**Length-Tension Relationship**
- Amount of tension and force of contraction depends on how stretched or contracted muscle was before it’s stimulated
- If overly contracted at rest, a weak contraction results
  - If Sarcomere is < 60% or >175% of original length develop no tension
- Optimum resting length produces greatest force when muscle contracts
  - CNS adjusts our muscle tone – state of partial contraction
  - Maintains optimum length – i.e., always ready for action

**Behavior of Whole Muscles**
- **threshold** - minimum voltage necessary to generate an action potential in the muscle fiber and produce a contraction
- **twitch** – a quick cycle of contraction and relaxation
- Subthreshold electrical stimulus causes = no contraction

**Contraction Strength of Twitches**
- **subthreshold stimulus** – no contraction at all
- **at threshold intensity and above** - a twitch is produced
  - Twitches caused by increased voltage are no stronger than those at threshold
  - I.e., muscles follow all-or-none law (contracting to its maximum or not at all)
- Not exactly true
  - Twitches vary in strength depending upon:
    - Stimulus frequency - stimuli arriving closer together produce stronger twitch
    - Concentration of Ca^{2+} in sarcoplasm can vary the frequency
    - How stretched muscle was before it was stimulated
    - Temperature - warmed up muscle contracts more strongly – enzymes work more quickly
    - Ph: if low in sarcoplasm weakens contraction - fatigue
    - Hydration of muscle affects overlap of actin & myosin

**Phases of twitch contraction**
- **Latent Period**: time required for excitation, excite/coupling and tension
  - Internal tension, no shortening
- **Contraction phase**: sliding filaments
  - External tension
- **Relaxation phase**: SR reabsorbs Ca^{2+}, myosin releases actin - tension declines
  - Muscle returns to resting length
  - Twitch lasts from 7 to 100 msec

**Recruitment and Stimulus Intensity**
- Stimulating nerve with higher and higher voltages produces stronger contractions
  - Higher voltages excite more nerve fibers in the motor nerve which stimulates more motor units to contract
- Recruitment or multiple motor units (MMU) summation – bringing more motor units into play
**Twitch Strength & Stimulus Frequency**

- Twitch muscle twitches
- Stimuli

**Treppe:** stimulus right after relaxation following tension is greater than previous.

**Incomplete tetanus:** stimuli before muscle relaxes = summation of twitches – rapid cycles of contr. & relax. Tension rises!

**Complete tetanus:** freq so great there is no relaxation

**Fatigue**

- Muscle shortens, tension remains constant
- Movement
- Muscle develops tension but does not shorten
- No movement

**Isometric and Isotonic Phases of Contraction**

- at the beginning of contraction – **isometric phase**
  - muscle tension rises but muscle does not shorten
- when tension overcomes resistance of the load
  - tension levels off
- muscle begins to shorten and move the load – **isotonic phase**

**Muscle Metabolism**

- all muscle contraction depends on **ATP**
- ATP supply depends on availability of:
  - oxygen
  - organic energy sources such as glucose and fatty acids
- two main pathways of ATP synthesis
  - **aerobic respiration**
    - produces far more ATP
    - less toxic end products (CO₂ and water)
    - requires a continual supply of oxygen
  - **anaerobic fermentation**
    - produce ATP in the absence of O₂
    - yields little ATP and lactic acid, a major factor in muscle fatigue

**Overview of ATP Production**

- ATP consumed within 60 seconds of formation

**Glycogen:**
- Stored in Liver, Skeletal muscles, heart
- Can be changed into glucose

**Modes of ATP Synthesis During Exercise**

- At rest most ATP generated by aerobic respir. of fatty acids
- During short intense exercise lactic acid formation increases from glycogen – ATP is used up quickly until Phosphocreatine is depleted
- During anaerobic fermentation until Phosphocreatine is depleted
- Aerobic respiration supported by cardiorespiratory bringing O₂ to muscles
Immediate Energy Needs

Fatigue

- Causes of muscle fatigue
  - ATP synthesis declines as glycogen is consumed
  - ATP shortage slows down the Na⁺ - K⁺ pumps
  - lactic acid lowers pH of sarcoplasm
    - inhibits enzymes involved in contraction,
    - inhibits enzymes used in ATP synthesis
  - release of K⁺ with each action potential causes the accumulation of extracellular K⁺
    - hyperpolarizes the cell and makes the muscle fiber less excitable
  - motor nerve fibers use up their Achetelcholine
  - CNS fatigues ??????? less signal output to skeletal muscles

Endurance

- endurance – ability to maintain high-intensity exercise for > 4 to 5 minutes
  - determined in large part by one’s maximum oxygen uptake (VO₂max)
  - maximum oxygen uptake – point at which rate of oxygen consumption reaches a plateau and does not increase further with added workload

Physiological Classes of Muscle Fibers

- slow oxidative (SO), slow-twitch, red, or type I fibers
  - Lots of mitochondria, myoglobin and capillaries – deep red color
  - adapted for aerobic respiration – slow to fatigue
  - long lasting twitch (~100 msec)

- fast glycolytic (FG), fast-twitch, white, or type II fibers
  - few mitochondria, myoglobin, and blood capillaries – pale appearance
  - adapted for quick responses – fast to fatigue (lactic acid)
  - rich in enzymes of phosphagen and glycogen-lactic acid systems generate lactic acid causing fatigue
  - fast twitches (~ 7.5 msec)

