The Muscular System

Muscular System

- Types of muscles
  - Cardiac
  - Skeletal
  - Smooth

Introduction

- Characteristics of muscle tissue
  1. Excitability
  2. Ability to receive and respond to stimuli
  3. Contractility
  4. Ability to shorten when stimulated
  5. Extensibility
  6. Ability to be stretched
  7. Elasticity
  8. Ability to recoil to original shape

Introduction

- Functions
  1. Movement
  2. Posture and body position
  3. Heat production
  4. Stabilizing joints

Introduction

- Types of muscle tissue
  - Skeletal muscle features
    - Striated
    - Voluntary
    - Powerful
    - Generates heat

Table 9.3

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>SKELETAL MUSCLE</th>
<th>CARDIAC MUSCLE</th>
<th>SMOOTH MUSCLE</th>
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<tbody>
<tr>
<td>Body Location</td>
<td>Attached to bone or bone</td>
<td>Walls of the heart</td>
<td>Septa of hollow organs</td>
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<tr>
<td>Cell shape and appearance</td>
<td>Branched, multipolar, striated fibers</td>
<td>Branched, multipolar, striated fibers</td>
<td>Branched, multipolar, striated fibers</td>
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<tr>
<td>Function</td>
<td>Generation of force</td>
<td>Generation of force</td>
<td>Generation of force</td>
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</tbody>
</table>

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Introduction

Types of muscle tissue
- Smooth (visceral) muscle features
  - Around hollow organs
  - Stomach, urinary bladder, blood vessels, and airways
- Not striated
- Involuntary

Cardiac muscle features
- Only in the heart
- Striated
- Involuntary
- Myogenic

Macroanatomy of Skeletal Muscle

Muscle fibers (cells) are organized into muscles
- Organized by connective tissue

Connective Tissue Organization

Fascia
- Thin sheets of fibrous connective tissues
- Supports muscles
- Participates in muscle attachment
- Passageway for nerves and blood vessels
Connective Tissue Organization

- **Fascia**
  - **Direct attachment**
    - Epimysium is continuous with periosteum
    - Example: intercostal muscles
  - **Indirect attachment**
    - Epimysium becomes a special connective structure that merges into periosteum as perforating fibers
    - 2 forms
      - Tendon
        - Strap-like cord that attaches a muscle to a bone
      - Aponeurosis
        - Broad, flattened, sheet-like tendon

Accessory Structures

- **Blood vessels**
  - Oxygen delivery and waste disposal

- **Neurons**
  - Skeletal muscle cells are individually innervated
  - Cardiac and visceral muscles are linked by gap junctions
    - Allows impulse conduction between adjacent cells
    - Also respond to nerve impulses and hormonal signals

Connective Tissue Organization

- 3 components of the musculotendinous unit are continuous with one another
  1. Contractile component (muscle fibers)
     - Creates internal tension; transfers to SEC
  2. Parallel-elastic component or PEC (muscle membranes)
     - Provides resistive tension when muscle is stretched
  3. Series-elastic component or SEC (tendons)
     - Extensible and elastic
     - Not excitable or contractile (but do display recoil)
     - External tension
     - Passive – the tendon itself does not create the tension
Review

- Muscle types
- Muscle characteristics
- Fascia

Microstructure of Skeletal Muscle

- A muscle is composed of muscle cells (fibers)
  - Thin but very long

(b) Diagram of part of a muscle fiber showing the myofibrils. One myofibril is extended from the cut end of the fiber.

Cell Structure

- Muscle fiber
  - Sarcolemma
    - Plasma membrane
  - Sarcoplasm
    - Cytoplasm
  - Sarcoplasmic reticulum
    - Modified ER, stores calcium
  - Terminal cisternae
    - Enlargements of SR that store calcium
  - Transverse tubules (T tubules)
    - Tubules extending from sarcolemma
  - Myofibrils
    - Contractile organelles composed of myofilaments
Myofibrils are composed of myofilaments

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**Cell Structure**

- **Myofilaments**
  - Thin filaments
    - Fibrous (F) actin composed of globular (G) actin subunits
  - Thick filaments
    - Myosin
      - Interacts with active sites on G actin

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**Sliding of myofilaments causes shortening of muscle = muscle contraction**

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**Myofilaments within Myofibril**

- Thin filament
  - Myosin tail
  - Myosin heads
  - Myosin-binding site (covered by tropomyosin)

- Thick filament
  - A thin filament consists of two strands of actin subunits twisted into a helix plus two types of regulatory proteins (troponin and tropomyosin).
  - Actin subunits
    - Active sites for myosin attachment

**Cell Structure**

- **Myofilaments**
  - Troponin and tropomyosin
  - Block active site on thin filament during relaxation of muscle
  - Prevents interaction between actin and myosin
  - No cross bridge formation = no contraction

