of type I/A (fast oxidative) fibers