The Cyprus International Institute for the Environment and Public Health
In collaboration with the Harvard School of Public Health

Lecture 5

Neuromuscular Physiology
(240-249, 253-267,270-286,288-297)

Excluded: muscle length, tension, contraction and velocity, phosphorylation of myosin

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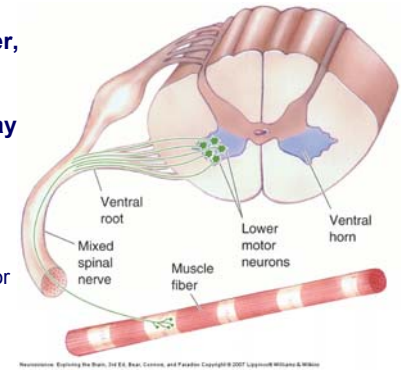
Somatic Nervous System

- **Consists of axons of motor neurons**
  - Originate in spinal cord or brain stem and end on skeletal muscle
- **Motor neuron releases neurotransmitter, ACh**
  - Stimulates muscle contraction
- **Motor neurons = final common pathway**
  - Various regions of CNS exert control over skeletal muscle activity
    - Spinal cord, motor regions of cortex, basal nuclei, cerebellum, and brain stem
- **Pathologies**
  - Polio virus destroys the cell bodies of motor neurons
  - Amyotrophic Lateral Sclerosis (ALS)
    - A.k.a. Lou Gehrig's Disease
    - Most common motor neuron disease
    - Gradual degeneration of motor neurons
    - Unknown cause

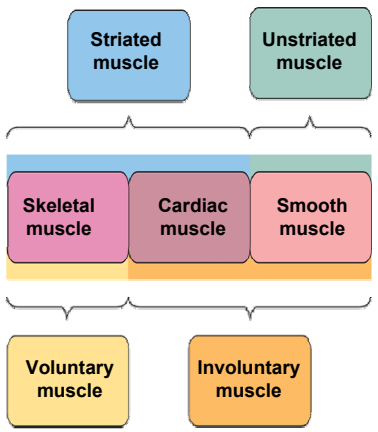


Somatic Nervous System

FEATURE	AUTONOMIC NERVOUS SYSTEM	SOMATIC NERVOUS SYSTEM
Site of Origin	Brain or spinal cord	Spinal cord for most; those supplying muscles in head originate in brain
Number of Neurons from Origin in CNS to Effector Organ	Two-neuron chain (preganglionic and postganglionic)	Single neuron (motor neuron)
Organs Innervated	Cardiac muscle, smooth muscle, exocrine and some endocrine glands	Skeletal muscle
Type of Innervation	Most effector organs dually innervated by the two antagonistic branches of this system (sympathetic and parasympathetic)	Effector organs innervated only by motor neurons
Neurotransmitter at Effector Organs	May be acetylcholine (parasympathetic terminals) or norepinephrine (sympathetic terminals)	Only acetylcholine
Effects on Effector Organs	Either stimulation or inhibition (antagonistic actions of two branches)	Stimulation only (inhibition possible only centrally through IPSPs on dendrites and cell body of motor neuron)
Types of Control	Under involuntary control	Subject to voluntary control; much activity subconsciously coordinated
Higher Centers Involved in Control	Spinal cord, medulla, hypothalamus, prefrontal association cortex	Spinal cord, motor cortex, basal nuclei, cerebellum, brain stem

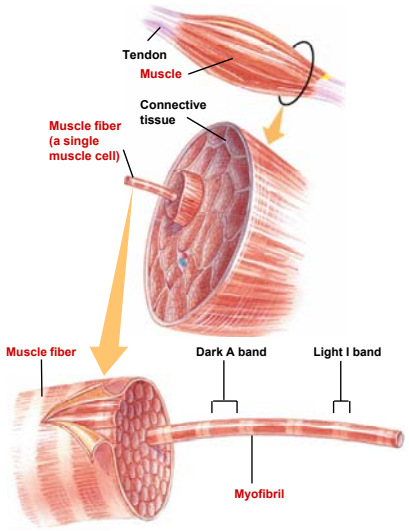
Muscle

- **Comprises largest group of tissues in body**
  - Skeletal (30-40% BW), smooth and cardiac (10% BW)
- **Controlled muscle contraction allows**
  - Purposeful movement of the whole body or parts of the body
  - Manipulation of external objects
  - Propulsion of contents through various hollow internal organs
  - Emptying of contents of certain organs to external environment
- **Three types of muscle**
  - Skeletal muscle
    - Make up muscular system
  - Cardiac muscle
    - Found only in the heart
  - Smooth muscle
    - Appears throughout the body systems as components of hollow organs and tubes
- **Classified in two different ways**
  - Striated or unstriated
  - Voluntary or involuntary



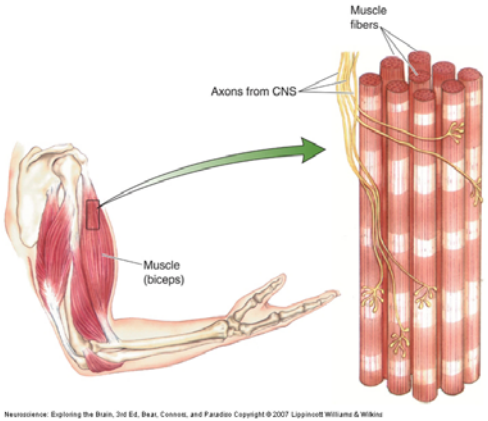
Structure of Skeletal Muscle

- **Muscle consists a number of muscle fibers lying parallel to one another and held together by connective tissue**
- **Single skeletal muscle cell is known as a muscle fiber**
  - Multinucleated
  - Large, elongated, and cylindrically shaped
  - Fibers usually extend entire length of muscle



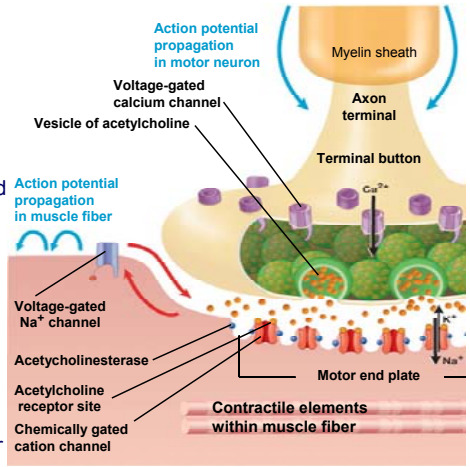
Neuromuscular Junction

- **Axon terminal of motor neuron forms neuromuscular junction with a single muscle cell**
  - Terminal button (of neuron)
  - Motor End Plate (of muscle cell)



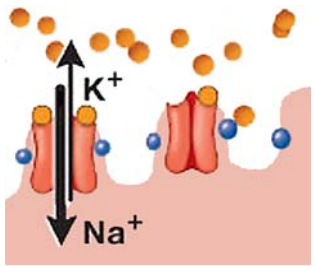
Neuromuscular Junction

- **Signals are passed between nerve terminal and muscle fiber by means of neurotransmitter ACh**
  - AP in motor neuron reaches terminal
  - Voltage-gated Ca^{2+} channels open
  - ACh is released by exocytosis
  - ACh diffuses across the space and binds to receptor sites on motor end plate of muscle cell membrane
  - Binding triggers opening of cation channels in motor end plate
  - Na^+ movements (larger than K^+ movements) depolarize motor end plate, producing end-plate potential
  - Local current flow between depolarized end plate and adjacent muscle cell membrane brings adjacent areas to threshold
  - Action potential is initiated and propagated throughout muscle fiber



