Metabolism of Skeletal Muscles

- Skeletal muscle respires anaerobically first 45 - 90 sec.
- If exercise is moderate, aerobic respiration contributes following the first 2 min. of exercise.
- Maximum oxygen uptake (aerobic capacity):
  - Maximum rate of oxygen consumption ($V\text{O}_2\text{ max}$).
  - Determined by age, gender, and size.

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Metabolism of Skeletal Muscles

- Lactate threshold:
  - Intensity of exercise
  - % of max. $O_2$ at which there is a significant rise in blood lactate.
  - Healthy individual, significant amount or blood lactate appears at 50 – 70% $V\text{O}_2\text{ max}$.
- During light exercise, most energy is derived from aerobic respiration of fatty acids.
- During moderate exercise, energy is derived equally from fatty acids and glucose.
- During heavy exercise, glucose supplies majority of energy.

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Muscle Fuel Consumption During Exercise

- Fig. 12.21

Data not available
Metabolism of Skeletal Muscles

• Oxygen debt:
  – Oxygen that was withdrawn from hemoglobin and myoglobin during exercise.
• When person stops exercising, rate of oxygen uptake does not immediately return to pre-exercise levels due to necessity of repaying oxygen debt.

Skeletal Muscle Energy Metabolism

• Rapid ATP turnover.
• Need formation of ATP during contractile activity.
• 3 sources of ATP.
  – Phosphorylation of ADP by creatine phosphate.
  – Oxidative phosphorylation of ADP in mito.
  – Substrate level phosphorylation of ADP by glycolytic pathway.

The three sources of ATP production

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Figure not in book
Metabolism of Skeletal Muscles

• Phosphocreatine:
  • Rapid source of renewal of ATP.
  • ADP combines with creatine phosphate.
  • Phosphocreatine concentration in muscle is 3 times concentration of ATP in muscle.

Muscle Fatigue

• Characteristics
  – Decreased shortening velocity
  – Slower rate of relaxation.
• Depends on
  – Type of active skeletal muscle.
  – Intensity and duration of contractile activity.

Muscle Fatigue

• High frequency fatigue
  – Fatigue rapidly but recover rapidly.
• Low frequency fatigue
  – Fatigue slowly but recover slowly.
• What causes fatigue?
### Muscle Fiber Types

- Distinguished by
  - Maximum velocities of shortening (fast and slow fibers) dependent on myosin isozymes.
  - Major pathway used to generate ATP.
    - Oxidative vs. glycolytic fibers.

### Slow- and Fast-Twitch Fibers

- Skeletal muscle fibers can be divided on basis of contraction speed:
  - Slow-twitch (type I fibers):
  - Fast-twitch (type II fibers):
  - Differences due to different myosin ATPase isoenzymes (among other things: see table 12-4).

#### Slow- and Fast-Twitch Fibers

- **Slow-twitch (type I fibers):**
  - High oxidative capacity:
  - Resistant to fatigue.
  - Have rich capillary supply (red fibers).
  - Numerous mitochondria and aerobic enzymes.
  - High concentration of myoglobin.
Slow- and Fast-Twitch Fibers

• Fast-twitch (type II fibers):
  – Adapted to respire anaerobically.
  – Have large stores of glycogen.
  – Have few capillaries (white fibers).
  – Have few mitochondria.

Types of Skeletal Muscle Fibers Found in Humans

• Type I = Slow oxidative fibers
  – Low myosin-ATPase activity with high oxidative capacity.
• Type IIA = Fast oxidative fibers
  – High myosin-ATPase activity with high oxidative capacity.
• Type IIX(humans) = Fast glycolytic fibers
  – High myosin-ATPase activity with high glycolytic capacity. Low oxidative capacity.

Muscle Fatigue

• Inability to maintain a muscle tension when the contraction is sustained.
  – Due to an accumulation of ECF K⁺ due to repolarization phase of AP.
• During moderate exercise fatigue occurs when slow-twitch fibers deplete their glycogen reserve.
• Fast twitch fibers are recruited, converting glucose to lactic acid.
  – Interferes with Ca⁺⁺ transport.
Control of Muscle Tension.

- Depends on
  - Amount of tension developed by each fiber.
  - Number of fibers contracting at any one time.
    - Motor unit size
    - Number of active motor units.
- Recruitment - process of increasing the number of motor units that are active at any given time.