- **Calcium binding to troponin moves tropomyosin out of the way**
  - Cross bridge formation \(\rightarrow\) contraction

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**Myofilaments within a myofibril**

- (a) One thick filament and a myosin molecule
- (b) Portion of a thin filament

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**Sarcomeres are the functional units of contraction**

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**Striations of skeletal muscle are due to spatial arrangement of myofilaments**
Motor Units

- Motor neuron and all of the muscle fibers it serves
  - Neuromuscular junction
  - All of the fibers contract simultaneously

Contraction of Skeletal Muscle

- Membrane potential
  - Difference in electrical charge across the membrane
  - Potential energy
  - Measured in millivolts (mV)
    - Normal resting potential usually -70 mV

Contraction of Skeletal Muscle

- Cells at rest
  - Internally negative
  - Externally positive

- Stimulated cell
  - Channels allows passage of ions
    - Reduces the membrane potential
      - Inside temporarily less negative = action potential
      - Sufficient reduction = release of calcium from SR
        - Contraction begins

Motor Units

- Few fibers
  - Fine control

- Many fibers
  - Coarse, crude movements

- Strength of contraction
  - Determined by number of motor units activated
  - Neuron may control 1 to 500 fibers
    - All fibers in a single motor unit contract simultaneously
Contraction of Skeletal Muscle

- **Action potential**
  - Transient depolarization of membrane
  - Decreases membrane potential
  - Events at neuromuscular junction spread action potential along membrane of muscle fiber (sarcolemma)
  - Allows release of calcium which initiates contraction

Excitation of muscle cell initiates contraction

Action potential is generated

- Na⁺ influx activates voltage-gated Na⁺ channels
- Action potential (AP) propagates through transverse tubules
- Ca²⁺ release channels in the sarcoplasmic reticulum (SR) open

Excitation sets the stage for contraction

1. ATP binds to myosin, making it detach from actin
2. ATP/T provides energy for myosin heads tobind to actin
3. Calcium binds to troponin, allowing myosin heads to interact with actin
4. Myosin then performs a power stroke, pushing on the actin

Contraction: power strokes

- The thin filament is pulled toward the center of the sarcomere
- Troponin–tropomyosin complex slides back, exposing the binding sites for myosin
- Myosin heads bind to actin, swivel, and release
- ATP is used for these power strokes
- Troponin–tropomyosin complex releases actin
- Myosin heads detach from actin, readying for another cycle

Transverse tubule opens Ca²⁺ release channels in the sarcoplasmic reticulum

- Calcium ions are released
- Calcium ions activate the troponin–tropomyosin complex
- The thin filament is pulled toward the center of the sarcomere
- Troponin–tropomyosin complex releases actin
- Myosin heads detach from actin, readying for another cycle

Contraction begins...
Relaxation
1. Motor neuron activity ends
2. Acetylcholine broken down
3. Calcium returned to SR
4. Tropomyosin returns to position
5. Cross bridges broken
6. Filaments slide apart
7. Relaxed state

Rigor Mortis
- Cross bridge detachment is ATP driven
  - Cell death → no ATP formed
  - Cross bridges remain intact
  - Muscles stiffen 3-4 hours following death
  - Peaks at 12 hours and gradually dissipates over 48-60 hours

Muscle Energetics
- ATP is essential in muscle metabolism
  - 60% for contraction
  - 30% calcium recycling
  - 10% plasma membrane ion transport during repolarization
- Muscles store very little ATP

Muscle Energetics
- ATP production
  1. Direct phosphorylation of ADP by creatine phosphatase (unique to muscle cells)
  2. Anaerobic pathways
     a. Glycolysis
     b. Lactic acid fermentation
  3. Aerobic respiration

  Extent to which each mechanism is used depends upon length and intensity of activity

Muscle Energetics
- Initially...
  - ATP stored in muscles
  - 2-3 seconds of activity
  - Transfer of phosphate from creatine phosphate
    - CP + ADP → ATP + C
    - 15-20 seconds of activity

Figure 9.19a
Coupled reaction of creatine phosphate (CP) and ADP

Energy source: CP

Creatine
Creatine kinase
CP
ADP
Creatine
ATP

Oxygen use: None
Products: 1 ATP per CP, creatine
Duration of energy provision: 15 seconds
Muscle Energetics

- **Anaerobic pathways**
  - Combined with phosphate transfer system can provide energy for short bursts of activity
  - Includes glycolysis and lactic acid fermentation
  - Produces ATP and lactic acid from stored glycogen and glucose
  - Occurs in cytoplasm

**Figure 9.19b**

- Energy source: glucose
- Glycolysis and lactic acid formation
- Oxygen use: None
- Products: 2 ATP per glucose, lactic acid
- Duration of energy provision: 60 seconds, or slightly more

**Figure 9.19c**

- Energy source: glucose; pyruvic acid; free fatty acids from adipose tissue; amino acids from protein catabolism
- Aerobic pathway
- Aerobic cellular respiration
- Oxygen use: Required
- Products: 32 ATP per glucose, CO$_2$, H$_2$O
- Duration of energy provision: Hours

**Figure 9.20**

- Short-duration exercise
- Prolonged-duration exercise

1. ATP stored in adenine nucleotide used first.
2. ATP is formed from creatine phosphate and ADP.
3. Glycogen stored in muscles is broken down to glucose, which is oxidized to generate ATP.

