UNIT II MUSCULOSKELETAL SYSTEMS

Musculoskeletal System

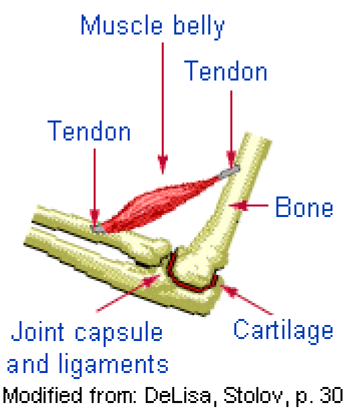
The **musculoskeletal system** consists of the skeletal system -- bones and joints (union of two or more bones) -- and the ***skeletal* muscle system** (voluntary or striated muscles). These two systems work together to provide basic functions that are essential to life, including:

- Protection: protects the brain and internal organs
- Support: maintains upright posture
- Blood cell formation: *hematopoiesis*
- Mineral homeostasis
- Storage: stores fat and minerals.
- Leverage: A lever is a simple machine that magnifies speed of movement or force. The levers are mainly the long bones of the body and the axes are the joints where the bones meet.

Tissues

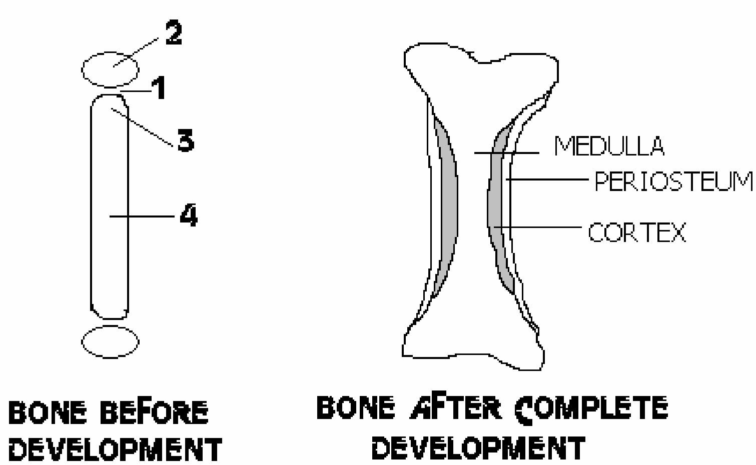
There are 5 basic tissues comprising the musculoskeletal system:

1. **bones**,
2. **ligaments** (attaching bone to bone)
3. **cartilage** (protective gel-like substance lining the joints and intervertebral discs),
4. **skeletal muscles**, and
5. **Tendons** (attaching muscle to bone).



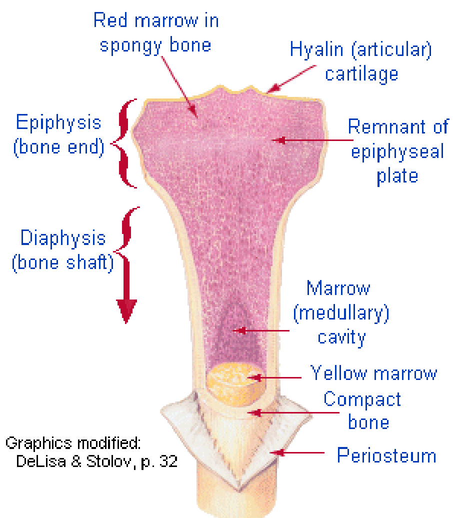
Schematic representation of the typical arrangement of musculoskeletal tissues

Tissues:
Bones, Cartilage, and Ligaments



1- PHYSIS (GROWTH PLATE)
2- EPIPHYSIS
3- METAPHYSIS
4- DIAPHYSIS

Cutaway section of an adult long bone. Only a residual line remains of the epiphyseal plate (where bone growth occurs).



A living **bone** consists of three layers, all honeycombed with nerves and blood vessels:
1) the *periosteum*, or outside skin of the bone;
2) the hard *compact bone*, supporting the weight of the body; and
3) *spongy bone* (bone marrow). Spongy bone occurs at the ends of long bones and is less dense than compact bone. The spongy bone of the femur, humerus, and sternum contains **red marrow**, producing red blood cells (which carry oxygen), white blood cells (which fight infection), or platelets (that help stop bleeding). **Yellow marrow**, at the center, is used to store fats.

A specialized form of connective tissue, bone consists of both organic components (e.g. collagen) and inorganic minerals (calcium, phosphorus, magnesium, potassium, and sodium). The minerals calcium and phosphorus give bone its hardness, strength, and rigidity to resist compressive forces. The collagen fibers impart flexibility. Magnesium, sodium, potassium, and other trace elements act as "mortar" bonding the calcium and phosphorous. The bone cells themselves are embedded in mineralized calcium "matrix" and collagen fibers.

Bone continuously remakes itself: New bone is produced and old bone is removed. *Osteoblasts*, the cells responsible for making bone, maintain the balance of calcium in the blood and bone. When this balance is disrupted, as in osteoporosis, the removal of bone exceeds its production, making bone thin and brittle, thus more easily fractured. The intestines, vitamin D, the kidney, parathyroid gland, and sex and adrenal hormones also play important roles in bone/calcium balance. In long bone, illustrated above, growth occurs at the **diaphysis** side (shaft) of the **epiphyseal plate**, thus increasing the length of the shaft. Long bone growth stops when the hyaline cartilage stops reproducing itself and fully converts to bone.

A **joint**, or *articulation*, is a union of two or more bones. **Ligaments** attach bone to bone, stabilizing and strengthening joints and determining the range of motion. **Cartilage**, a gel-like

substance high in <u>*proteoglycans*</u>, provides protective cushioning. There are three types of cartilage:
1) <u>fibrocartilage</u> (found in intervertebral discs),
2) <u>elastic cartilage</u> (found in the external ear and epiglottis), and
3) hyaline cartilage. **Hyaline** (or *articular*) **cartilage** is the most important cartilage: It serves as the "original" skeleton in the embryo from which bones develop; it spurs growth of long bones; and it lines and protects <u>joints</u>.

General Classifications of Bones

1. Long Bones -- "longer than they are wide:" clavicle, humerus, radius, ulna, femur, tibia, fibula, metatarsals, metacarpals. Purpose: provide support and serve as the <u>interconnected set of levers</u> and linkages that allow us to create movement. (formed from hyaline/articular cartilage)
2. Short Bones: carpals and tarsals: consist mainly spongy bone covered with a thin layer of compact bone. Purpose: allow movement, provide elasticity, flexibility, & shock absorption.
3. Flat Bones: ribs, sternum and scapula. Purpose: protect and provide attachment sites for muscles.
4. Irregular Bones: skull, pelvis, and vertebrae. Purposes: support weight, dissipate loads, protect the spinal cord, contribute to movement and provide sites for muscle attachment.
5. Sesamoid Bones: a short bone embedded within a <u>tendon</u> or <u>joint capsule</u>, i.e. patella. Purpose: alter the angle of insertion of the muscle.

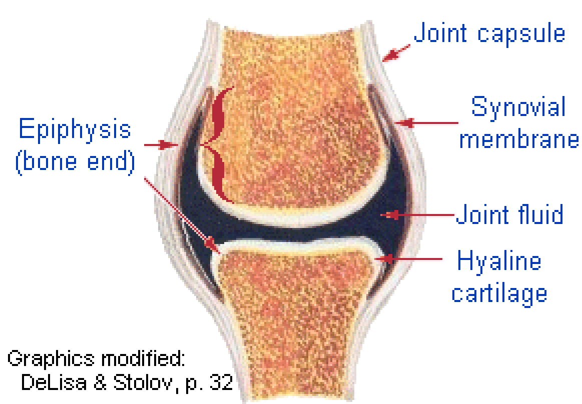
Joints

Joints are classifiied into three groups: 1) immovable (**fibrous**) joints, e.g. skull bones; 2) slightly movable (**cartilagenous**) joints, e.g. intervertebral discs; and 3) freely movable (**synovial**) joints, e.g. limb joints. Synovial joints permit the greatest degree of flexibility and have the ends of bones covered with a connective tissue (synovial membrane) filled with joint (synovial) fluid.

A typical synovial joint, seen at right, has four main featues:

1. *joint capsule* - the joint enclosure, reinforced by and strengthened with ligaments
2. *synovial membrane* - a continuous sheet of connective tissue lining the capsule; its cells produce synovial fluid that lubricates the joint and prevents the two cartilage caps on the bones from rubbing together
3. *synovial fluid* - produced by the synovial membrane, the fluid lubricates the joint. In the normal joint, very little fluid (less than 5cc) exists in the cavity.
4. *hyaline (articular) cartilage* - where the bones actually "meet"

Typical synovial joint



Human Skeleton

The average human *adult* skeleton consists of 206 bones, attached to the muscles by tendons. Babies are born with 270 soft bones - about 64 more than an adult. These will fuse together by the age of twenty or twenty-five into the 206 hard, permanent bones.

