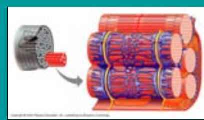
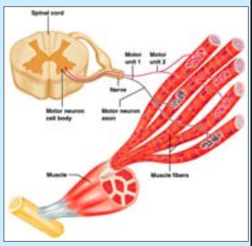
Anatomy & Physiology

Muscles and Muscle Tissue



Motor Unit: The Nerve-Muscle Functional Unit

Each muscle has at least one motor nerve that may contain hundreds of motor neuron axons. Axons branch into terminals, each forming a neuromuscular junction with a single muscle fiber



A motor neuron and all the muscle fibers it supplies is called a Motor Unit

Motor Unit

The number of muscle fibers per motor unit can vary from a few to several hundred

Muscles that control fine movements (fingers, eyes) have small motor units

Large weight-bearing muscles (thighs, hips) have large motor units

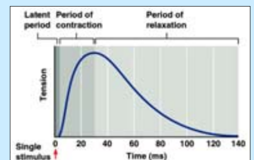
Muscle fibers in a single motor unit are spread throughout the muscle. As a result, stimulation of a single motor unit causes weak contraction of the entire muscle

Muscle Twitch

A muscle twitch is the response of a muscle to a single action potential of its motor neuron. The fibers contract quickly and then relax.

Three phases:

- Latent Period
- Period of Contraction
- Period of Relaxation



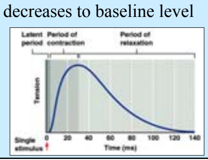
Myogram – graphic recording of contractile activity

Muscle Twitch

Latent Period – the first few ms after stimulation when excitation-contraction is occurring

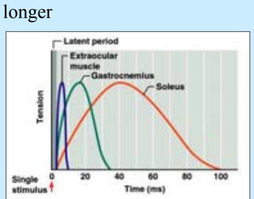
Period of Contraction – cross bridges are active and the muscle shortens if the tension is great enough to overcome the load

Period of Relaxation – Ca^{2+} is pumped back into SR and muscle tension decreases to baseline level



Muscle Twitch

Twitch contraction of some muscles (extraocular) are rapid and brief, others (gastrocnemius, soleus) are slower and longer



Graded Muscle Responses

Graded muscle responses are:

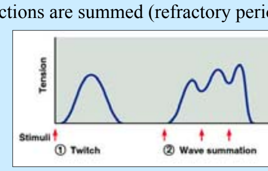
- Variations in the degree or strength of muscle contraction in response to demand
- Required for proper control of skeletal movement

Muscle contraction can be graded (varied) in two ways:

- By changing the Frequency of the stimulus
- By changing the Strength of the stimulus

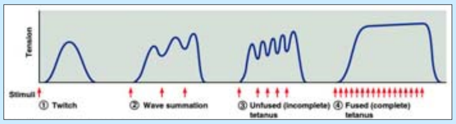
Muscle Response to Stimulation Frequency

- A single stimulus results in a single contractile response – a muscle twitch (contracts and relaxes)
- More frequent stimuli increases contractile force – wave summation - muscle is already partially contracted when next stimulus arrives and contractions are summed (refractory period applies)



Muscle Response to Stimulation Frequency

- More rapidly delivered stimuli result in incomplete tetanus – sustained but quivering contraction
- If stimuli are given quickly enough, complete tetanus results – smooth, sustained contraction with no relaxation period



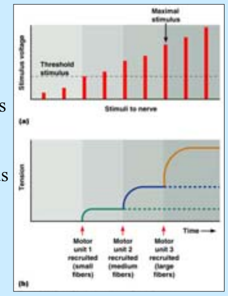
Muscle Response to Stronger Stimuli

- Threshold stimulus – the stimulus strength at which the first observable muscle contraction occurs
- Beyond threshold, muscle contracts more vigorously as stimulus strength is increased
- Force of contraction is precisely controlled by multiple motor unit summation
- This phenomenon, called recruitment, brings more and more muscle fibers into play

Stimulus Intensity and Muscle Tension

Below threshold – no muscle response

Above threshold – increases in voltage excite (recruit) more (and larger) motor units until maximal stimulus is reached



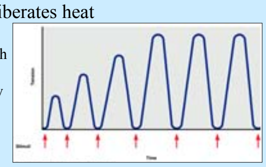
Treppe: The Staircase Effect

Increased contraction tension in response to multiple stimuli of the same strength. May be due to:

Increasing availability of Ca^{2+} in the sarcoplasm

Muscle enzyme systems become more efficient and muscle pliability increases as muscle contracts and liberates heat

Same intensity stimuli with relaxation between contractions – the first few contractions get stronger and stronger



Muscle Tone

Muscle tone:

- The constant, slightly contracted state of all muscles - does not produce active movements
- Keeps the muscles firm and ready to respond to stimulus
- Helps stabilize joints and maintain posture
- Due to spinal reflex activation of motor units in response to stretch receptors in muscles and tendons

Contraction of Skeletal Muscle Fibers

The force exerted on an object by a contracting muscle is called muscle tension, the opposing force or weight of the object to be moved is called the load.