Neuromuscular Junction

- **Acetylcholinesterase**
  - On the chemically-gated cation channels of the end plate
  - Inactivates ACh (as ACh molecules attaches and detaches from the receptors)
  - Ends end-plate potential and the action potential
  - Ensures prompt termination of contraction

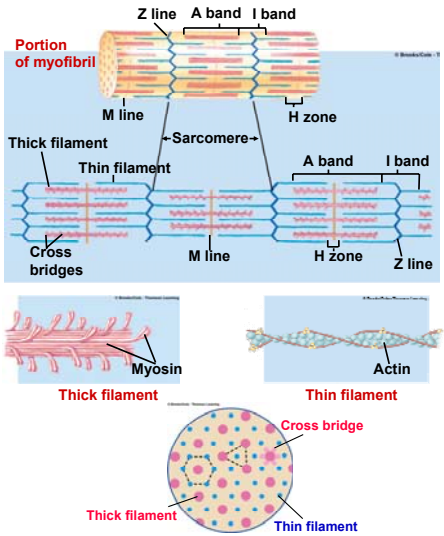


Neuromuscular Junction

- **Neuromuscular junction is vulnerable to chemical agents and diseases**
  - Black widow spider venom
    - Causes explosive release of ACh
    - Prolonged depolarization keeps Na^+ channels at inactive state
    - Respiratory failure from diaphragm paralysis
  - Botulism toxin
    - From food infected with *Clostridium Botulinum* → Botulism
    - Blocks release of ACh
    - Respiratory failure from inability to contract diaphragm
  - Curare
    - Poisonous arrowheads
    - Binds at ACh receptor sites but has no activity and is not degrated
  - Organophosphates
    - Pesticide and military nerve gases
    - Prevent inactivation of Ach by inhibiting AChE
    - Effect similar to Black widow spider venom
  - Myasthenia gravis inactivates ACh receptor sites
    - Autoimmune condition (Antibodies against ACh receptors)
    - ACh is degraded before it can act.
    - Antidote is neostigmine (inhibits AChE and prolongs ACh action)

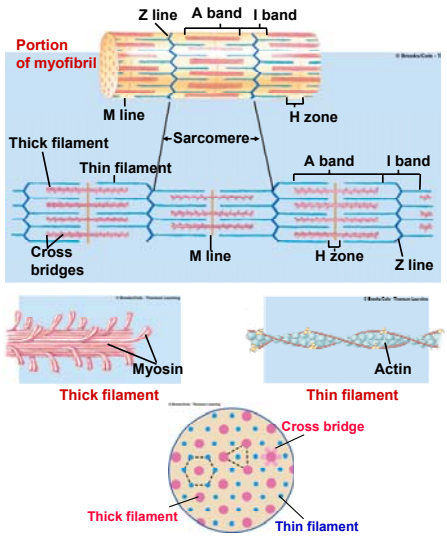
Structure of Skeletal Muscle

- **Myofibrils**
  - Contractile elements of muscle fiber
  - Viewed microscopically myofibril displays alternating dark (the A bands) and light bands (the I bands) giving appearance of striations
  - Regular arrangement of thick and thin filaments
    - Thick filaments – myosin (protein)
    - Thin filaments – actin (protein)
- **Sarcomere**
  - Functional unit of skeletal muscle
  - Found between two Z lines
    - Z lines connect thin filaments of two adjoining sarcomeres



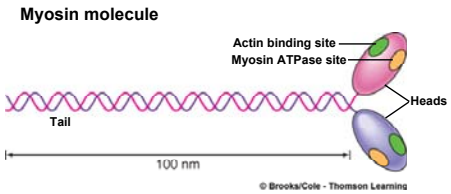
Structure of Skeletal Muscle

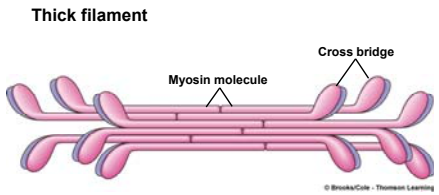
- **Titin**
  - Giant, highly elastic protein
  - Largest protein in body
  - Extends in both directions from along length of thick filament to Z lines at opposite ends of sarcomere
  - Two important roles:
    - Helps stabilize position of thick filaments in relation to thin filaments
    - Greatly augments muscle's elasticity by acting like a spring



Myosin

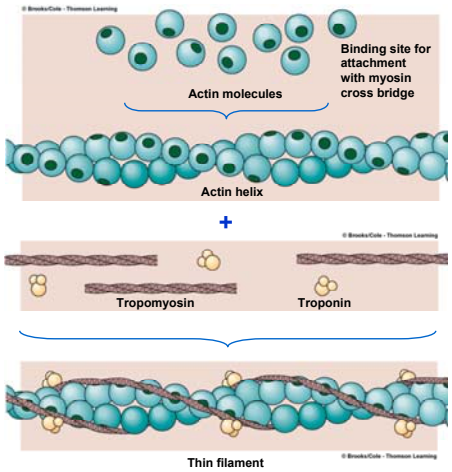
- **Component of thick filament**
  - Several hundred of them
- **Protein molecule consisting of two identical subunits shaped somewhat like a golf club**
  - Tail ends are intertwined around each other
  - Globular heads project out at one end
- **Tails oriented toward center of filament and globular heads protrude outward at regular intervals**
  - Heads form cross bridges between thick and thin filaments
    - Cross bridge has two important sites critical to contractile process
      - An actin-binding site
      - A myosin ATPase (ATP-splitting) site





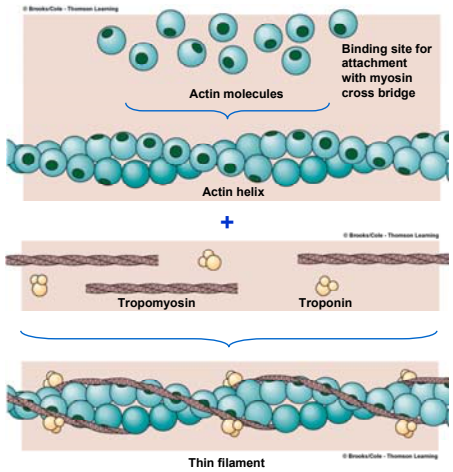
Actin

- **Primary structural component of thin filaments**
- **Spherical in shape**
- **Thin filament also has two other proteins**
  - Tropomyosin and troponin
- **Each actin molecule has special binding site for attachment with myosin cross bridge**
  - Binding results in contraction of muscle fiber
- **Actin and myosin are often called contractile proteins. Neither actually contracts.**
- **Actin and myosin are not unique to muscle cells, but are more abundant and more highly organized in muscle cells.**