The skeleton has two main parts: the *axial* skeleton and the *appendicular* skeleton. The axial skeleton consists of the skull, the spine, the ribs and the sternum (breastbone) and includes 80 bones. The appendicular skeleton, consisting of 126 bones, includes two limb girdles (the shoulders and pelvis) and their attached limb bones.

Axial Skeleton (80 bones)

- skull - consiting of 1) the cranium (which encloses and protects the brain) and 2) the facial skeleton. The upper teeth are embedded in the maxilla; the lower teeth, in the mandible.
- mandible (jaw) - the only freely movable bone of the skull
- ribs, sternum (breastbone) - comprising the "thorax"/thoracic cage, protecting the heart and lungs
- vertebral column - the "spine"

The vertebral column (illustrated below and to the left) transmits the body weight from the head, throax, and abdomen to the lower extremities and encloses and protects the spinal cord. Each vertebra has essentially the same basic components, with some variation based on location and allowed movements.

VC divided into various segments depending upon the location in the body

1) In the neck it is called **cervical spine.**

Movements: to rotate, flex forward, flex sideways, and extend backward;

2) In the chest it is called **thoracic spine**

MOVEMENT: to rotate; and

3) In the abdomen it is called the **lumbar spine**

MOVEMENTS: to flex forward, flex sideways, and extend backward.

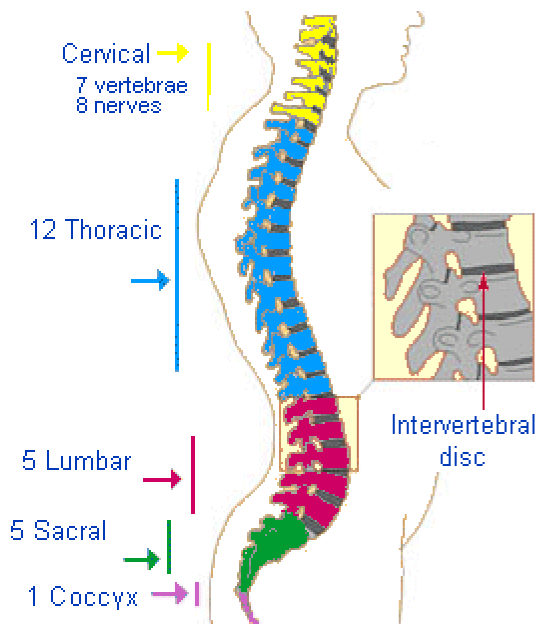
4) In the pelvic region it is called The **sacrum**

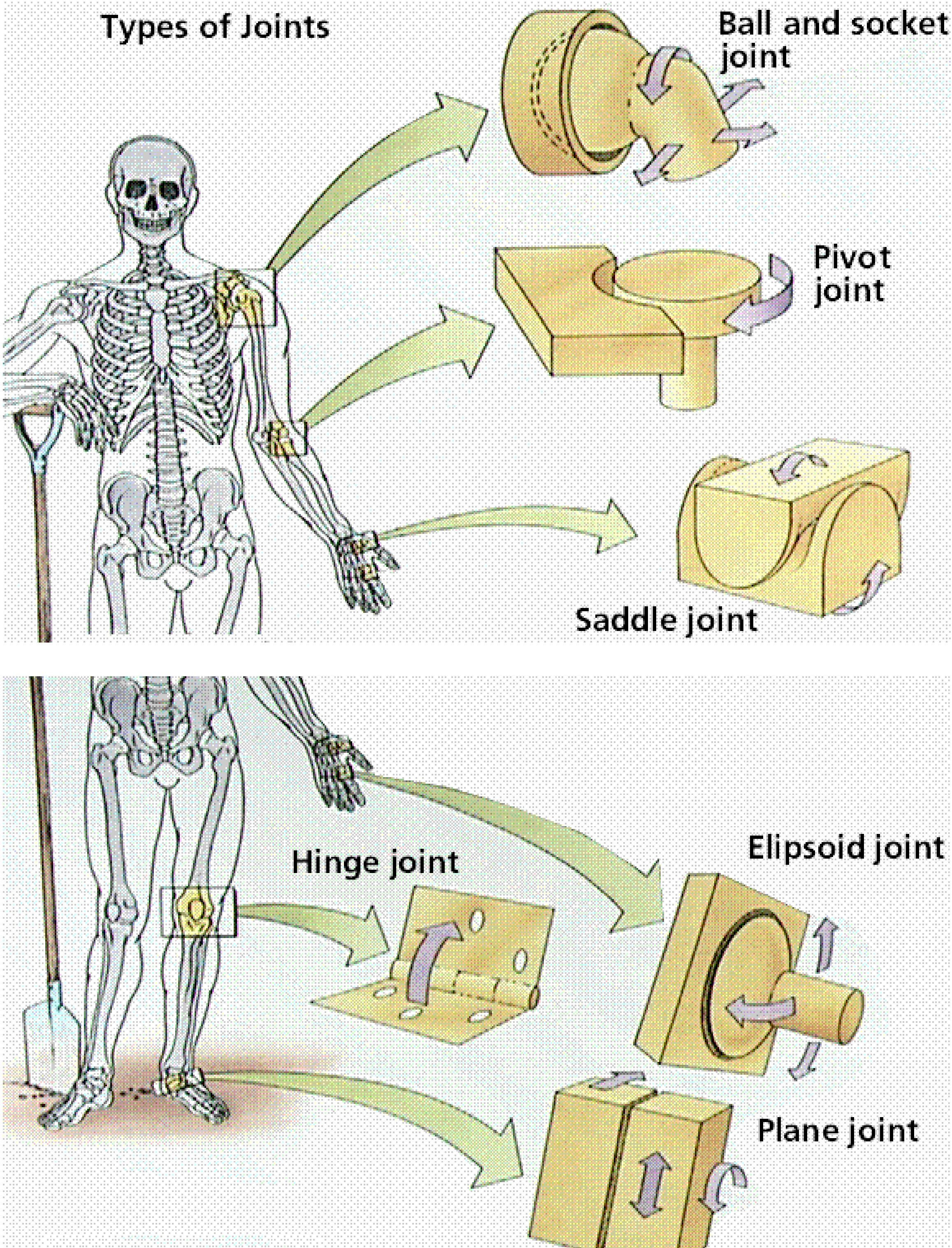
It has a dual character, being part of both the vertebral column and pelvis. As such, it transmits the upper body weight to the lower exterminites.

5) Then we have **COCCYX** which are rudimentary in human beings because we don't have a tail

Appendicular skeleton (126 bones, 64 in the shoulders and upper limbs and 62 in the pelvis and lower limbs)

- **Upper Extremity -** The arms (*humerus* - upper arm bone) are ultimately attached to the thorax, via synovial joints, at the collarbone (*clavicle*) and shoulder bone (*scapula*) (shoulder joint). The scapula is attached to the thoracic cage only by muscles. The elbow joint unites the humerus with the two lower arm bones - the *ulna* and *radius*. Three sets of joints connect the radius and ulna to the bones of the palm (*metacarpals*), via the eight small wrist *carpals*. Further, the knuckles (*metacarpophalangeal*, or MCP, joints) connect the metacarpals to the proximal *phalanx* of the fingers. Each finger has 3 phalanges (proximal, middle, distal), except the thumb which has only two.
- **Lower Extremity -** The pelvis transmits the upper body weight from the sacrum (at the sacroiliac joint) to the legs. It begins as 3 hip bones (*ilium*, *ischium*, and *pubis*) which fuse together when growth is completed. The hip joint unites the pelvis to the thigh bone (*femur*); the knee joint, which includes the knee cap (*patella*), links the femur to the lower leg bones - the *tibia* and *fibula*. The ankle joint links the lower leg bones to the *talus*. The body weight is then transmitted to the heel (*calcaneous*) and to the balls of the feet via the *tarsal* and *metatarsal* foot bones. The toes have a phalangeal structure like the fingers.




Types of Joints
Ball and socket joint
Pivot joint
Saddle joint
Hinge joint
Elipsoid joint
Plane joint

TYPES OF MUSCLES

- Skeletal- striated or voluntary
- Smooth or visceral - non striated or involuntary
- Cardiac- striated with intercalated disks

They can also be described as striated, spindle shaped and nonstriated because of the way the cells may look under a microscope. Each fine thread is called a muscle fiber.

SMOOTH OR VISCERAL MUSCLES

Smooth muscles are unmarked by any distinctive striations. Unattached to bones, they act slowly, so not tire easily and can remain contracted for a long time. They are also called involuntary muscles because they are not under conscious control. Their actions are controlled by the autonomic nervous system. Smooth muscles are found in the walls of the internal organs including the stomach, intestines and blood vessels. They help to push food through the alimentary canal, contract uterus and constrict or dilate the blood vessels.

CARDIAC MUSCLES

Cardiac muscles are found only in the heart. Cardiac muscles are striated and branched and they are involuntary. They contract rapidly and are very strong. Cardiac muscles require a continuous supply of O_2 to be functional.