Two types of Muscle Contraction:

When muscle tension develops, but the load is not moved (muscle does not shorten) the contraction is called Isometric

If muscle tension overcomes (moves) the load and the muscle shortens, the contraction is called Isotonic

Isometric Contraction

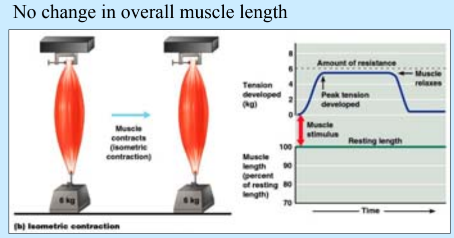
Tension increases up to the muscle's capacity, but the muscle neither shortens nor lengthens

Occurs if the load is greater than the tension the muscle is able to develop

The cross bridges generate force, but do not move the thin filaments

Isometric Contractions

No change in overall muscle length



In isometric contractions, increasing muscle tension (force) is measured

Isotonic Contraction

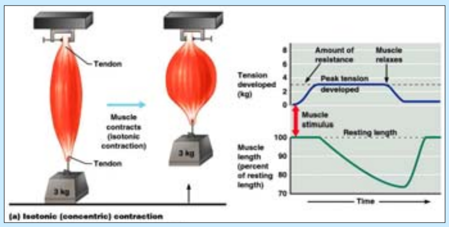
In isotonic contractions, the muscle changes length and moves the load. Once sufficient tension has developed to move the load, the tension remains relatively constant through the rest of the contractile period.

Two types of isotonic contractions:

- Concentric contractions – the muscle shortens and does work
- Eccentric contractions – the muscle contracts as it lengthens

Isotonic Contraction

This illustrates a concentric isotonic contraction



In isotonic contractions, the amount of shortening (distance in mm) is measured

Muscle Metabolism: Energy

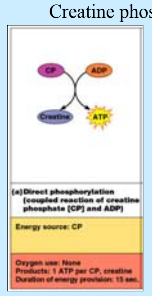
ATP is the only energy source that is used directly for contractile activity

As soon as available ATP is hydrolyzed (4-6 seconds), it is regenerated by three pathways:

- Interaction of ADP with Creatine Phosphate (CP)
- From stored glycogen via Anaerobic Glycolysis
- From Aerobic Respiration

CP-ADP Reaction

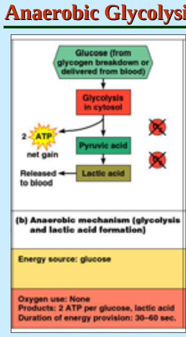
Creatine phosphate + ADP → creatine + ATP



Transfer of energy as a phosphate group is moved from CP to ADP – the reaction is catalyzed by the enzyme creatine kinase

Stored ATP and CP provide energy for maximum muscle power for 10-15 seconds

Anaerobic Glycolysis

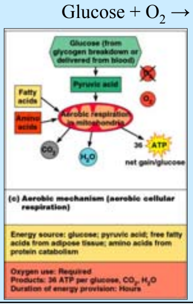


When muscle contractile activity reaches 70% of maximum:

- Muscles compress blood vessels and O_2 delivery is impaired (anaerobic conditions)
- Pyruvic acid is converted into lactic acid
- Lactic acid diffuses into the bloodstream – can be used as energy source by the liver, kidneys, and heart
- Can be converted back into pyruvic acid, glucose, or glycogen by the liver

Glycolysis and Aerobic Respiration

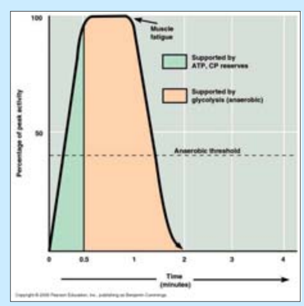
Glucose + O_2 → CO_2 + H_2O + ATP



Aerobic respiration occurs in mitochondria - requires O_2

A series of reactions where glucose is fully broken down with a high yield of ATP

Energy System or Source during peak activity



Muscle Fatigue

Muscle fatigue – the muscle is physiologically not able to contract

Occurs when oxygen is limited and ATP production fails to keep pace with ATP use

- Lactic acid accumulation and ionic imbalances may also contribute to muscle fatigue