Recruitment

- Achieved by greater synaptic input to motor units.
- Greater the number of active motor neurons, the ________ motor neurons recruited, the ________ the muscle tension.
Control of Shortening Velocity

- Velocity of single muscle fiber
  - Load on fiber
  - Type of fiber (fast or slow)
- Velocity of whole muscle
  - Load on whole muscle
  - Types of motor units in muscle.
  - Recruitment of motor units.

Adaptation to Exercise.

- What effects a muscle?
Adaptations to Exercise Training

- Maximum oxygen uptake in trained endurance athletes increases up to 86 ml of \( \text{O}_2 \)/min.
- Increases lactate threshold.
- Increase proportion of energy derived from fatty acids.
- Lower depletion of glycogen stores.
- Endurance training increase in type IIA fibers and decrease in type IIX fibers.

Adaptation to Exercise.

- Long duration, low intensity exercise
  - Increase in mitochondria and vascularization.
- Short duration, high intensity exercise.
  - Affects fast glycolytic fibers.
  - Increase in fiber diameter.
  - Increase in glycolytic activity (i.e., increase in glycolytic enzymes.)

Sensory Information

- Lower motor neurons activity influenced by:
  - Sensory feedback from the muscles and tendons.
  - Facilitory and inhibitory effects of upper motor neurons.
Voluntary vs. Involuntary Actions

- Voluntary
- -
- Involuntary
- -

!Almost all motor behavior involves both components!

Local afferent input.

- Length monitoring systems
  - Absolute muscle length
  - Changes in muscle length
- Tension monitoring systems
  - Feedback on absolute tension on a muscle from
    - Muscle length
    - Load
    - Muscle fatigue.

Sensory Information

- To control skeletal muscle movements, it must receive continuous sensory feedback.
- Sensory feedback includes information from:
  - Golgi tendon organs:
    - Sense tension that the muscle exerts on the tendons.
  - Muscle spindle apparatus:
    - Measure muscle length.
**Structure and Innervation of a Muscle Spindle**

- Extramuscular fibers
- Intramuscular fibers: Nuclear chain fibers
- Nuclear bag fiber
- Connective tissue sheath
- Afferent nerve fibers (sensory)
- Primary fiber
- Secondary fiber
- Efferent nerve fibers (motor)
- Gamma fiber
- Alpha fiber
- Motor end plates

**Stretch receptors**

- How much muscle is stretched.
  - Magnitude and speed of stretch.

**Muscle Spindle Apparatus**

- Contains thin muscle cells called intrafusal fibers.
  - Insert into tendons at each end.
  - Contractile apparatus absent from central regions.
- 2 types of intrafusal fibers:
  - Nuclear bag fibers:
    - Nuclei arranged in loose aggregate.
  - Nuclear chain fibers:
    - Nuclei arranged in rows.
Muscle Spindle Apparatus

- **Extrafusal fibers:**
  - Ordinary muscle fibers outside to the spindles.
  - Contain myofibrils along entire length.
  - Spindles are arranged in parallel with the extrafusal muscle fibers.

Muscle Spindle Apparatus

- **Sensory neurons:**
  - Primary, annulospiral endings:
    - Wrap around the central regions of both nuclear bag and chain fibers.
    - Most stimulated at onset of stretch.
  - Secondary, flower-spray endings:
    - Located over the contracting poles of chain fibers.
    - Respond to tonic (sustained) stretch.
  - Stretching a muscle causes spindles to stretch, stimulating both primary and secondary endings.

Motor Neurons

- **Alpha motor neurons:**
  - Neurons that innervate extrafusal fibers.
  - Fast conducting fibers.
- **Gamma motor neurons:**
  - Neurons that innervate the intrafusal fibers.
  - Cause isometric muscle contraction.
- **Only extrafusal muscle fibers are strong and numerous to cause muscle contraction.**
Coactivation of Alpha and Gamma Motorneurons

- Coactivation:
  - Upper motor neurons usually stimulate alpha and gamma motorneurons simultaneously.
  - Stimulation of alpha motoneurons results in muscle contraction and shortening.
  - Stimulation of gamma motoneurons stimulate intrafusal fibers and take out the slack.
- Activity of gamma motoneurons is maintained to keep muscle spindles under proper tension.