**Muscle Energetics**

- **Aerobic metabolism**
  - Produces 95% of ATP during rest and light to moderate exercise
  - Necessary for activity of longer duration
  - Requires oxygen
  - Myoglobin and hemoglobin
  - Fuels
    - Stored glycogen
    - Blood glucose
    - Pyruvic acid from glycolysis
    - Amino acids
    - Free fatty acids

**Figure 12.16**

- Oxygen use: Required
- Products: 32 ATP per glucose, CO$_2$, H$_2$O
- Duration of energy provision: Hours
Muscle Fatigue

- **Physiological inability to contract**
  - Not due to lactic acid accumulation

- **Causes**
  - Glycogen reduction
  - Slowing of membrane pumps
  - Lack of acetylcholine

Muscle Fatigue

- **VO₂ max**
  - Peaks at 20 years
  - Proportional to body mass
  - Men > women
  - Increases with training

Muscle Fatigue

- **Post-exercise heavy breathing = oxygen debt**
  - Replacing oxygen
  - Regenerating stored ATP and CP
  - Oxidation of lactic acid
  - Accommodate increased metabolic rate

Types of Skeletal Muscle

- **Three types described**
  - Different rates of cross bridge formation
  - Fatigue resistance varies
  - Many muscles have all three fiber types

Types of Skeletal Muscle

- **Three types**
  1. Slow twitch, slow oxidative, red, type I fibers
  2. Fast twitch, fast oxidative, red, type IIa fibers
  3. Fast twitch, fast glycolytic, white, type IIx and IIb fibers

Types of Skeletal Muscle

- **Classified according to:**
  1. Speed of contraction
     - Fast twitch
     - Slow twitch
  2. Metabolic pathways for ATP synthesis
     - Oxidative fibers = use aerobic pathways
     - Glycolytic fibers = use anaerobic glycolysis
Types of Skeletal Muscle

- **Oxygen supply to oxidative fibers**
  - Myoglobin stores oxygen
  - Hemoglobin transports oxygen

### Types of Skeletal Muscle

- **Examples**
  - Soleus, erector spinae, and quadratus lumborum
    - Dominated by slow oxidative fibers
  - Fatigue resistance
  - Extrinsic eye muscles
  - Dominated by fast glycolytic fibers
  - Contract rapidly but fatigue easily

### Distribution of fiber type is genetically determined

- Athletes usually excel at one type of activity
- Training doesn’t change number of fibers present
- Increased muscle size
- Due to increased number of capillaries, mitochondria, myoglobin molecules, and myofibrils

### Table 2

<table>
<thead>
<tr>
<th>Activity</th>
<th>Slow oxidative</th>
<th>Fast oxidative</th>
<th>Fast glycolytic</th>
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<tbody>
<tr>
<td>Marathon</td>
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<td>18</td>
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<tr>
<td>Swimmers</td>
<td>74</td>
<td>25</td>
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<tr>
<td>Sprinters</td>
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<td>63</td>
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</tr>
<tr>
<td>Average male</td>
<td>45</td>
<td>55</td>
<td></td>
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</tbody>
</table>
Motor Unit

Notes:
- Each fiber has only one neuron that controls it
- One neuron can control many fibers
- A nerve consists of many neurons
  - One nerve can control more than one muscle

Introduction

Myogram
- Measures muscle response to nervous stimulation

Summary of Types of Muscle Contraction

Muscle twitch
- Involuntary
- Can happen in any muscle in the body
- Usually provoked in laboratory setting

Graded muscle responses
- Voluntary
- Force of contraction varies depending on circumstance

Graded Muscle Responses

Treppe (not in textbook)
- Muscle relaxes between successive stimuli
- Successive stimuli of the same strength produce contractions of increasing strength – why we “warm up” muscles
- Also called the staircase effect

Graded Muscle Responses

Wave summation
- Sustained contractions
- Muscle doesn’t relax completely before next stimulus

Types
- Complete/fused tetanus
- Incomplete/unfused tetanus
  - Tonic – maintain continuous partial muscle contraction; muscle tone
  - Isotonic (e.g. weight lifting)
    - Concentric – muscle fibers get shorter
    - Eccentric – muscle fibers get longer
  - Isometric (e.g. yoga)
    - Muscle length remains the same but tension increases