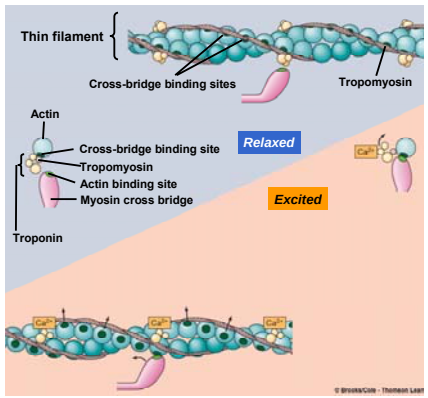
Tropomyosin and Troponin

- **Often called regulatory proteins**
- **Tropomyosin**
  - Thread-like molecules that lie end to end alongside groove of actin spiral
  - In this position, covers actin sites blocking interaction that leads to muscle contraction
- **Troponin**
  - Made of three polypeptide units
    - One binds to tropomyosin
    - One binds to actin
    - One can bind with Ca^{2+}



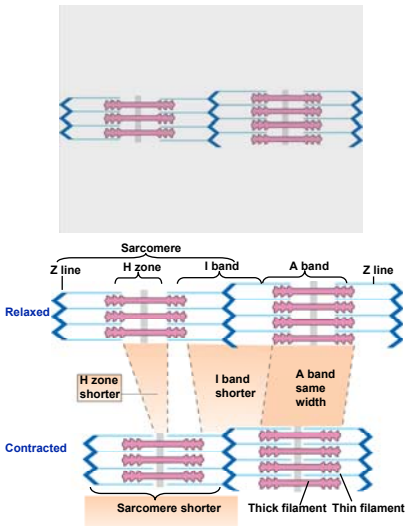
Tropomyosin and Troponin

- **Troponin**
  - When not bound to Ca^{2+}, troponin stabilizes tropomyosin in blocking position over actin's cross-bridge binding sites
  - When Ca^{2+} binds to troponin, tropomyosin moves away from blocking position
  - With tropomyosin out of way, actin and myosin bind, interact at cross-bridges
  - Cross-bridge interaction between actin and myosin brings about muscle contraction by means of the sliding filament mechanism



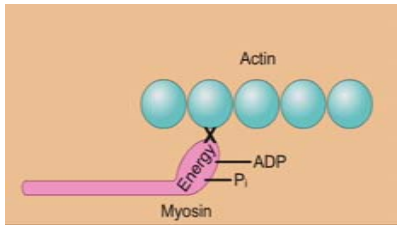
Sliding Filament Mechanism

- **Thin filaments on each side of sarcomere slide inward**
  - Over stationary thick filaments
  - Toward center of A band
  - They pull Z lines closer together
- **Sarcomere shortens**
  - All sarcomeres throughout muscle fiber's length shorten simultaneously
  - Contraction is accomplished by thin filaments from opposite sides of each sarcomere sliding closer together between thick filaments
- **Ca^{2+} plays a key role**
  - Increase in Ca^{2+} starts filament sliding
  - Decrease in Ca^{2+} turns off sliding process



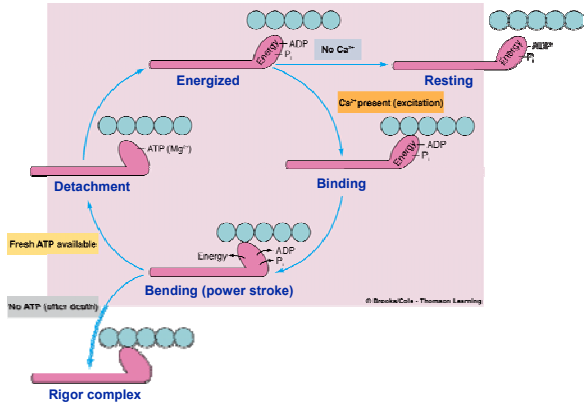
Power Stroke

- **Activated cross bridge bends toward center of thick filament, "rowing" in thin filament to which it is attached**
  - Sarcoplasmic reticulum releases Ca^{2+} into sarcoplasm
  - Myosin heads bind to actin
  - Myosin heads swivel toward center of sarcomere (***power stroke***)
  - ADP released
  - ATP binds to myosin head and detaches it from actin
  - Hydrolysis of ATP transfers energy to myosin head and reorients it
- **Energy expended in the form of ATP**



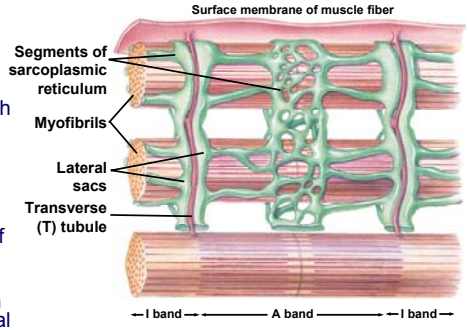
Power Stroke

- **Contraction continues if ATP is available and Ca^{2+} level in sarcoplasm is high**
- **Myosin head remains attached until ATP binds → rigor mortis**
  - Ca^{2+} released
  - ATP quickly depleted
  - Onset in a few hours
  - Can last 1-2 days
- **Ca^{2+} stores are in the sarcoplasmic reticulum**



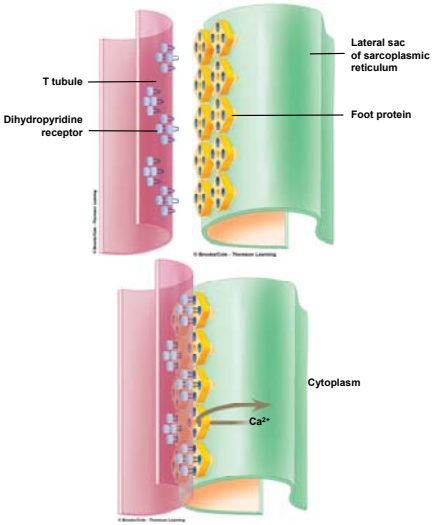
Sarcoplasmic Reticulum

- **Sarcoplasmic Reticulum (SR)**
  - Modified endoplasmic reticulum
  - Consists of fine network of interconnected compartments that surround each myofibril
  - Not continuous but encircles myofibril throughout its length
  - Segments are wrapped around each A band and each I band
    - Ends of segments expand to form saclike regions – lateral sacs (terminal cisternae)
- **T tubules**
  - Run perpendicularly from surface of muscle cell membrane into central portions of the muscle fiber
  - Since membrane is continuous with surface membrane – action potential on surface membrane also spreads down into T-tubule
  - Spread of action potential down a T tubule triggers release of Ca^{2+} from SR into cytosol