SKELETAL MUSCLES

A skeletal muscle is composed primarily of striated muscle cells and connective tissue. Most skeletal muscles attach to 2 bones that have a movable joint between them. Muscles extend from one bone across a joint to another bone. One of the two bones is usually more stationary than the other.

The muscle's attachment to this more stationary bone is called its origin. The muscle's attachment to the more movable bone is called the muscle's insertion. The rest of the muscle is called the body of the muscle.

The fleshy body parts are made of skeletal muscles.

Small fluid filled sacs called bursae lie between some tendons and bones, they are made up of connective tissue and are lined with synovial membranes which secrete the slippery lubricating fluid known as synovial fluid.

MICROSCOPIC CHARACTERISTICS OF MUSCLES

Muscle tissues consist of specialized contractile cells or muscle fibers that are grouped together in a highly organized way. Each muscle fiber is filled with two different kinds of very fine and threadlike structures called thick and thin myofilaments.

Thick myofilaments are formed from a protein called myosin and the thin myofilaments are formed mostly of a protein called actin.

The functional unit of the skeletal muscle is the sarcomere it is considered the contractile unit.
When looking under a microscope there are numerous arrangements of both thick and thin myofilaments which lie parallel to each other and overlap with a separating dark band called a Z band. A sarcomere is the length of the myofibrils between the Z bands.

Contraction of a muscle causes the two types of myofilaments to slide toward each other and shorten the sarcomere thus the muscle itself. When the muscle relaxes the sarcomere can return to its resting length and the filaments return to their resting positions.

Calcium is a vitally needed mineral for our muscles to function. Calcium is released into the cytoplasm when the muscle is stimulated to contract. In addition to calcium the shortening of a muscle cell requires energy. This is supplied by the breakdown of ATP molecules or the energy storage molecules of the cell.

FUNCTIONS OF A SKELETAL MUSCLE

The 3 primary functions of the muscular system are:

- movement
- posture or muscle tone
- heat production

For any of these muscles to produce movement in any part of the body it must be able to exert a force upon a movable object. Muscles must be attached to bones for leverage in order to have something to pull against.
Muscles are attached to the bones by nonelastic cords called tendons. Bones are connected by joints. So when the skeletal muscles contracts the bone to which it is attached will move.
Muscles are attached at both ends to bones, cartilage, ligaments, tendons, skin and sometimes to each other.
Muscles move bones by pulling on them. As a rule only the insertion bone moves. The origin bone stays put, holding firm while the insertion bone moves toward it.

REMEMBER...A MUSCLE'S INSERTION BONE MOVES TOWARD ITS ORIGIN BONE.

The muscles of the body are arranged in pairs. One produces movement in a single direction called the prime mover. The other does so in the opposite direction is called the antagonist. This arrangement of muscles with opposite actions is known as an antagonist pair.
The synergist muscle is the muscle that helps the prime mover. A flexor muscle such as the biceps allows for bending. An extensor muscle allows for straightening or extension and an example of this would be the triceps.

Levator and depressor muscles raise and lower body parts. Dilator muscles assist with the decreasing or increasing of openings.

When muscles do their work to move body parts they also produce heat. Between 98.6-99.8 is the normal temperature to maintain body heat.

ATP or adenosine triphosphate must be present for muscles to contract. To produce ATP however, the cell requires O2 and glucose, which is supplied by our circulating blood.

When a muscle is stimulated ATP is released producing heat that our bodies need and the energy for the muscles to contract.

Types of contractions of the muscles
twitch- is a single stimulus
tetany- sustained contracture or lockjaw
treppe- successive threshold of stimuli from the same intensity i.e. warm up of athletes

Muscle Tone

Muscle tone refers to the continued state of partial contraction present in the muscles.
Muscle tone maintains posture and makes sure that the body is ready for action. Skeletal muscles are stimulated to contract by special nerve cells called motor neurons. Acetylcholine is the neurotransmitter that diffuses across the synaptic cleft to stimulate the muscle fiber.
Rigor Mortis literally means the stiffness of death. Within a short time after death, the ATP breaks down so there is no longer any ATP available to bridge the actin and the myosin. Therefore, the myofilaments are blocked in a contracted or rigid position.
The rigor mortis can last for up to 2 days then the protein, which makes up the myofilaments breaks down and the rigor mortis subsides or disappears.

ISOTONIC CONTRACTION
when the tension exceeds the weight load and the muscle shortens and produces movement or when the muscle produces movement between two body parts
ISOMETRIC CONTRACTION
when tension increases but does not exceed the weight load, there is no shortening or movement or to say that there is an increased muscle tension without a production of movement.

MUSCLE FATIGUE
muscle fatigue happens when there is an increase in the lactic acid in the muscles

(lactic acid is a waste product of cell metabolism)

During vigorous activity the blood cannot transport enough O2 for glucose to be utilized. Without O2 muscles start to contract anerobically. After exercise, you must stop to rest and take in the O2 to change the lactic acid back to glucose.

CHARACTERISTICS OF MUSCLES

Skeletal muscle has four primary characteristics that relate to it's functions:

- ***excitability;*** is the ability to receive and respond to a stimulus. In order to function properly, muscles have to respond to a stimulus from the nervous system.
- ***contractility;*** is the ability to shorten or contract. When a muscle responds to a stimulus, it shortens to produce movement.
- ***extensibility;*** means that a muscle can be stretched or extended. Skeletal muscles are often arranged in opposing pairs. When one muscle contracts, the other muscle is relaxed and is stretched.
- ***elasticity;*** is the capacity to recoil or return to the original shape and length after contraction or extension.

Muscle contraction fulfills four important functions in the body:

- movement- integrated action of muscles, joints, and bones.
- posture- such as sitting and standing is maintained as a result of muscle contraction.
- joint stability- muscle tendons are the major factor in stabilizing such joints as the knee and the shoulder.
- heat production- to maintain body temperature is an important by product of muscle metabolism. Nearly 85% of the heat produced in the body is the result of muscle contraction.

STRUCTURE OF THE SKELETAL MUSCLE

A whole skeletal muscle is considered an organ of the muscular system. Each organ or muscle consists of skeletal muscle tissue, connective tissue, nerve tissue, and blood or vascular tissue.

Each fine thread is called a muscle fiber. This type of muscle tissue has three names; skeletal muscle because it attaches to bone, striated muscle because it has cross stripes or striations, and voluntary muscle because its contractions can be controlled voluntary.

Most skeletal muscles attach to two bones that have a movable joint between them. Most muscles extend from one bone across a joint to another bone. The muscle's attachment to this more stationary bone is called its origin. Its attachment to a more movable bone is called its insertion. The rest of the muscle is called the body of the muscle.

Tendons anchor firmly to bone. They are a dense fibrous connective tissue in the shape of heavy cords and they have great strength. They do not tear or pull away from the bone easily.

The basic structural and functional unit of the skeletal muscle is called the sarcomere. The microscopic structure of the sarcomere consists of many myofilaments.

Muscle fibers are arranged in a highly organized way. Each muscle fiber has two kinds of very fine and threadlike structures called thick and thin myofilaments.

The thick myofilaments are formed by the protein myosin. The thin filaments are formed by the protein actin. When seen under a microscope, dark and light striations are seen. Dark bands called Z bands separate the repeating units of the sarcomeres from each other.

Contraction of a muscle causes the two types of myofilaments to slide toward each other shortening the sarcomere thus shortening the muscle. When the muscle relaxes, the sarcomeres return to their resting length, and the filaments resume their resting positions. The typical myofibril consists of 10,000 or more sarcomeres that are strung together in long chains.

SLIDING FILAMENT THEORY

In a relaxed muscle fiber, the receptor sites on the actin thin filaments are covered and inactivated. Heads on the myosin thick filaments are also inactivated and are bound or attached to ATP or (adenosine triphosphate). Ah... ATP you say. I remember that. That is a chemical compound that stores chemical energy within the cell for use by body cells. All if this lays in waiting for the correct signal. Calcium also is stored in the channels of the muscle cell endoplasmic reticulum.

Because the muscle cell needs energy for contraction, there are multiple nuclei and numerous mitochondria (power plants of the cells....coming back to you now??)

When an impulse travels from the nerve cell to the cell membrane of the muscle cell, calcium ions are released. This rapid influx of calcium ions into the cytoplasm of the muscle cell causes a change in the shape of the actin thin filaments and exposes the myosin thick binding sites.

At the same time, ATP is broken down to become ADP and the previous inactive myosin heads become energized and begin to interact with the actin thin filaments. They form a ?cross bridge? so that the actin slides toward the center of the myosin. This action shortens the length of the sarcomere.

This is not as confusing as one would think. Just take it step by step and it begins to make sense.

When there are no more nerve impulses, muscle impulses stop and calcium is actively transported from the cytoplasm of the muscle cell back into the endoplasmic reticulum to be stored for the next round. Without the calcium, the actin and myosin are reconfigured or redesigned into their noncontracting state and the muscle fiber relaxes

Individual muscle fibers contract according to the all or none principle. When the muscle fibers receive sufficient stimulus to contract, all the sarcomeres shorten at the same time. A greater stimulus will not produce a greater contraction. If there is insufficient stimulus, then none of the sarcomeres contract. Therefore, it is all or none.