Structure and Innervation of a Muscle Spindle

Extrahalo fibers  Intrahalo fibers  Neuronal chains fibers  Nociceptor fiber
Connective tissue sheath  Afferent nerve fibers (sensory):
  Primary fiber  Afferent terminal endings  Secondary fiber  Efferent nerve fibers (motor):
  Gamma fiber  Alpha fiber  Motor end plates

Monosynaptic Reflex

- Consists of only one synapse within the CNS.
- Sensory neuron synapses directly with the motor neuron.
- Strike patellar ligament, passively stretches the spindles, activating sensory neuron.
- Synapse with alpha motoneuron resulting in the knee jerk.
Golgi Tendon Organ Reflex

- Disynaptic reflex.
  - 2 synapses are crossed in the CNS.
- Sensory neurons synapse with interneurons in spinal cord.
- Interneurons have inhibitory synapses with motor neurons.
- Helps prevent excessive muscle contraction.

Reciprocal Innervation

- Sensory neuron stimulates motor neuron and interneuron, inhibiting motor neurons of antagonistic muscles.

Crossed-extensor Reflex

- Double reciprocal innervation.
- Affect muscles on the contralateral side of the cord.
- Step on tack:
  - Foot is withdrawn by contraction.
  - Contralateral leg extends to support body.
Upper Motor Neuron Control of Skeletal Muscles

- **Pyramidal tracts:**
  - Neurons in precentral gyrus contribute axons that cross to contralateral sides in the pyramids of medulla.
- **Extrapyramidal tracts:**
  - Neurons in the other areas of the brain.

Upper Motor Neuron Control of Skeletal Muscles

- **Cerebellum:**
  - Receives sensory input from muscle spindles, Golgi tendon organs, and areas of cerebral cortex devoted to vision, hearing and equilibrium.
  - No descending tracts from the cerebellum.
  - Influences motor activity indirectly.
  - All output from cerebellum is inhibitory.
  - Aids motor coordination.

Upper Motor Neuron Control of Skeletal Muscles

- **Basal nuclei:**
  - Include caudate nucleus, putamen, globus pallidus, and nuclei of thalamus, substantia nigra and red nucleus.
  - Profound inhibitory effects on the activity of lower motor neurons.
  - Damage to basal nuclei result in increased muscle tone.
Cardiac Muscle

- Contain actin and myosin arranged in sarcomeres.
- Contract via sliding-filament mechanism.
- Adjacent myocardial cells joined by gap junctions.
  - AP spread through cardiac muscle through gap junctions.
  - Behaves as one unit.
  - All cells contribute to contraction.

**Fig. 12.31**

**Myocardial Cells Interconnected by Gap Junctions**
**Smooth Muscle and Its Contractile Apparatus**

- Do not contain sarcomeres.
- Contain greater content of actin than myosin (ratio of 16:1).
- Myosin filaments attached at ends of the cell to dense bodies.
- Contain gap junctions.

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**Smooth Muscle Contraction**

- No troponin
- Contraction controlled by calcium regulated enzyme that phosphorylates myosin = myosin light-chain kinase.
- Only phosphorylated myosin can bind actin and undergo cross-bridge cycling.
- Contraction stopped by myosin dephosphorylation.

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**Excitation-Contraction Coupling in Smooth Muscle**

- Depolarization
- Voltage-gated Ca\(^2+\) channels open in plasma membrane
- Ca\(^2+\) + calmodulin
- Cross-bridge activation and contraction

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Smooth Muscle Contractions
(Comparison to skeletal muscle contractions)

- Activated by calcium from
  - Sarcoplasmic reticulum.
  - Extracellular fluid
- No T-tubules.
- Rate of calcium removal much slower than in skeletal muscle.
- Only portion of cross bridges activated in smooth muscle in response to stimuli.
- Ability to have “smooth muscle tone” in some smooth muscle.

Exciting smooth muscle

- Many inputs to smooth muscle alter contractile activity.
  - Increase activity
  - Inhibit activity
- Contraction in response to
  - Change in membrane potential (via calcium voltage-gated channels)
  - Or no change in membrane potential.
- Graded depolarizations and hyperpolarizations
Spontaneous electrical activity

- Plasma membranes do not maintain a constant resting potential.
- Pacemaker potential - change occurring during spontaneous depolarization to threshold.

Multiunit smooth muscle

- No or few gap junctions.
- Richly innervated.
- Contractile response depends on number of fibers activated and frequency of stimulation.
- Examples:
  - Large airway smooth muscle, large artery smooth muscle and hair follicle smooth muscle.