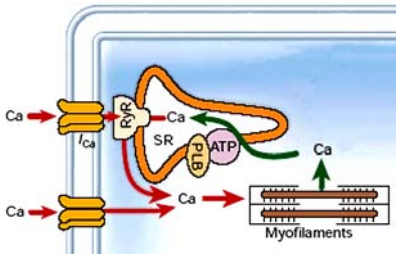
Sarcoplasmic Reticulum

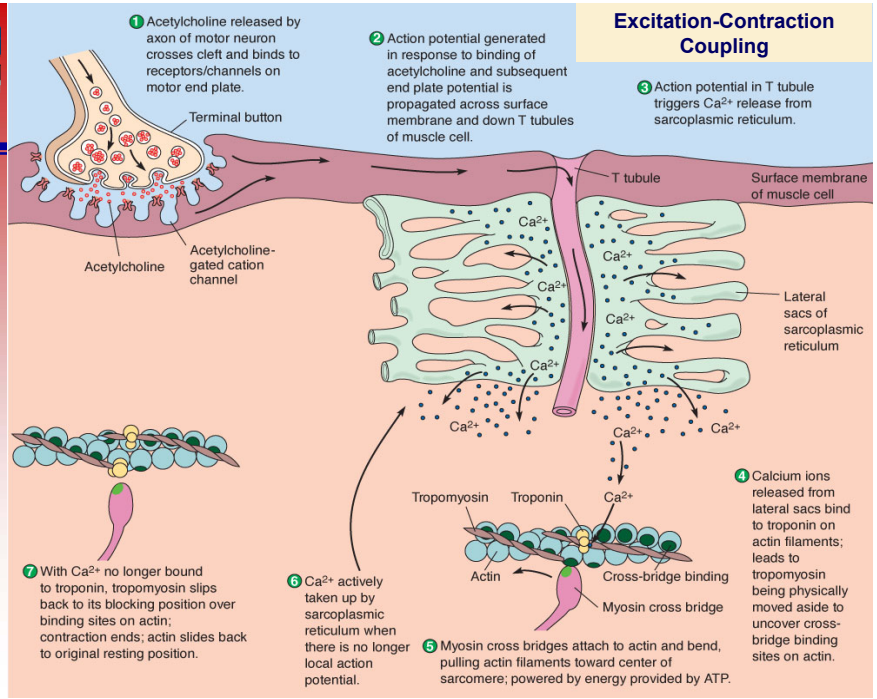
- **Release of Ca^{2+}**
  - Foot proteins
    - Cover the lateral sacs of the sarcoplasmic reticulum
    - Span the gap between the SR and T tubules as well as SR membrane
    - Half interlock ("zipped") with Dihydropyridine (DHP) receptors on T tubules
  - Dihydropyridine (DHP) receptors
    - Voltage sensors
    - Depolarization from AP opens Ca^{2+} channels of attached foot proteins
    - Ca_{2+} release opens the remaining foot proteins



Sarcoplasmic Reticulum

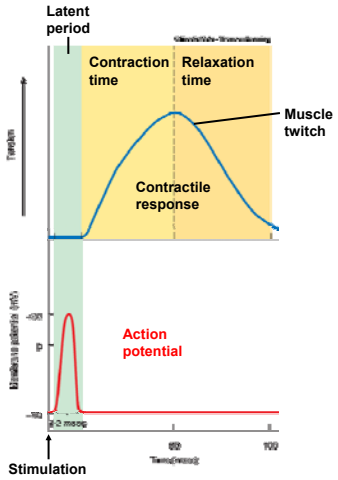
- **Relaxation - Reuptake of Ca^{2+}**
  - AChE degrates ACh at the endplate
  - Electrical activity stops
  - On-going activite of Ca^{2+}-ATPase pump returns the Ca^{2+} to the SR
  - Trponin-tropomyosin complex returns to blocking position
  - No interaction between actin and myosin
  - Muscle fiber passively relaxes





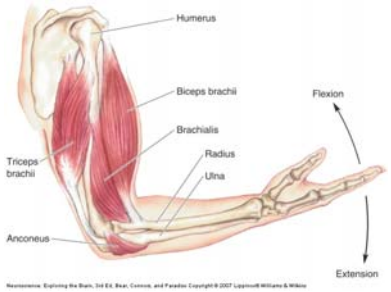
Excitation-Contraction Coupling

- **Contractile activity**
  - AP is very short (1-2 msec)
  - Contraction does not start until enough Ca^{2+} is released
    - Latent period
  - Contraction process requires time to complete
    - Contraction time (~50 msec)
  - Relaxation also requires time to complete
    - Relaxation time (~50 msec)



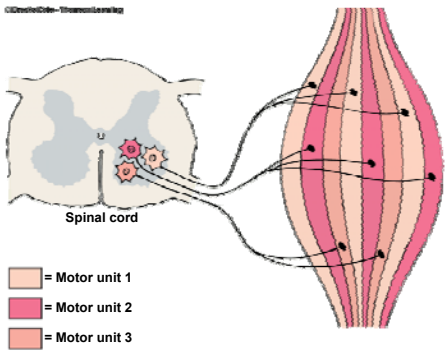
Skeletal Muscle Mechanics

- **Muscle consists of groups of muscle fibers bundled together and attached to bones**
  - Connective tissue covering muscle divides muscle internally into bundles
  - Connective tissue extends beyond ends of muscle to form tendons
    - Tendons attach muscle to bone
- **Muscle Contraction**
  - Contractions of whole muscle can be of varying strength
  - Twitch – Contraction of single muscle fiber from single AP
    - Brief, weak contraction
    - Produced from single action potential
    - Too short and too weak to be useful
    - Normally does not take place in body
  - Two primary factors which can be adjusted to accomplish gradation of whole-muscle tension
    - Number of muscle fibers contracting within a muscle
    - Tension developed by each contracting fiber



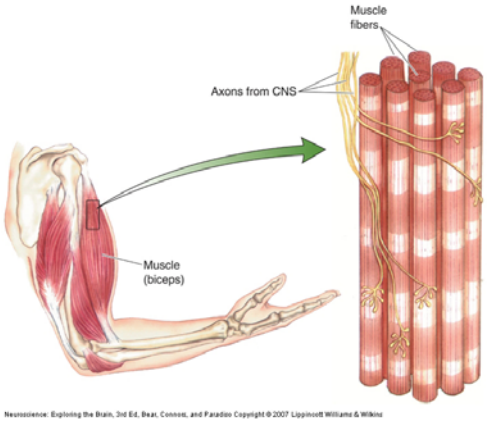
Motor Unit Recruitment

- **Motor unit**
  - One motor neuron and the muscle fibers it innervates
- **Number of muscle fibers varies among different motor units**
- **Number of muscle fibers per motor unit and number of motor units per muscle vary widely**
  - Muscles that produce precise, delicate movements contain fewer fibers per motor unit
  - Muscles performing powerful, coarsely controlled movement have larger number of fibers per motor unit
- **Asynchronous recruitment of motor units helps delay or prevent fatigue**
- **Muscle fibers which fatigue easily are recruited later**
  - Can engage in endurance activities for a long time but can only deliver full force for brief periods of time



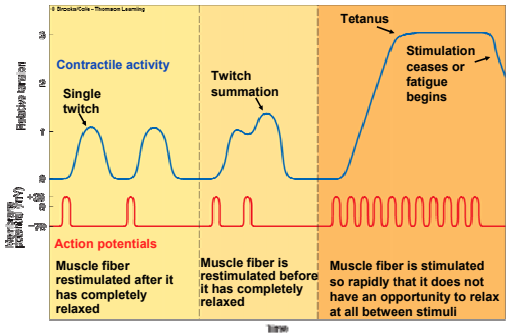
Factors Influencing Tension

- **Factors influencing extent to which tension can be developed**
  - Varying from contraction to contraction
    - Frequency of stimulation
    - Length of fiber at onset of contraction
  - Permanent or long term adaptation
    - Extent of fatigue
    - Thickness of fiber