The minimal stimulus to cause muscle fiber contraction is called a threshold; a lesser stimulus that is insufficient to cause contraction is called a subthreshold.

OK...I know that you are dying to know this.... What exactly is rigor mortis?

Rigor mortis means the ?stiffness of death?. Within a short time of death, the ATP in muscle breaks down so there is no ATP available to detach the cross bridges between the actin and the myosin. The myofilaments remain locked in a contracted position and the body becomes rigid. Day or so later, muscle proteins begin to break down and the rigor mortis disappears.

A muscle's response to a single threshold stimulus is called a twitch. This is not the way a muscle in the body normally functions

A muscle twitch, the response to a single stimulus shows a lag phase when initially there is no response to the stimulus. Then there is a contraction phase where the tension of the muscle increases to a peak. If the tension is great enough to overcome the weight load, then movement occurs. This is followed by a relaxation phase, when the tension is decreased and a relaxed state is achieved.

If a second stronger stimulus is applied during the relaxation phase, the second twitch is stronger than the first. If the muscle is stimulated at an increasingly faster rate the relaxation disappears and the contractions merge into a smooth, sustained contraction called tetany.

Treppe is a staircase effect and it is an increase in the force of muscle contraction in response to a successive threshold of stimuli of the same intensity.

The word tetanus is often confusing because it means different things to different people. In reference to muscle contraction, it produces a steady contraction of a muscle fiber without a relaxation phase. The term also refers to a disease commonly called ?lockjaw?, that is caused by the bacterium Clostridium tetani. The toxin causes the nerves to become highly excitable, which in turn causes uncontrollable muscle contractions, or spasms.

Muscle tone refers to the continued state of partial contraction that is present in muscles. This produces a constant tension in the muscles and keeps them ready for activity.

MOVEMENTS

Muscles move bones by pulling on them. When the muscle contracts, the insertion moves toward the origin.

FUNCTIONS OF THE SKELETAL SYSTEM

¨ Provides a framework that supports the body; the muscles that are attached to bones move the skeleton.

¨ Protects some internal organs from mechanical injury; the rib cage protects the heart and lungs.

¨ Contains and protects the red bone marrow, one of the hemopoietic (blood-forming) tissues.

¨ Provides a storage site for excess calcium. Calcium may be removed from bone to maintain a normal blood calcium level, which is essential for blood clotting and proper functioning of muscles and nerves.

TYPES OF BONE TISSUE

Bone cells are called osteocytes, and the matrix of the bone is made of calcium salts and collagen. The calcium salts give bones the strength for its supportive and protective functions. The function of osteocytes is to regulate the amount of calcium that is deposited in or removed from the bone matrix.

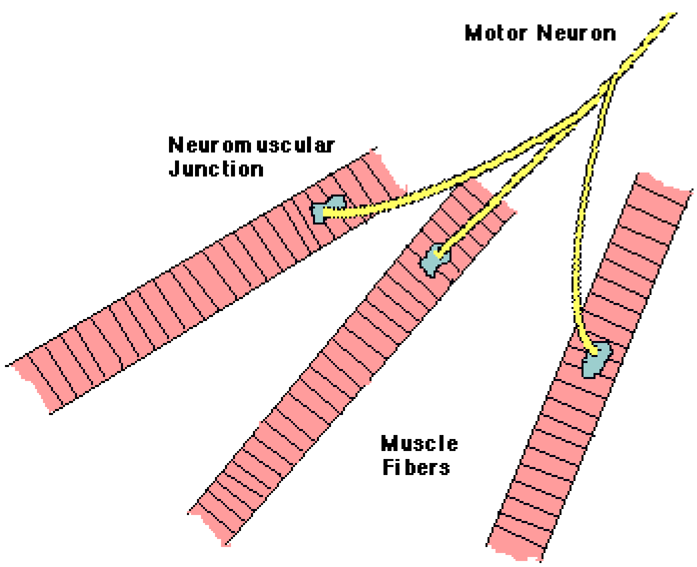
Bone is an organ, it has its own blood supply and is made up of two types of tissue; compact and spongy bone.

Compact bone is made of haversian systems or cylinders of bone matrix with osteocytes in concentric rings around central haversian canals. Each haversian system consists of mature osteocytes arranged in concentric circles around large blood vessels. The area surrounding the osteocytes is filled with protein fibers, calcium, and other minerals. Each haversian system looks like a long cylinder. Compact bone consists of many haversian systems running parallel to each other. The network of blood vessels ensures that the bone tissue receives an adequate supply of blood. Blood supplies tissues with oxygen and necessary nutrients.

Spongy or cancellous bone has a much different structure from compact bone. Unlike compact bone, spongy bone does not contain haversian systems. In spongy bone, the bone tissue is arranged in plates called trabeculae. These bony plates are separated by irregular spaces, or holes, and give spongy bone a punched out ?Swiss cheese? appearance. The spaces in the bone are important for two reasons: they decrease the weight of the bone, making it lighter, and they contain red bone marrow. The red bone marrow richly supplies the spongy bone with blood and also produces cells for use throughout the body.

Muscles Are Organized Into Motor Units

- When a single nerve enters a muscle it splits and makes neuromuscular junctions (NMJs) with several muscle cells
- A nerve and the muscle cells it makes NMJs with is called a motor unit
- When the nerve fires the whole motor unit is stimulated and the muscle cells contract together
- Muscles with large motor units have coarse movements
- Muscles with small motor units give fine, graded movements



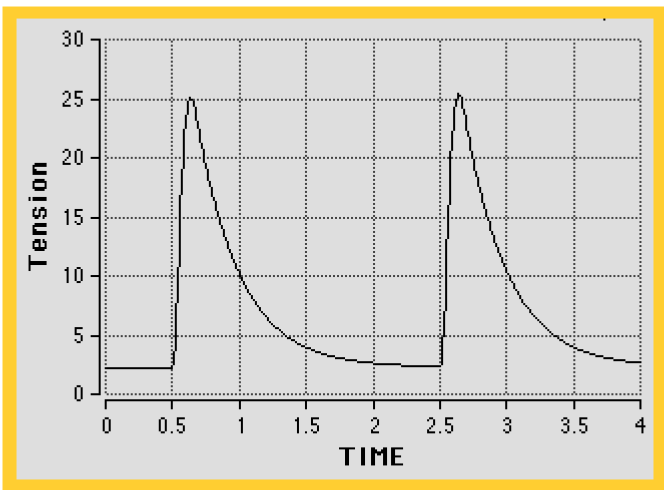
- This is a small motor unit with only 3 muscle fibers

Two Basic Types of Contraction Are Isotonic and Isometric

- In an isotonic contraction the muscle shortens, keeping a constant tension
- In an isometric contraction the muscle does not shorten and tension builds up
- Most real contractions are mixtures of the 2 types

A Single Nerve Impulse Produces a Muscle Twitch

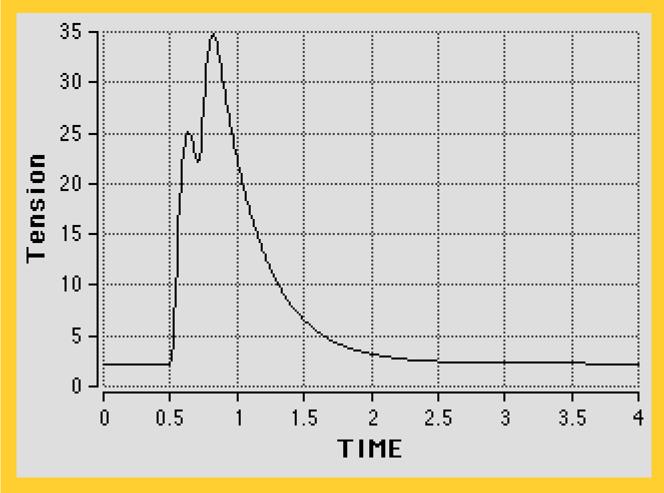
- Single stimuli usually release enough acetylcholine in the NMJs of the motor unit to produce action potentials in the muscle membranes
- This will cause the muscle to contract after a short delay
- Order of events: ACh release -> muscle action potential -> Ca release -> contraction
- A simple twitch gives only 20-30% of the maximum tension possible- the muscle starts to relax before the maximum is reached
- In the figure below a muscle is stimulated at 0.5 seconds and again at 2.5 seconds; there is complete relaxation between the stimuli and the tension reaches only 25% of maximum