Isometric Contraction

No movement (constant length) with changing tension

Example: Trying to lift a piano alone
Fig. 9.18a

**Isotonic Contraction**

Muscle length changes and moves the load
Example: lifting a book
May be concentric or eccentric

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**Types of Tetanic Muscle Contraction**

- Concentric (shortens, tension increases)
- Eccentric (lengthens, tension decreases)
- Isometric (no movement, tension constant)

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**Heat Production**

- 70-80% of energy released during contraction lost as heat
  - Heat derived from
    - ATP breakdown
    - Breakdown of glucose and lactic acid
  - Shivering

---

**The Muscle Twitch**

- Three phases of a twitch
  1. Latent period
  2. Contraction phase
  3. Relaxation phase
- Heat derived from
  - ATP breakdown
  - Breakdown of glucose and lactic acid
  - Shivering

---

**The Muscle Twitch**

- Threshold
  - Minimum stimulus (voltage) required to cause contraction
  - *stimulus strength ≠ increased contractility
  - All or none principle
Graded Muscle Responses

- **Motor unit recruitment**
  - Assists in creating graded muscle responses

![Diagram of motor unit recruitment](image)

- **Graded Muscle Responses**
  - Increased frequency of stimulation
    - Increases force of contraction
    - If stimuli are delivered in rapid succession
    - Second twitch will be stronger than the first
    - Motor unit recruitment
    - Not all Ca²⁺ will be taken up by the SR after first contraction, so more is available for the next contraction

![Diagram of increased frequency of stimulation](image)

- **Wave summation**
  - 2nd contraction occurs before muscle has completely relaxed
  - Further increase in stimulus frequency → unfused (incomplete) tetanus
    - Sustained but quivering contraction
    - Common type of contraction

![Diagram of wave summation](image)

- **Complete tetanus**
  - Maximal contraction
  - All evidence of relaxation disappears
  - Rare
  - Causes rapid fatigue
  - Disease caused by *C. tetani* bacteria causes tetanic contractions all over the body

![Diagram of complete tetanus](image)
Graded Muscle Responses

- **Refractory period**
  - Time required for sarcolemma to repolarize
  - New contractions cannot occur
  - Skeletal muscle = thousandths of a second
  - Cardiac muscle = very long
  - Prevents tetanus

Types of Tetanic Contraction

- **Tonic**
  - Motor units alternate
  - Keeps muscles firm, healthy and ready to respond
  - Variations
    - Flaccidity (hypotonia)
    - Spasticity (hypertonia)
    - Atrophy
    - Hypertrophy

How Muscles Move the Body

- **Lever systems**
  - Muscle contraction → pulling on bones

- **Components of a lever system**
  1. Lever
     - Rigid bar (bone) that moves on a fixed point or fulcrum (joint)
  2. Effort
     - Force (supplied by muscle contraction) applied to a lever to move a load
  3. Load
     - Resistance (bone + tissues + any added weight) moved by the effort

How Muscles Move the Body

- **Levers**
  - Allow movement of heavy loads
  - Alter rate of movement
  - Increase distance over which a load can be moved
  - Classified by position of force, load and fulcrum
How Muscles Move the Body

Organization at joints
1. Prime movers
   - Provide the major force for producing a specific movement
2. Antagonists
   - Oppose or reverse a particular movement
3. Synergists
   - Add force to a movement
   - Reduce undesirable or unnecessary movement

Name that movement!

<table>
<thead>
<tr>
<th>Prime mover</th>
<th>Antagonist</th>
<th>Synergist</th>
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<tbody>
<tr>
<td>Biceps brachii</td>
<td>Triceps brachii</td>
<td>Brachioradialis</td>
</tr>
<tr>
<td>Flexor digitorum</td>
<td>Extensor digitorum</td>
<td>Biceps brachii</td>
</tr>
<tr>
<td>Triceps</td>
<td>Biceps brachii</td>
<td>Pectoralis, Deltid</td>
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</table>
Muscular Disorders

- **Fibrosis**
  - Fibrous scar tissue

- **DOMS**
  - Microtrauma that damages the fibrils and sarcolemma

Muscular Disorders

- **Fibromyositis**
  - Inflammation of connective tissue of muscle
    - Lumbago
    - Fibromyalgia

- **Cramping**
  - Electrolyte imbalances
  - Dehydration

Muscular Disorders

- **Duchenne muscular dystrophy**
  - Hereditary disease (dystrophin gene; X-linked)
  - Skeletal muscle degeneration
    - Abnormal protein causes Ca\(^{2+}\) leakage
    - Leads to mitochondria taking on water and bursting

- **Myasthenia gravis**
  - Acetylcholine receptors destroyed

Micrograph of the dystrophin

Micrograph of the sarcotubules

Micrograph of the mitochondria