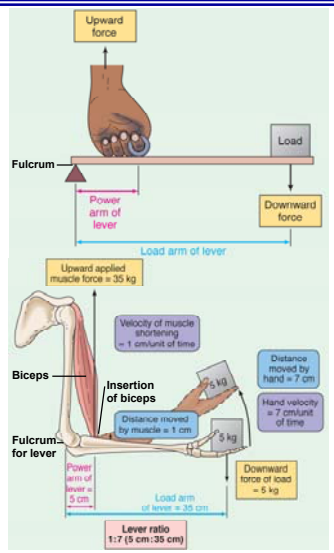
Frequency of Stimulation

- **Twitch summation**
  - Individual twitches are summed
    - AP much sorter in time than contraction → Multiple APs can be delivered
  - Results from sustained elevation of cytosolic calcium
- **Tetanus**
  - Occurs if muscle fiber is stimulated so rapidly that it does not have a chance to relax between stimuli
  - Contraction is usually three to four times stronger than a single twitch
  - Do not confuse with the disease of the same name!



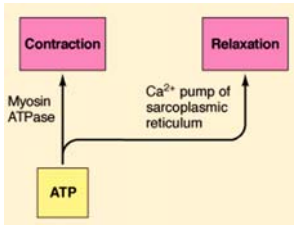
Lever Systems

- **Bones, muscles, and joints interact to form lever systems**
  - Bones function as levers
  - Joints function as fulcrums
  - Skeletal muscles provide force to move bones
- **Muscles usually exert more force than actual weight of load!**
  - Advantages: higher speed, more distance



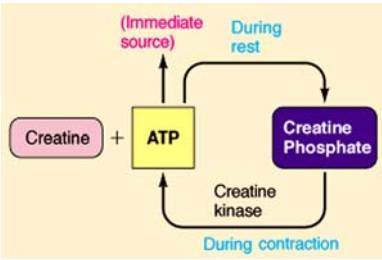
Skeletal Muscle Metabolism

- **Contraction-Relaxation Steps Requiring ATP**
  - Splitting of ATP by myosin ATPase provides energy for power stroke of cross bridge
  - Binding of fresh molecule of ATP to myosin lets bridge detach from actin filament at end of power stroke so cycle can be repeated
  - Active transport of Ca^{2+} back into sarcoplasmic reticulum during relaxation depends on energy derived from breakdown of ATP
- **Energy Sources for Contraction**
  - Transfer of high-energy phosphate from creatine phosphate to ADP
    - First energy storehouse tapped at onset of contractile activity
  - Oxidative phosphorylation (citric acid cycle and electron transport system)
    - Takes place within muscle mitochondria if sufficient O_2 is present
  - Glycolysis
    - Supports anaerobic or high-intensity exercise



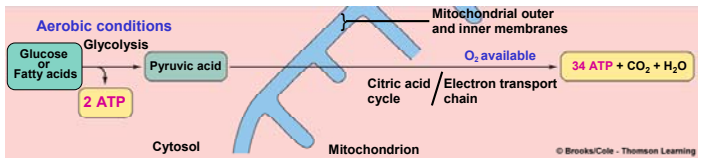
Skeletal Muscle Metabolism

- **Transfer of high-energy phosphate from creatine phosphate to ADP**
  - First energy storehouse tapped at onset of contractile activity
  - Reversible reaction
    - Stores Creatine Phosphate when ATP ↑
    - Contributes ATP when ATP ↓
  - Short duration or bursts of exercise
    - ~160g or 12.5 kcal
    - E.g. 100 m running



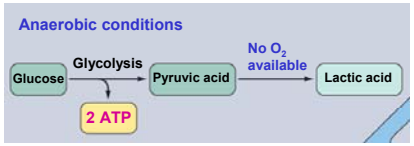
Skeletal Muscle Metabolism

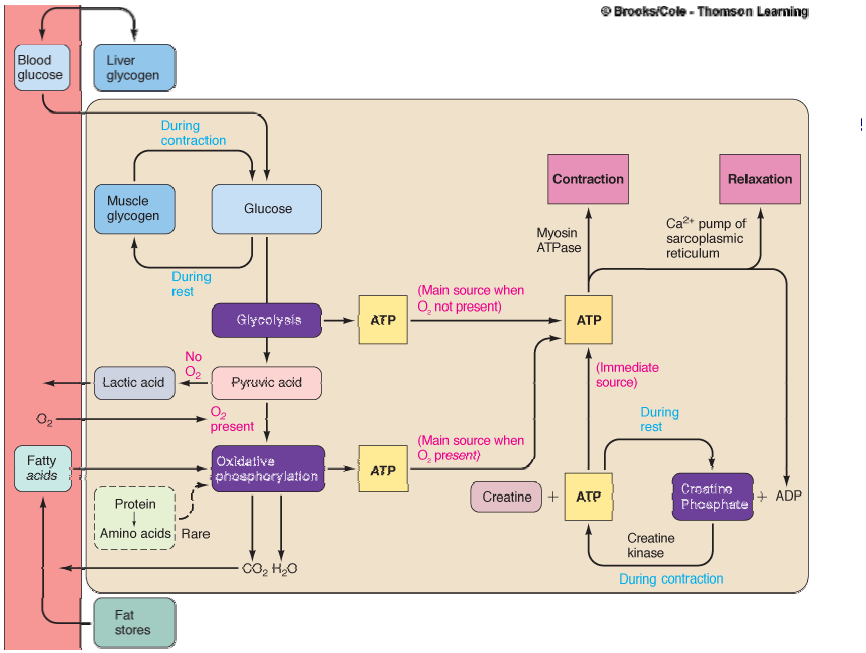
- **Oxidative phosphorylation (citric acid cycle and electron transport system)**
  - Takes place within muscle mitochondria
  - Moderate exercise
  - Sufficient O_2 must be present
    - ***Aerobic*** or ***endurance-type exercise***
    - Deeper, faster breathing
    - ↑ Heart rate and contraction
    - Dilation of blood vessels
    - Myoglobin
      - Similar to hemoglobin
      - Increase the transfer and store O2 in muscle cells
  - Uses glucose or fatty acids
    - Glucose derived from muscle glycogen (chains of glucose) stores
      - Limited (~ 150g or 600 kcal)
      - Athletes can store more (2000 kcal for marathon runners)
    - Glucose derived from liver glycogen stores
      - Limited (~80-200g or 320-800 kcal)
    - Fatty acids derived from lipolisis
      - Plenty of these! (~15kg or 135.000 kcal)



Skeletal Muscle Metabolism

- **Anaerobic or high-intensity exercise**
  - Limit to the amount of O2 that can be delivered
    - Respiratory and cardiac maxima
    - Muscle contraction constricts the blood vessels
- **Glycolysis**
  - Supports anaerobic or high-intensity exercise
  - Less efficient but much faster than oxidative phosphorylation
  - Quickly depletes glycogen supplies
  - Lactic acid is produced
    - Soreness that occurs during the time (not after) intense exercise
  - Energy depletion and ↓ pH contribute to muscle fatique