When no ATP is available, contractures (continuous contraction) may result because cross bridges are unable to detach

Muscle Fatigue

Intense exercise produces rapid muscle fatigue (with rapid recovery)

Na^+-K^+ pumps cannot restore ionic balances quickly enough

Low-intensity exercise produces slow-developing fatigue (with longer recovery period)

SR may be damaged, interfering with Ca^{2+} regulation

Oxygen Debt

Vigorous exercise can cause dramatic changes in muscle chemistry

For a muscle to return to its pre-exercise state:

- 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

Oxygen debt – the extra amount of O_2 needed for the above restorative processes

Heat Production During Muscle Activity

Only 40% of the energy released in muscle activity is useful as work

The remaining 60% is given off as heat

Heat is dissipated by radiation of heat from the skin and sweating

Force of Muscle Contraction

Affected by:

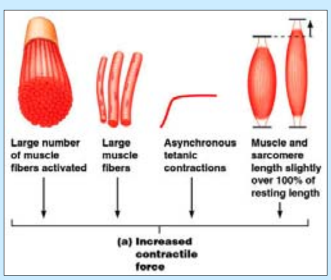
The number of muscle fibers stimulated – the more motor units recruited, the stronger the contraction

The relative size of the muscle fibers – the bulkier the muscle (greater cross-sectional area), the greater its strength

Frequency of stimulation – takes time to take up slack and stretch the series elastic components

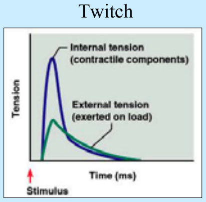
Degree of muscle stretch – muscles contract strongest when muscle fibers are 80-120% of their normal resting length (think about filament overlap)

Force of Muscle Contraction

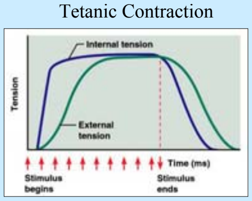


Stimulus Frequency and Tension

Twitch



Tetanic Contraction



Velocity and Duration of Contraction

Speed of contraction – determined by how fast their myosin ATPases split ATP

- Oxidative fibers – use aerobic pathways
- Glycolytic fibers – use anaerobic glycolysis

Based on these two criteria skeletal muscles can be classified as:

slow oxidative fibers,
fast oxidative fibers,
and fast glycolytic fibers

See Table 9.2

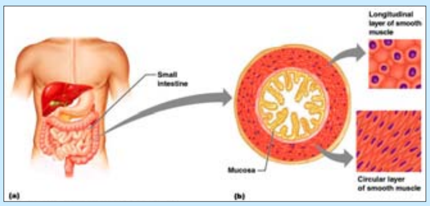
Muscle Fiber Type: Speed of Contraction

- Slow oxidative fibers contract slowly, have slow acting myosin ATPases, and are fatigue resistant
- Fast oxidative fibers contract quickly, have fast myosin ATPases, and have moderate resistance to fatigue
- Fast glycolytic fibers contract quickly, have fast myosin ATPases, and are easily fatigued

Smooth Muscle

- Composed of spindle-shaped fibers with a diameter of 2-10 µm and lengths of several hundred µm
- Lack the coarse connective tissue sheaths of skeletal muscle, but have fine endomysium
- Generally organized into two layers (longitudinal and circular) of closely apposed fibers
- Found in walls of hollow organs (except the heart)
- Have essentially the same contractile mechanisms as skeletal muscle

Smooth Muscle



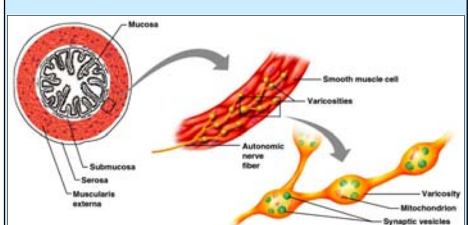
Peristalsis

- When the longitudinal layer contracts, the organ shortens and dilates
- When the circular layer contracts, the organ elongates and constricts (lumen is narrower)
- Peristalsis – alternating contractions and relaxations of smooth muscles that mix and squeeze substances through the lumen of hollow organs

Innervation of Smooth Muscle

- Smooth muscle lacks highly structured neuromuscular junctions – the innervating nerve fibers are part of the autonomic nervous system
- Innervating nerves have bulbous swellings called varicosities
- Varicosities release neurotransmitters into wide synaptic clefts called diffuse junctions