- ratio of different fiber types have genetic predisposition

Oxygen Debt

- When exercise stops, rate of oxygen uptake does not immediately return to pre-exercise levels
- Because oxygen debt accumulated during exercise:
  - When oxygen is withdrawn from hemoglobin and myoglobin
  - And because of O₂ needed for metabolism of lactic acid produced by anaerobic respiration
  - Turn it back to pyruvic acid then to glycogen
**Strength and Conditioning**

- muscles can generate more tension than bones and tendons can withstand
- muscular strength depends on:
  - primarily on muscle size
  - fascicle arrangement
    - pennate are stronger than parallel, and parallel stronger than circular
  - size of motor units
  - multiple motor unit summation – recruitment of many motor units
  - temporal summation
    - nerve impulses usually arrive at a muscle in a series of closely spaced action potentials
  - length – tension relationship (resting muscle at optimal length)
  - fatigue

**Resistance Training** (weight lifting)

- contraction of a muscles against a load that resist movement
- Couple times a week
- Hypertrophy
- more myofilaments and myofibrils synthesized

**Endurance Training** (aerobic exercise)

- improves fatigue resistant muscles
- slow twitch fibers produce more mitochondria, glycogen, and acquire a greater density of blood capillaries
- improves skeletal strength
- increases red blood cell count and oxygen transport capacity of the blood
- enhances cardiovascular, respiratory, and nervous systems

**Cardiac Muscle**

- Location?
- Function?
- Required properties of cardiac muscle
  - Autorhythmic cells
  - contraction with regular rhythm
  - muscle cells of each chamber must contract in unison
  - contractions must last long enough to expel blood
  - must be highly resistant to fatigue

**Cardiac Muscle**

-autorhythmic cells!!!!
- autonomic nervous system can influence it
- slow twitches!!
- uses aerobic respiration almost exclusively
  - rich in myoglobin and glycogen
  - has especially large mitochondria
- highly fatigue resistant

**Smooth Muscle**

- myocytes have a fusiform shape & one nucleus
- no visible striations
- Actin and myosin do not overlap
- z discs absent
- No troponin
- Cytoplasm has:
  - dense bodies = Like z disks
  - protein plaques on the inner face of the plasma
  - cytoskeleton of intermediate filaments: attach to the membrane plaques and dense bodies
- Ca²⁺ needed for muscle contraction comes from ECF
- ANS controlled
- capable of mitosis (hyperplasia)
2 Types of Smooth Muscle

- **multunit smooth muscle**
  - occurs in some of the largest arteries and pulmonary air passages, in piloerector muscles of hair follicle, and in the iris of the eye
  - Single neuron stimulates many myocytes
    - i.e., like a motor unit

- **single-unit smooth muscle** (visceral muscle)
  - myocytes are electrically coupled to each other by gap junctions
  - stimulate each other and a large number of cells contract as a single unit
  - i.e., each cell does NOT have to be stimulated directly by a motor neuron

**Layers of Visceral Smooth Muscle**

- **Epithelium**
- **Mucosa**
  - Lamina propria
  - Muscularis mucosae
- **Muscularis externa**
  - Circular layer
  - Longitudinal layer

**Stimulation of Smooth Muscle**

- Involuntary and can contract without nervous stimulation!!
  - chemical stimuli: hormones, carbon dioxide, low pH, and oxygen deficiency
  - in response to stretch
  - Cold stimulus – (vasa and scrotum)
  - Stretching - peristalsis
- most innervated by ANS nerve fibers
  - can trigger and modify contractions
  - Neurotransmitters: acetylcholine or norepinephrine

**Contraction and Relaxation**

- contraction is triggered by Ca\(^{2+}\), ATP, and sliding thin past thick myofilaments
- contraction begins in response to Ca\(^{2+}\) that enters the cell from ECF
  - voltage, ligand, and mechanically-gated (stretching) Ca\(^{2+}\) channels open (Ca\(^{2+}\) enters cell)
- Ca\(^{2+}\) binds to calmodulin
  - activates myosin light-chain kinase – adds phosphate to myosin head
  - This activates myosin ATPase - hydrolyzing ATP – allowing myosin head to move Actin
  - thick filaments pull on thin ones, this pulls on dense bodies and membrane plaques
Figure 11.24

**Activation of Contraction in Smooth vs. Skeletal Muscle**

**Stretching Smooth Muscle**

- **stretch** can open mechanically-gated calcium channels in the sarcolemma causing contraction
  - **peristalsis** – waves of contraction brought about by food distending the esophagus or feces distending the colon
    - propels contents along the organ
- **stress-relaxation response** (receptive relaxation) - helps hollow organs gradually fill (urinary bladder)
  - when stretched, tissue briefly contracts then relaxes – helps prevent emptying while filling

**Contraction and Stretching**

- smooth muscle contracts forcefully even when greatly stretched
  - Remember what happens when Skeletal muscle is stretched?
- **plasticity** – the ability to adjust its tension to the degree of stretch
  - a hollow organ such as the bladder can be greatly stretched yet not become flabby when it is empty

**Dense body**

**Intermediate filaments of cytoskeleton**

**Actin filaments**

**Myosin**

**Figure 11.24**

(a) Relaxed smooth muscle cells

(b) Contracted smooth muscle cells