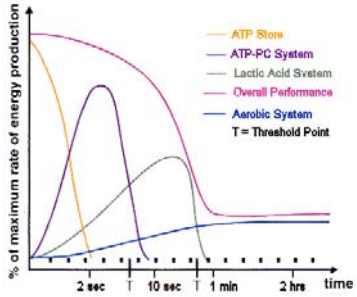




Skeletal Muscle Metabolism

Sport	Creatine & Glycolisis	Glycolysis & Oxidative	Oxidative
Golf swing	95	5	
Sprints	90	10	
Volleyball	80	5	15
Gymnastics	80	15	5
Tennis	70	20	10
Basketball	60	20	20
Soccer	50	20	30
Skiing	33	33	33
Rowing	20	30	50
Distance running	10	20	70
Swimming 1.5km	10	20	70

Table adapted from Fox E. L. et al, The Physiological Basis for Exercise and Sport, 1993



Fatigue

- **Contractile activity can not be sustained indefinitely → Fatigue**
- **Muscle Fatigue**
  - Occurs when exercising muscle can no longer respond to stimulation with same degree of contractile activity
  - Defense mechanism that protects muscle from reaching point at which it can no longer produce ATP
  - Underlying causes of muscle fatigue are unclear. Implicated
    - ADP increase (interferes with cross-bridges and Ca^{2+} uptake in the SR)
    - Lactic acid accumulation (may interfere with key enzymes in energy-producing pathways)
    - Accumulation of extracellular K^+ (decrease in membrane potential)
    - Depletion of glycogen
- **Central Fatigue**
  - Occurs when CNS no longer adequately activates motor neurons supplying working muscles
  - Often psychologically based
    - Discomfort, boredom or tiredness
  - Mechanisms involved in central fatigue are poorly understood
- **Recovery**
  - Excess postexercise O_2 consumption (EPOC) helps
    - Restore Creatine Phosphate (few minutes)
    - Replenish ATP
    - Convert Lactic acid to pyruvate for oxidative ATP generation
    - Cover increased general O2 demand because of higher temperature
  - Nutrient replenishment (1-2 days after a marathon)

Major Types of Muscle Fibers

- **Classified based on differences in speed of contraction and ATP hydrolysis and synthesis**
- **Three major types**
  - Slow-oxidative (type I) fibers
    - Low intensity contractions for long periods of time (e.g. back)
  - Fast-oxidative (type IIa) fibers
    - High intensity for medium periods (e.g. limbs)
  - Fast-glycolytic (type IIx) fibers
    - Rapid forceful movements (e.g. arms)
- **Fast fibers can contract ~ 10 x faster**
- **Oxidative fibers contain more mitochondria and myoglobin and have a richer blood supply → red meat**

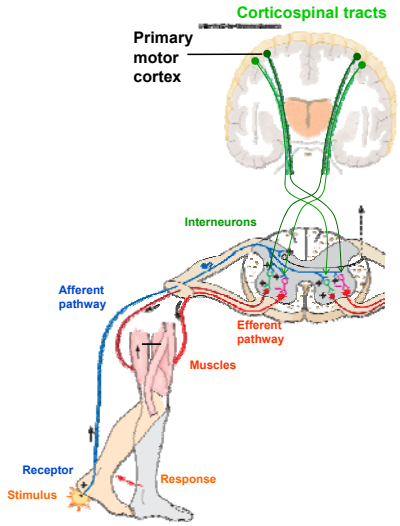
	TYPE OF FIBER		
CHARACTERISTIC	Slow-oxidative (Type I)	Fast-oxidative (Type IIa)	Fast-glycolytic (Type IIb)
Myosin-ATPase Activity	Low	High	High
Speed of Contraction	Slow	Fast	Fast
Resistance to Fatigue	High	Intermediate	Low
Oxidative Phosphorylation Capacity	High	High	Low
Enzymes for Anaerobic Glycolysis	Low	Intermediate	High
Mitochondria	Many	Many	Few
Capillaries	Many	Many	Few
Myoglobin Content	High	High	Low
Color of Fiber	Red	Red	White
Glycogen Content	Low	Intermediate	High

Muscle Adaptation & Repair

- **Muscle has a high degree of plasticity**
  - Improvement of oxidative capacity
    - From regular aerobic exercise
    - Capillaries and mitochondria increase
  - Hypertrophy
    - From anaerobic high intensity exercise
    - Muscle fiber diameter increases (more actin and myosin)
    - Mainly fast-glycolytic fibers
- **Testosterone and other steroids increase the synthesis of actin and myosin**
  - Steroid abuse
- **Fast muscle fibers are interconvertible**
  - Oxidative ↔ glycolytic
  - But NOT fast ↔ slow
- **Muscle atrophy**
  - Disuse atrophy (e.g. space exploration)
  - Denervation atrophy (e.g. paralysis)
- **Muscle has limited repair cababilities**
  - Satellite cells can create a few myoblasts which fuse and create a few muscle fibers

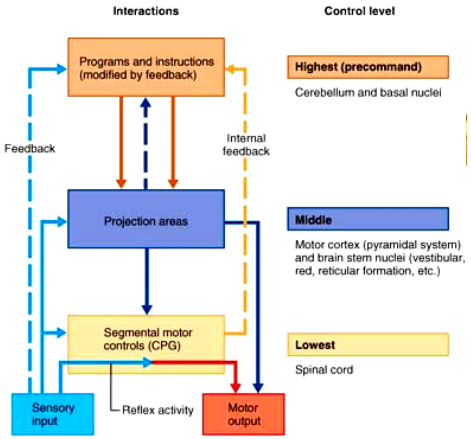
Control of Motor Movement

- **Input to motor-neurons**
  - Input from afferent neurons
  - Input from primary motor cortex
- **Input from afferent neurons**
  - Usually through intervening interneurons
  - Responsible for spinal reflexes (e.g. withdrawal)
- **Input from the primary motor cortex**
  - Corticospinal motor system beginning from the motor cortex
  - Responsible for fine voluntary movement



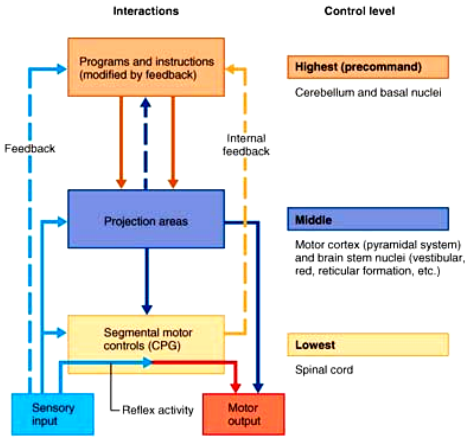
Control of Motor Movement

- **Afferent sensory neuron provide continues feedback**
- **Three levels of control and coordination**
  - The Segmental Level
  - The Projection Level
  - The Precommand Level