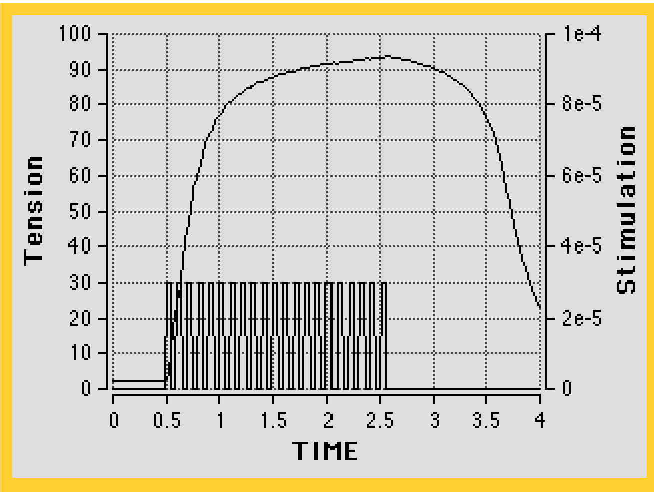
- These graphs are Madonna computer simulations of muscle contraction. It is assumed that tension is proportional to the amount of Ca bound to troponin

Muscle Contractions Can Summate to Produce More Force

- If a second stimulus is given before a muscle relaxes the muscle will shorten further, building up more tension than a simple twitch- this is called summation



- In the graph above the muscle is stimulated at 0.5 seconds and again at 0.7 seconds. The muscle does not completely relax between stimuli and the tension summates to 35% of maximum
- If many stimuli are given very close together the muscle will go into a smooth continuous contraction called tetanus



- In this computer experiment the muscle was given 20 stimuli 0.1 seconds apart (lower trace). The contractions fuse to produce a tetanus that rises to over 90% of maximum
- Tetanus gives the maximum tension, about 4X higher than a simple twitch (isometric contraction)

Another Way to Increase the Force of Contraction is to Recruit More Motor Units

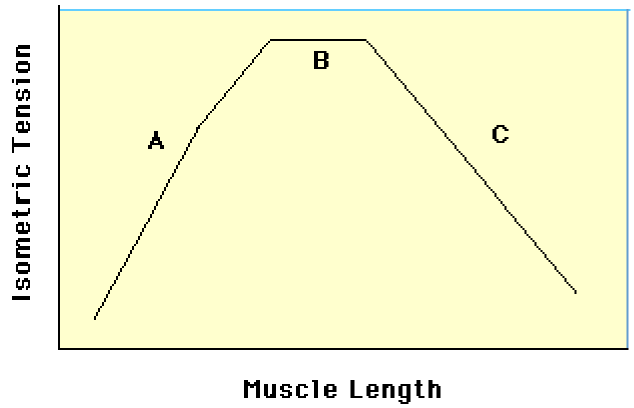
- Each muscle is made up of tens of thousands of motor units
- Force generated by a muscle can be increased by firing more and more motor units

Different Types of Skeletal Muscle Fibers Specialize for Endurance or Speed

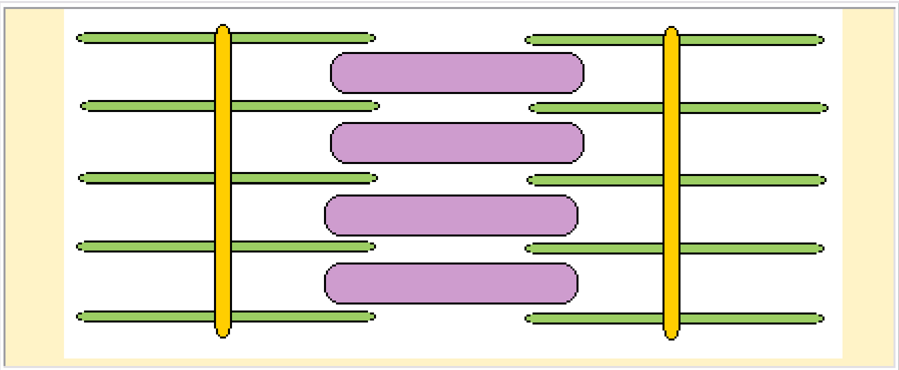
- Muscle cells (fibers) specialize for their type of activity
  - Athletes have fiber types that match their activities
- Endurance fibers (type I)
  - Have many mitochondria- the mitochondria give these fibers a red appearance because one of the mitochondrial enzymes contains Fe.
  - Also contain a red pigment called myoglobin which stores $O2$.
  - Contract slowly but resist fatigue
- Fast twitch fibers (type II)
  - Fibers specialized for fast contractions are white- they contain few mitochondria
  - Relying on glycolysis to supply energy (glycolysis is faster than respiration).
  - Contract rapidly but fatigue quickly
- Fiber type is mostly genetically determined, but some experiments have shown conversion of one fiber type into another

Muscle Produces the Greatest Isometric Tension at Intermediate Lengths

- If you measure the isometric tension of a muscle when it is fixed at different lengths you will find that there is an optimum length for producing tension
  - At rest many of the body's muscles are close to their optimum lengths
- There is a connection between the chemical anatomy of actin and myosin and the amount of tension produced when they interact
- The chemical connection is based upon 2 principles:
  - 1) actin and myosin connect through crossbridges- the more crossbridges the more tension
    - Suppose the muscle is stretched so far that actin and myosin hardly overlap- then there will be few crossbridges and little tension
    - As the muscle is shortened from this extreme length more and more overlap will occur and the tension will rise
  - 2) when the muscle proteins interfere with crossbridges it will weaken the tension
    - If the muscle is shortened too much the actin filaments will bump into each other and bend- this distorts the sarcomere and weaken the contraction

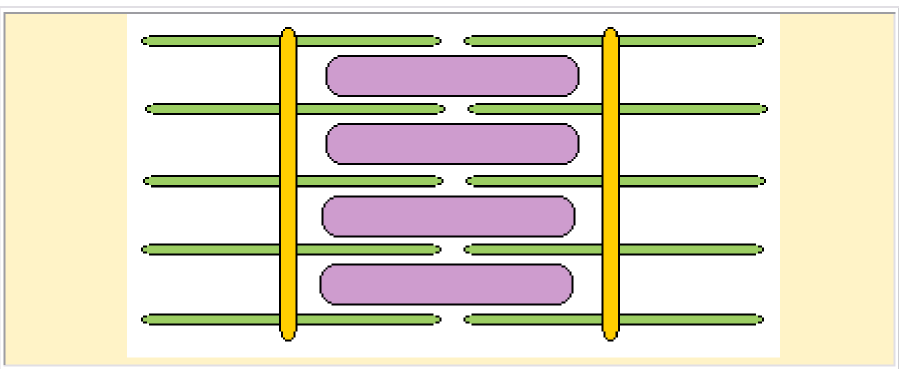


- Sarcomere at point C:



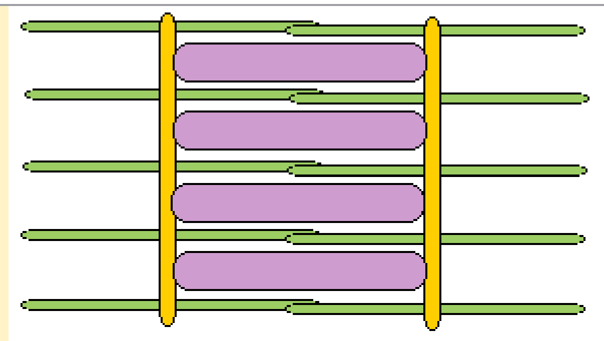
This figure corresponds to point C on the graph. The muscle is stretched to a point where there is very little overlap between actin and myosin. The isometric tension will be low.

- Sarcomere at point B:



At point B on the graph there is considerable overlap between actin and myosin. There are many active crossbridges, so the isometric tension will be high.

- Sarcomere at point A:



At point A there is a lot of overlap between actin and myosin, but the actin filaments are pushing on each other. This distorts the filaments, weakening the crossbridges.

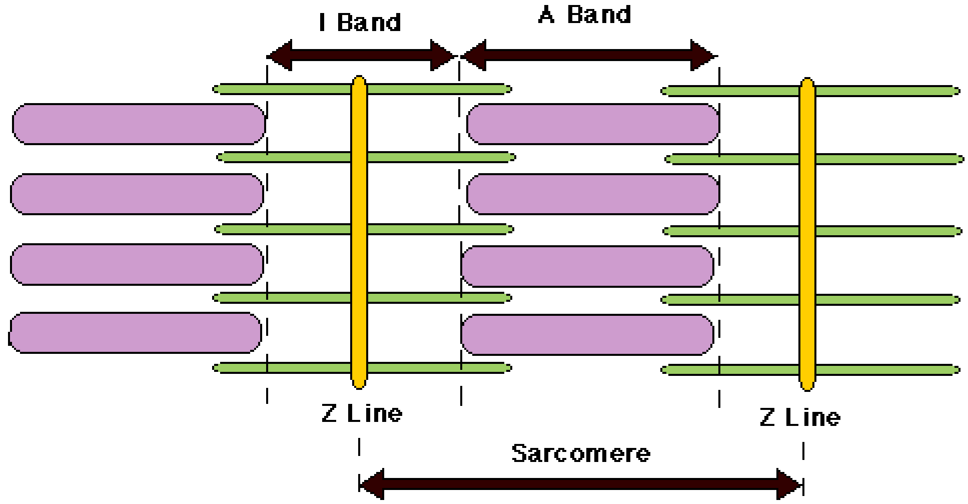
Muscle Refractory Periods are Related to Function