Innervation of Smooth Muscle



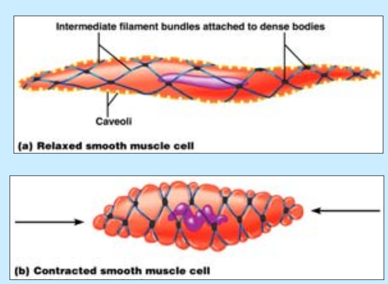
Microscopic Anatomy of Smooth Muscle

- SR is less developed than in skeletal muscle and lacks a specific pattern
- T tubules are absent
- Plasma membranes have pouchlike infoldings called caveoli
- Ca^{2+} is sequestered in the extracellular space near the caveoli, allowing rapid influx when channels are opened
- There are no visible striations and no sarcomeres
- Thin and thick filaments are present

Myofilaments in Smooth Muscle

- Ratio of thick to thin filaments is much lower than in skeletal muscle
- Thick filaments have heads along their entire length
- There is no troponin complex
- Thick and thin filaments are arranged diagonally, causing smooth muscle to contract in a corkscrew manner
- Noncontractile intermediate filament bundles attach to dense bodies (analogous to Z discs) at regular intervals

Myofilaments in Smooth Muscle



Contraction of Smooth Muscle

- Whole sheets of smooth muscle exhibit slow, synchronized contraction
- They contract in unison, reflecting their electrical coupling with gap junctions
- Action potentials are transmitted from cell to cell
- Some smooth muscle cells:
  - Act as pacemakers and set the contractile pace for whole sheets of muscle
  - Are self-excitatory and depolarize without external stimuli

Contraction Mechanism

- Actin and myosin interact according to the sliding filament mechanism
- The final trigger for contractions is a rise in intracellular Ca^{2+}
- Ca^{2+} is released from the SR and also moves from the extracellular space into the cell
- Ca^{2+} interacts with calmodulin and myosin light chain kinase to activate myosin

Role of Calcium Ion

- Ca^{2+} binds to calmodulin and activates it
- Activated calmodulin activates the kinase enzyme
- Activated kinase transfers phosphate from ATP to myosin cross bridges
- Phosphorylated cross bridges interact with actin to produce shortening
- Smooth muscle relaxes when intracellular Ca^{2+} levels drop

Features of Smooth Muscle Contraction

- Unique characteristics of smooth muscle include:
  - Smooth muscle tone
  - Slow, prolonged contractile activity
  - Low energy requirements
  - Response to stretch

Response to Stretch

- Smooth muscle exhibits a phenomenon called stress-relaxation response in which:
  - Smooth muscle responds to stretch only briefly, and then adapts to its new length
  - The new length, however, retains its ability to contract
  - This enables organs such as the stomach and bladder to temporarily store contents

Hyperplasia

- Certain smooth muscles can divide and increase their numbers by undergoing hyperplasia
- This is shown by estrogen's effect on the uterus
  - At puberty, estrogen stimulates the synthesis of more smooth muscle, causing the uterus to grow to adult size
  - During pregnancy, estrogen stimulates uterine growth to accommodate the increasing size of the growing fetus

Types of Smooth Muscle: Single Unit

- The cells of single-unit smooth muscle, commonly called visceral muscle:
  - Contract rhythmically as a unit
  - Are electrically coupled to one another via gap junctions
  - Often exhibit spontaneous action potentials
  - Are arranged in opposing sheets and exhibit stress-relaxation response

Types of Smooth Muscle: Multiunit

- Multiunit smooth muscles are found:
  - In large airways to the lungs
  - In large arteries
  - In arrector pili muscles
  - Attached to hair follicles
  - In the internal eye muscles

Types of Smooth Muscle: Multiunit

- Their characteristics include:
  - Rare gap junctions
  - Infrequent spontaneous depolarizations
  - Structurally independent muscle fibers
  - A rich nerve supply that forms motor units with a number of muscle fibers,
  - Graded contractions in response to neural stimuli

Muscular Dystrophy

- Muscular dystrophy – group of inherited muscle-destroying diseases where muscles enlarge due to fat and connective tissue deposits, but muscle fibers atrophy

Muscular Dystrophy

- Duchenne muscular dystrophy (DMD)
  - Inherited, sex-linked disease carried by females and expressed in males (1/3500)
  - Diagnosed between the ages of 2-10
  - Victims loose coordination as their muscles fail

Websites

Gateway Community College - Arizona

http://www.gwc.maricopa.edu/class/bio201/

Loyala University

http://www.meddean.luc.edu/lumen/MedEd/GrossAnatomy/dissector/mml/

University of Minnesota

http://www.gen.umn.edu/faculty_staff/jensen/1135/webanatomy/wa_muscle/default.htm