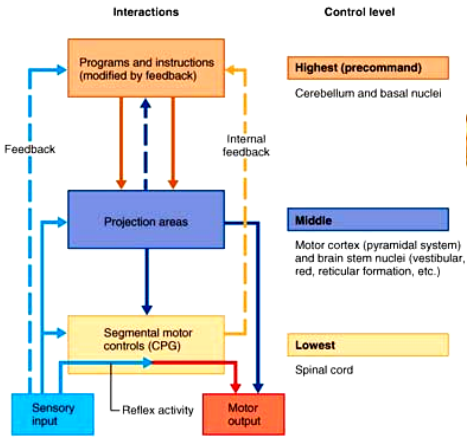
Control of Motor Movement

- **Three levels of control and coordination**
  - The Segmental Level
    - Spinal cord circuits including central pattern generators (CPGs)



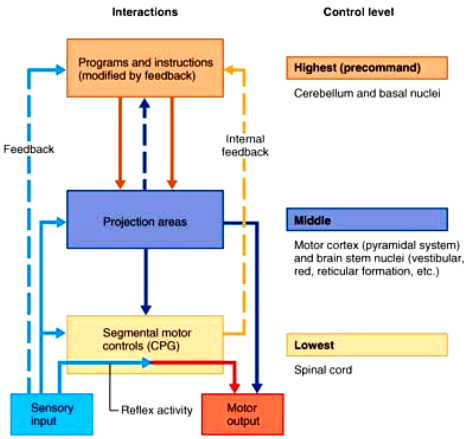
Control of Motor Movement

- **Three levels of control and coordination**
  - The Projection Level
    - Premotor and Primary motor cortex
      - Plan and execute voluntary movements
    - Brain stem
      - Multineural reflexes
      - Regulation of involuntary control of body posture



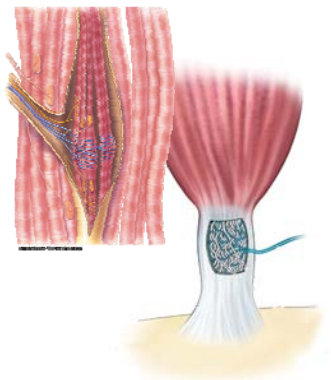
Control of Motor Movement

- **Three levels of control and coordination**
  - The Precommand Level
    - Cerebellum
      - Coordination of movement
      - Maintenance of balance
      - Control of eye movements
    - Basal Nuclei
      - Inhibit muscle tone
      - Select and maintain purposeful motor activity while suppressing unwanted patterns of movement
      - Monitor and coordinate slow and sustained contractions



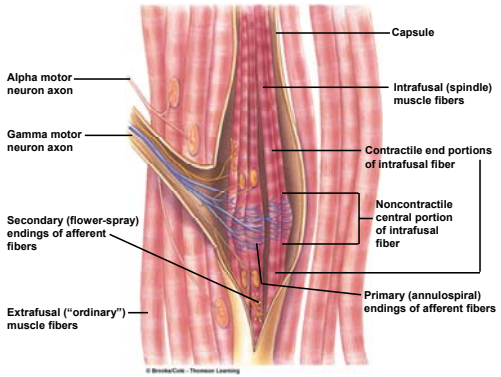
Muscle Receptors

- **Receptors are necessary to plan and control complicated movement and balance**
- **The brain receives information from all muscles and joints in the body → proprioception**
- **Two types of muscle receptors**
  - Muscle spindles
    - Monitor muscle length and tension
  - Golgi tendon organs
    - Monitor whole muscle tension



Muscle Receptors

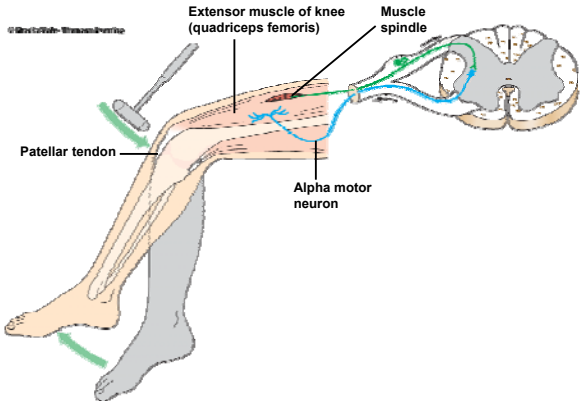
- **Muscle Spindles**
  - Consist of collections of specialized muscle fibers known as intrafusal fibers
    - Lie within spindle-shaped connective tissue capsules parallel to extrafusal fibers
    - Have contractile ends and a non-contractile central portion
  - Each spindle has its own private nerve supply
    - Plays key role in stretch reflex
    - Efferent
      - Gamma motor neurons*
    - Afferent
      - Primary (annulospiral) endings (in the central portion)
      - Secondary (flower-spray) endings (at the end segments)



* Efferent neurons to extrafusal fibers are called alpha motor neurons

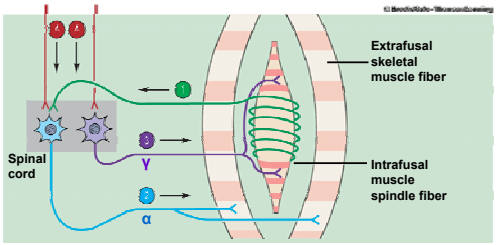
Muscle Receptors

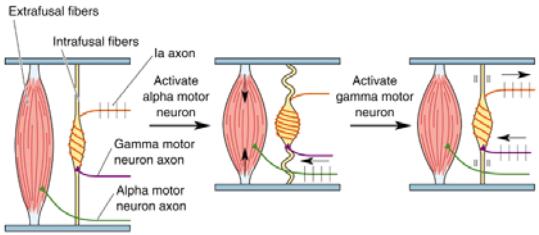
- **Stretch Reflex**
  - Primary purpose
    - Resist tendency for passive stretch of extensor muscles by gravitational forces when person is standing upright
  - Classic example is patellar tendon, or knee-jerk reflex



Muscle Receptors

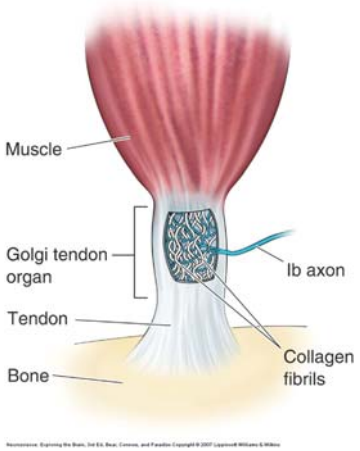
- **Coactivation of alpha and gamma motor neurons**
  - Spindle coactivation during muscle contraction
  - Spindle contracted to reduce length
    - With no coactivation
      - Slackened spindle
      - Not sensitive to stretch
  - Adjustment to keep muscle spindles sensitive to stretch





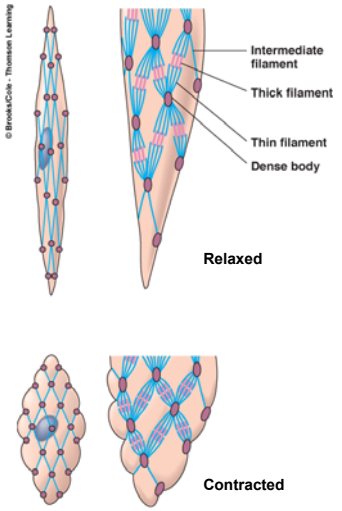
Muscle Receptors

- **Gogli Tendon Organs**
  - Provide necessary feedback for overall muscle tension
    - Integrates all factors which influence tension
  - Specialized nerve fibers embedded in the tendons
  - Stretch of tendons exerts force on nerve endings
    - Increase firing rate
  - Part of this information reaches conscious awareness
    - We are aware of tension (but not of length) of muscles