- The refractory period of the muscle membrane controls how rapidly a muscle can be fired
  - Muscle must recover before it can be fired a second time
- Examples:
  - Flight muscles of insects and hummingbirds can contract about 1000 times a second
    - To do that they must recover very rapidly so that they can fire again (very short refractory period)
  - The heart needs to slow down the firing rate so that it has time to fill
    - Hearts usually have quite long refractory periods that limit the maximum heart beat

The Basic Unit of Muscle Contraction is the Sarcomere

- Skeletal and cardiac muscle are striated (smooth muscle has a similar contractile mechanism but is not so highly organized and does not show striations)
- The striations are caused by alignment of bands: the most prominent are the A and I bands and the Z line

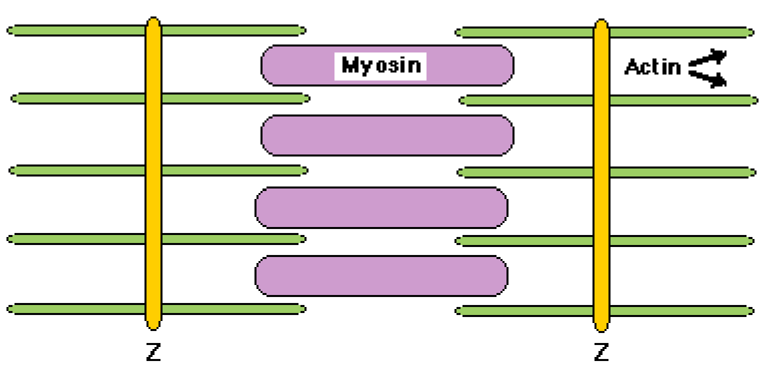
- The unit between 2 Z lines is called the sarcomere



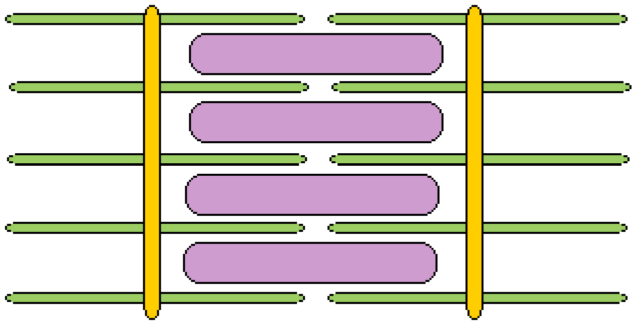
- The figure shows the structure of the bands in terms of the major proteins, actin & myosin: see below
  - In the A band the 2 proteins overlap
  - The I band contains only the actin protein
- When muscle contracts the sarcomere shortens and the Z lines move closer together
- The sarcomere is the basic unit of contraction; with electrodes it is possible to stimulate a single sarcomere and make it contract

When Muscle Contracts Protein Filaments Slide Together

- Electron microscopy combined with chemical experiments show that muscle is composed of 2 contractile proteins:
  - a) Thin filaments: actin, attached to Z line, found in both A and I bands
  - b) Thick filaments: myosin, found in A band
- Relaxed state:



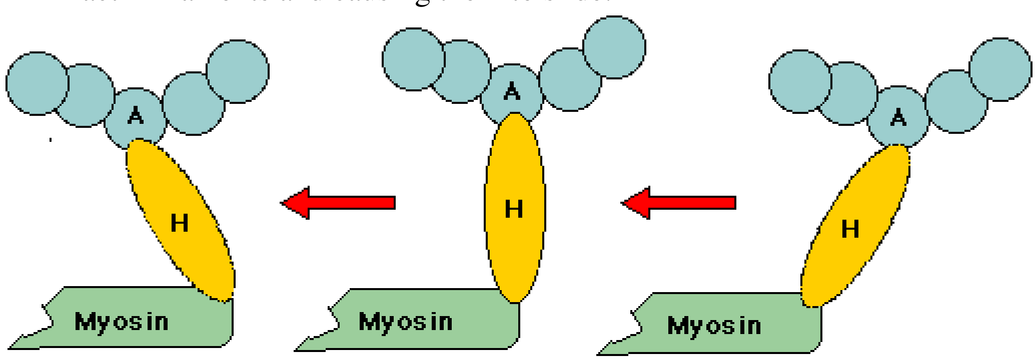
- When muscle contracts the actin filaments slide into the A band, overlapping with myosin



- Notice what happens when muscle contracts:
  - a) the Z lines move closer together
  - b) the I band becomes shorter
  - c) the A band stays at the same length
- This is called the "sliding filament" model of muscle contraction
- Maximum contraction of the sarcomere is about 30%

Muscle Contracts When Myosin Crossbridges Attach to Actin and the Molecule Bends

- The filaments slide together because myosin attaches to actin and pulls on it
  - Myosin head (H) attaches to actin filament (A), forming a crossbridge
  - After the crossbridge is formed the myosin head bends, pulling on the actin filaments and causing them to slide:



-
- Muscle contraction is a little like climbing a rope. The crossbridge cycle is: grab -> pull -> release, repeated over and over

ATP is Required for Both Contraction and Relaxation of Muscle

- ATP is the energy supply for contraction
- It is required for the sliding of the filaments which is accomplished by a bending movement of the myosin heads
- It is also required for the separation of actin and myosin which relaxes the muscle
- When ATP runs down after death muscle goes into a state of rigor mortis

The Trigger for Muscle Contraction is Ca2+

- A sudden inflow of Ca is the trigger for muscle contraction
- In the resting state the protein tropomyosin winds around actin and covers the myosin binding sites
- The Ca binds to a second protein, troponin, and this action causes the tropomyosin to be pulled to the side, exposing the myosin binding sites
- With the sites exposed muscle will contract if ATP is present

In Muscle Ca2+ is Stored in the Sarcoplasmic Reticulum

- Storage of Ca:
  - The Ca which causes muscle contraction is stored in the sarcoplasmic reticulum (this is a specialized version of the endoplasmic reticulum)
  - The SR has a powerful Ca pump which concentrates Ca
- Release of Ca:
  - Skeletal muscle is stimulated by nerves which contact muscle through a neuromuscular junction.
  - The nerve releases acetylcholine and generates a muscle action potential
  - The action potential travels down the T-tubule and causes the sarcoplasmic reticulum (SR) to release Ca
- After the contraction the Ca must be rapidly pumped back into the SR so the muscle can contract again

In Cardiac (Heart) and Smooth Muscle Special Junctions Help Spread the Excitation from One Cell to Another

- In skeletal muscle each fiber (cell) can contract independently
- In cardiac and smooth muscle the cells are interconnected by special junctions-intercalated disks in cardiac and gap junctions in smooth muscle
- This spreads the excitation from one cell to another and causes cardiac and most smooth muscle to contract as a unit
- Cardiac muscle beats spontaneously, even if all nerves to the heart are cut. The nerves do speed up or slow down the heart beat, however

Cutting the Nerve to a Muscle Will Cause it to Degenerate

- A healthy skeletal muscle requires stimulation
- If nerves to a muscle are cut or badly damaged the muscle will degenerate

How does skeletal muscle function?

A. Muscle structure.

1. Not part of the muscle, but an important part of its function is the **motor neuron** (nerve cell) that has one end attached to each muscle cell (the other end of the motor

neuron usually is in the brain-remember these are voluntary muscles).

a. Motor unit

2. The neuron contains packets (**synaptic vesicles**) of a **neurotransmitter** called **acetylcholine**. This is a small molecule made out of acetic acid and choline.

3. There is a small gap between the neuron and the muscle cell called the **neuromuscular junction.**

4. The muscle side of the neuromuscular junction (postsynaptic terminal) has embedded in the **sarcolemma** (plasma membrane) are **receptors** designed to accept acetylcholine. These receptor molecules are made out of protein.

5. The sarcolemma forms invaginations deep into the cell (the invaginations are referred to as the **T-system**.) The T-system comes in close contact with the **sarcoplasmic reticulum** (endoplasmic reticulum).

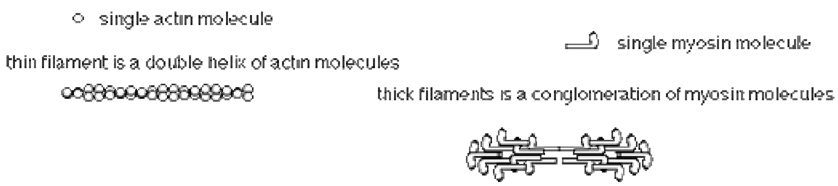
6. The sarcoplasmic reticulum has a powerful Ca++ pump that keeps the concentration of Ca++ inside the sarcoplasmic reticulum at a level about 2000 times higher than in the **sarcoplasm** (cytoplasm). The sarcoplasm also has electrosensitive Ca++ gates and presumably work much the same as Na+ and K+ gates work.

7. Back to the muscle cell as a whole: Each muscle is a family of cells (each cell generally the length of the muscle) surrounded by connective tissue and attached to bones by connective tissue (bundles of collagen known as tendons).

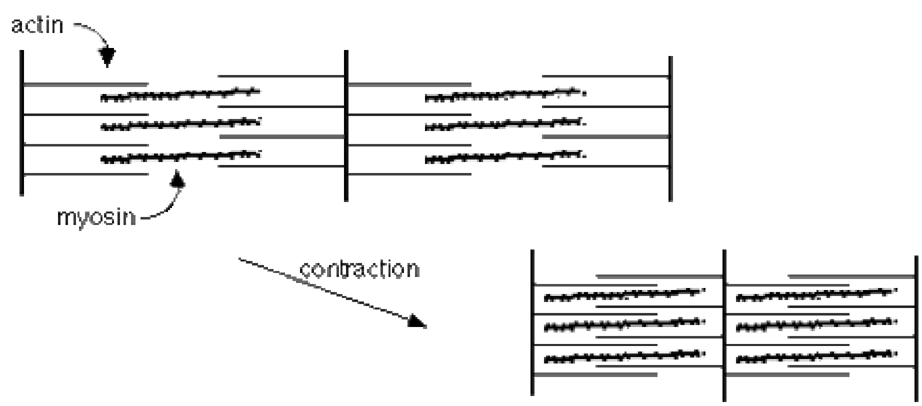
8. The muscle itself looks patterned, and the muscle cell (=**muscle fiber**) itself exhibits striations.

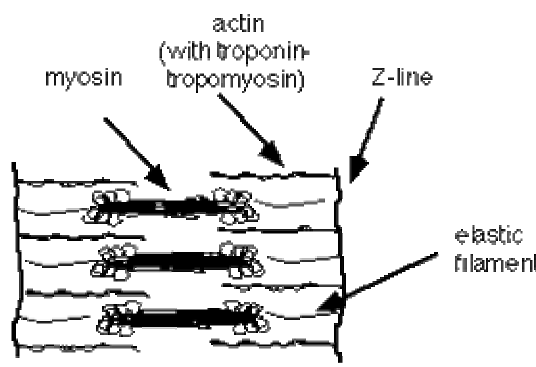
9. Each muscle cell fiber (10-100 μm x 30 cm) is made up of many fibrils (or **myofibrils**) surrounded by the other cellular constituents, .

10. Each fibril can be divided from **Z line** into units of **sarcomeres** (about 2 µm long). The Z-line itself is made of protein.



C. **Sliding filament model**: myosin "walks" along the actin molecule in the sarcomere structure.





11. **Actin** made up of two helical strands attached to the Z line. (thin filaments)

12. **Myosin** made up of many individual myosin protein molecules layered parallel upon each other. Each myosin molecule has a lollipop looking structure that demonstrates ATPase activity and also has the ability to attach actin. **A band** - length of myosin (thick filament). (**I-band** is where actin does not overlap with myosin in the Z-line region.)

13. **Myosin** and **actin** are the two major protein components of muscle.

14. **Elastic filament** holds the myosin to the z-lines.

B. Muscle at rest.

1. Resting membrane potential (~-70mv) exists for the neuron. The acetylcholine is sitting in small vesicles floating in the cytoplasm of the nerve cell ready to be released upon command.

2. Resting membrane potential (~-70mv) exists for the muscle cell.

3. Ca++ is in high concentration in the sarcoplasmic reticulum.

4. ATP is bound to the myosin, but the myosin can not bind to the actin because the **tropomyosin** (with attached **troponin**) is in the way. The muscle is flaccid or elastic in this condition.

a. In reality muscles of a living person are never completely in this condition. Muscles are always in a state of even mild contraction called **tone**. Muscles are probably most relaxed when we are asleep.

C. Muscle contraction. (cart demonstration)

1. Brain sends a signal down a motor neuron for contraction (in the form of an **action potential**)

2. When the signal reaches the end of the nerve, it causes an uptake of calcium.

3. The calcium uptake stimulates the release of acetylcholine into the neuromuscular junction.(Sir Bernard Katz) The acetylcholine is released in packets by exocytosis.

4. **Acetylcholinesterase** immediately starts to break down the acetylcholine into acetic acid and choline. However, some diffuses across the neuromuscular junction to attach to receptor proteins located on the muscle cell membrane.

5. The binding of the acetylcholine to these membrane proteins causes the membrane to become leaky to Na+ ions (similar to, but not the same as Na+ gates.)

a. Curare (dart poison) binds to these receptors and prevents acetylcholine from binding thus preventing any muscle contraction.

6. As the Na+ leaks it causes a depolarization which stimulates adjacent Na+ and K+ gates to open, thus starting an action potential in the muscle cell.

7. The action potential will propagate in both directions from this initial point. As the action potential propagates along the muscle cell membrane (**sarcolemma**) it will also weave in and out of the **T-tubule** system of the sarcolemma.

8. The T-Tubule system comes in close proximity to the endoplasmic reticulum (**sarcoplasmic reticulum**) inside the cell.

9. Some how this stimulates the opening of **Ca++** gates, allowing a large flow of calcium out of the sarcoplasmic reticulum into the cytoplasm (**sarcoplasm**).

10. The calcium gets into the **sarcomeres** and binds to receptor sites on the **troponin** molecules (which are resting on the **tropomyosin** and actin filaments). The binding of the calcium causes a shape change in the **troponin** protein such that it leads to a shape change in the tropomyosin molecule. The **tropomyosin** is changed in shape such that it uncovers the actin and exposes the myosin binding site that resides on the actin. The **myosin** can now bind to the **actin.** (Normally **tropomyosin** blocks the binding of myosin with actin).

11. The myosin, with an already bound **ATP** molecule, binds to the actin.

12. As the ATP reacts to form ADP, the released energy is used to bend the myosin head such that the actin filament slides along relative to the myosin filament. During contraction the filaments of actin and myosin not change length but the distance between Z bands does. Thus, developed the **<u>sliding filament theory</u>** versus contracting proteins.

13. The ADP is dropped by the myosin, myosin binds another ATP and only then does it release from the actin. The process is repeated. Several repetitions cause a significant movement. At full contraction the myosin is still trying to pull on the actin and ATP is still being used.

a. **Rigor mortis** is where ATP is not available and the myosin can not release from the actin. Certain types of cramps are caused by the same phenomenon.

14. This continues until the action potentials stop

D. Relaxation:

1. Action potentials stop coming from the brain down the motor neuron, thus acetylcholine is no longer released.

2. The always present **acetylcholinesterase** in the neuromuscular junction chews up the last of the acetylcholine. (The acetic acid wanders off and gets used by cells in the Kreb's cycle. The choline gets reabsorbed so it can combine with a newly made acetic acid molecule in the motor neuron.)

3. Without any acetylcholine, the action potentials in the muscle stop.

4. Without any action potentials in the muscle (and the T-system), then the Ca^{++} gates of the sarcoplasmic reticulum can close.

5. The Ca++ active transport pumps (which were working constantly all along) are no longer overwhelmed by the leak and thus they successfully pump calcium from the sarcoplasm back into the sarcoplasmic reticulum.

6. Without bound Ca++ the troponin-tropomyosin regain their resting shape. The very next time the myosin releases from the actin, the troponin-tropomyosin will sneak back in between and prevent any further interaction between the actin and myosin.

7. Without the actin myosin bonding, the sarcomeres and muscle can no longer contract, thus the muscle elastically moves back to its resting position (or more commonly , is passively pulled to a new position by a more dominant antagonistic muscle)

IV. Muscle energy

A. All possible energy sources for muscle contraction must be converted to an **ATP** energy. This is the ONLY energy source myosin can use.

$$ATP + H_2O \text{ -------> } ADP + H_3PO_4 + \text{energy}$$

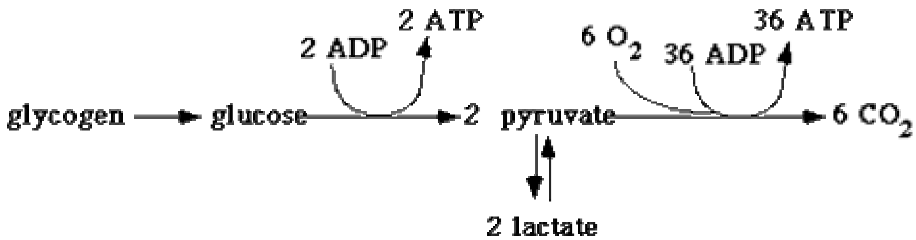
B. ATP is needed for several aspects of muscle contraction and relaxation:

1. Myosin ATPase.

2. Na+-K+ ATPase for developing a membrane potential (sarcolemma and nerve cell)

3. ATPase for sarcoplasmic reticulum Ca++ pump.

C. Since the normal concentration of ATP stored in a muscle cell is very small, then any significant contraction must involve indirect energy sources that lead to ATP formation:



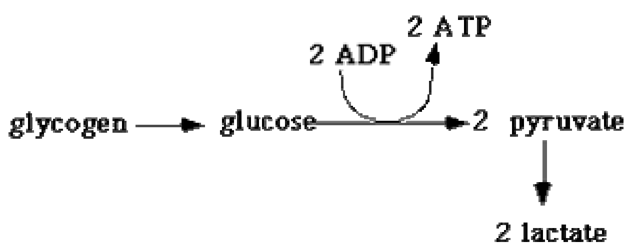
After the reserves of ATP are used (~5 sec), the first indirect source of energy generally used is **Creatine phosphate** (CP)(**phosphocreatine**) (~15 sec):

creatine phosphate + ADP ----> creatine + ATP

2. Next, glucose is used as an energy source:

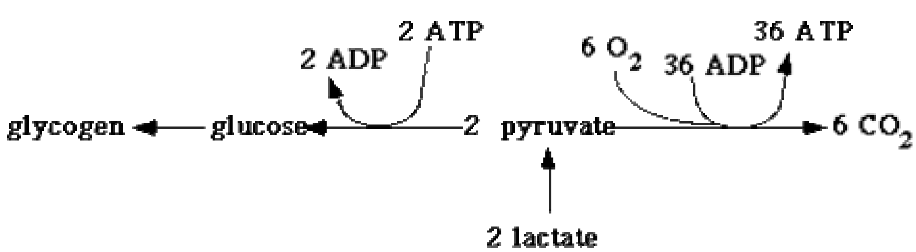
a. **ANAEROBIC** glucose breakdown to make ATP. (~40 sec)

1a.