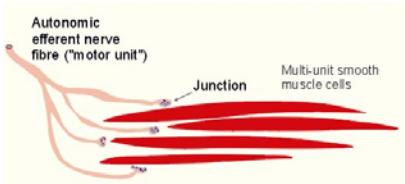
Smooth Muscle

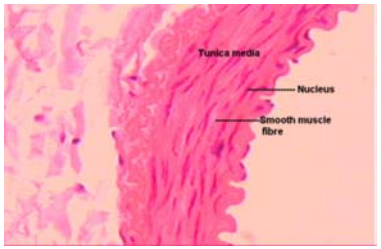
- **Found in walls of hollow organs and tubes**
- **No striations**
  - Filaments do not form myofibrils
  - Not arranged in sarcomere pattern found in skeletal muscle
- **Spindle-shaped cells with single nucleus**
- **Cells usually arranged in sheets within muscle**
- **Cell has three types of filaments**
  - Thick myosin filaments
    - Longer than those in skeletal muscle
  - Thin actin filaments
    - Contain tropomyosin but lack troponin
  - Filaments of intermediate size
    - Do not directly participate in contraction
    - Form part of cytoskeletal framework that supports cell shape
- **No sacromeres**
  - Have dense bodies containing same protein found in Z lines



Smooth Muscle

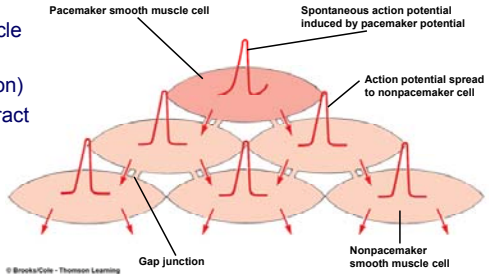
- **Two major types**
  - Multiunit smooth muscle
  - Single-unit smooth muscle
- **Multiunit Smooth Muscle**
  - Neurogenic (nerve initiated)
  - Consists of discrete units that function independently of one another
  - Units must be separately stimulated by nerves to contract
  - Found
    - In walls of large blood vessels
    - In large airways to lungs
    - In muscle of eye that adjusts lens for near or far vision
    - In iris of eye
    - At base of hair follicles

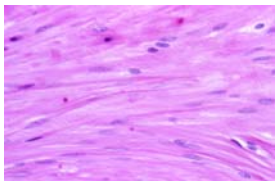




Smooth Muscle

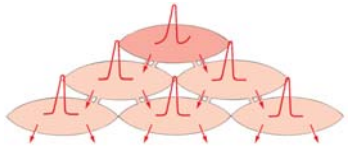
- **Single-unit Smooth Muscle**
  - Most smooth muscle
  - Also called visceral smooth muscle
  - Self-excitable (does not require nervous stimulation for contraction)
  - Fibers become excited and contract as single unit
    - Cells electrically linked by gap junctions
    - Can also be described as a functional syncytium
  - Contraction is slow and energy-efficient
    - Slow cross-bridge cycling
      - Cross-bridges "latch-on" the thin filaments → muscle maintains tension
    - Well suited for forming walls of distensible, hollow organs

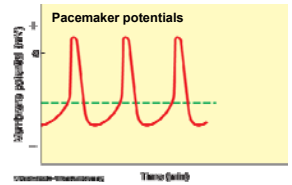


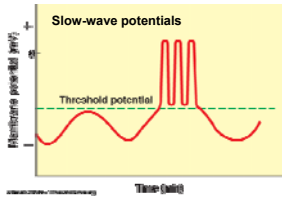


Smooth Muscle

- **Single-unit Smooth Muscle Excitation**
  - Myogenic activity (contraction initiated by the muscle itself)
  - Certain non-contractile cells can initiate their own APs (self-excitable)
    - Small number distributed at key locations
  - Electrical activity of two types
    - Pacemaker potentials
      - Cells depolarize and initiate APs spontaneously and regularly
    - Slow-wave potentials
      - Cells depolarize and hyperpoplarize rhythmically but not always initiate APs
  - Once initiated the action potential spreads to the contractile cells

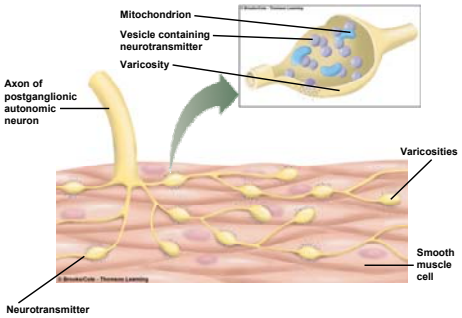






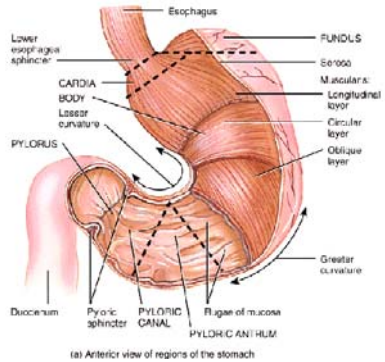
Smooth Muscle

- **Smooth muscle activity**
  - Gradation
    - All muscle fibers are contracting
    - Tension can be modified by varying the intracellular Ca^{2+}
      - Ca^{2+} from the ECF (no SR)
  - Tone
    - Many single-unit smooth muscle cells maintain a low level of tension (tone) even in the absence of APs
  - Effect of autonomic nervous system
    - Typically innervated by both branches
    - Does not initiate APs but can modify the activity (rate and strength of contraction)
      - Enhancement or inhibition
    - Smooth muscle cells interact with more than one neurons



Smooth Muscle

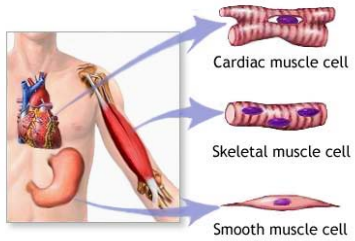
- **Smooth muscle activity**
  - Tension-Length relationship
    - Increased tension when stretched
      - Can produce near-maximal tension at lengths 2.5 x the normal length
    - When stretched, smooth muscle has the ability to relax
    - These two properties are very important for hollow organs
      - Can accommodate varying volumes while being able to produce adequate contractile force

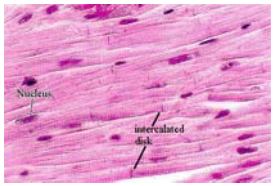


(a) Anterior view of regions of the stomach

Cardiac Muscle

- **Found only in walls of the heart**
- **Combines features of skeletal and smooth muscle**
  - Striated
  - Cells are interconnected by gap junctions
  - Fibers are joined in branching network
  - Innervated by autonomic nervous system
- **You will learn more about cardiac muscle in Cardiac Physiology**





Next Lecture …

No more of me!

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