2b. Fast but inefficient.

3c. The excess **lactate** must eventually be dealt with. A small amount of it is oxidized itself, the rest is converted back to glycogen. :



After the exercise, the amount that has to be oxidized is the amount necessary to bring the ATP, CP, lactate and the rest of the muscle back to homeostasis. This exactly corresponds to the amount of exercise that was done and the amount of oxygen necessary to reachieve this homeostasis is called the **oxygen debt**.

b. **AEROBIC** glucose breakdown to make ATP.

1a.

$$C_6H_{12}O_6 + 6O_2 + 38\ ADP \text{ ------> } 6CO_2 + 6H_2O + 38\ ATP$$

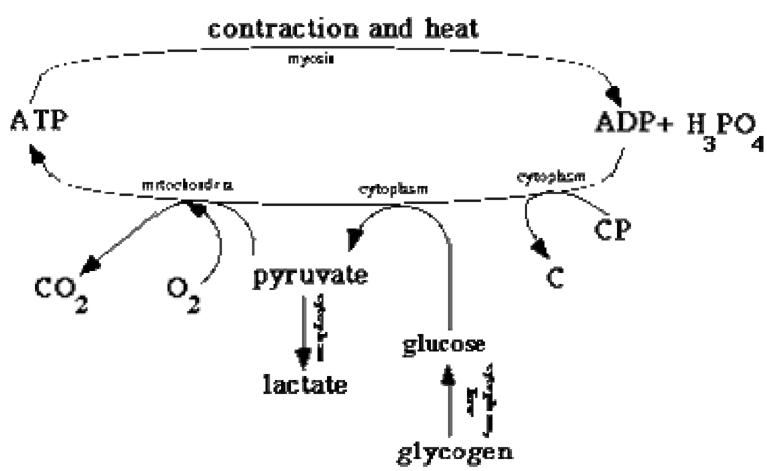
2b. Slow, but very efficient usage of glucose.

c. Glucose source. Often the amount of glucose stored as such is not sufficient for repeated muscle contractions. More glucose can be derived from stores of **glycogen** in the muscle itself and in the blood. The liver also plays a very important role in converting glycogen to glucose. The conversion of glycogen to glucose is relatively rapid compared to other methods of glucose formation (e.g. the development of glucose from fats would be very slow).

3. As a last ditch energy source, the ADP can be used in an unusual fashion to make ATP using the enzyme myokinase:

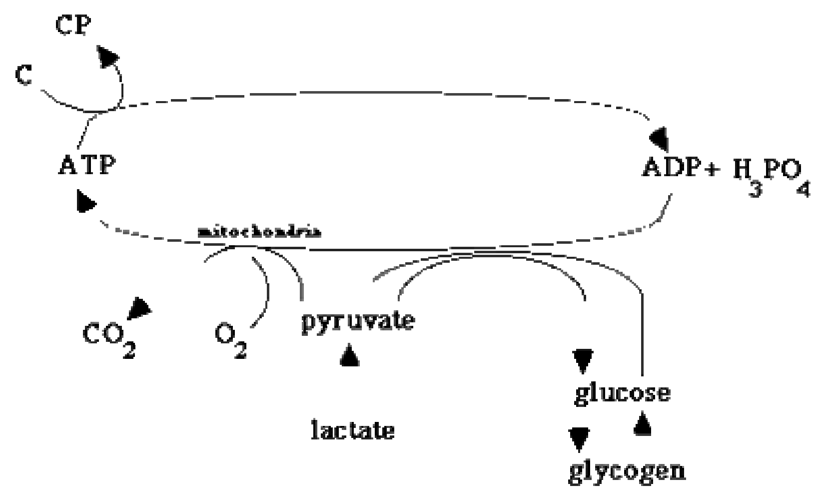
2 ADP ----> ATP + AMP

Summary of energy sources during contraction:



D. After contraction the reserves of ATP and creatine phosphate must be reestablished and the excess of lactic acid and AMP must be removed. Such processes must ultimately require aerobic respiration. The amount of oxygen required to reestablish such a homeostasis after a muscle contraction is referred to as an **OXYGEN DEBT**.

Summary of recovery:



V. Muscular ability is related to a) the actin-myosin cross bridges that can be formed and b) the system of levers that are used.

A. Contraction with movement (**ISOTONIC**) versus contraction without movement (**ISOMETRIC**).

B. Muscle usage increases the amount of actin and myosin in individual cells (**HYPERTROPHY**); there is not an increase in the number of cells (since skeletal muscle cells can not divide after birth). Lack of muscle usage causes decreased muscle size (**ATROPHY**).

C. Essentially all skeletal muscle are in the **ANTAGONISTIC** format.

D. All muscles are always in some state of contraction (**TONE**).

E. Despite all-or-none, each muscle can undergo varying degrees of contraction. This is because each muscle is made up of many individual cells and each cell can be independently controlled by nerves. Fewer than ten muscle cells are controlled per motor neuron.

F. There are "**quick**" muscle fibers (white = fast twitch fibers = twitch fibers=**Type IIB**) versus "**endurance**" muscle fibers (red = slow twitch fibers = tonic fibers=**TypeI**).

1. The proportion of white versus red that anyone has in muscle is primarily determined by genetics.

2. The red in red fibers comes from **MYOGLOBIN** which binds oxygen IN the muscle cell and is consistent with these types of cells undergoing more endurance. Also the red is due to a higher supply of capillaries. The myoglobin also facilitates oxygen diffusion from the blood to the mitochondria. In general these fibers are very good at Kreb's cycle and oxidative phosphorylation.

3. White muscle - fast twitch - type IIB - no myoglobin; can not be contracted repeatedly. Good at fast anaerobic contraction.

G. The greatest strength of a muscle is when it as at an intermediate length where the actin- myosin cross bridges can physically have the most interaction.

H. Speed versus strength.

1. The speed of a muscle is directly proportional to its length. Speed is a distance covered per unit time. In comparing a long muscle to a short muscle, the time it takes for individual sarcomeres to contract in each is unchanged, however the contraction will occur over a longer distance in the longer muscle. Thus, in one second, a much larger distance can be covered.

2. The strength of a muscle is directly proportional to its cross sectional area. The more cross section there is the more actin-myosin cross bridges one has to fight against. (Increasing a muscle in length does not increase its strength no more than does increasing a string in length increase its strength).

3. Trade offs between strength and speed can be made by using the bones as levers. (page 224-225).

a. For example, the biceps control the movement of the hand; the lever system allows a much larger range of movement of the hand whereas the biceps itself only moves over a small range. This large movement occurs in the same time that it takes the biceps to contract. Thus, because of the levers the hand moves much faster (larger distance per unit time) than does insertion end of the biceps itself. However, the hand can left very little weight compared to the weight that could be lifted if attached directly to the biceps insertion itself.

b. Conversely there are some lever systems in the foot that favor strength over speed.

•Finger grip demo•

VI. Twitch, stimulus, all-or-none, threshold

A. The basic unit of muscle contraction is the **twitch**.

1. A **Stimulation** is anything that causes the desired response. (An artificial stimulation is usually a voltage change).

2. A **twitch** is the quick, single muscle contraction caused by a single, brief stimulation.

[Demonstration - using flexor digitorium muscle

frequency => 1 event/sec

duration => 0.40 ms

stimulus => 65 volts

sweep speed => 3 sec/sweep

Increase events to show the loss of twitch.

B. The twitch <u>tends</u> to show the phenomenon of **ALL-OR-NONE**

1. If all-or-none was perfect then the following will be the case: Below a **threshold** stimulus no response (contraction) occurs; at threshold a complete response (contraction) occurs; for all stimuli above threshold you get the exact same response that you had at threshold.

2. In reality, muscle does not show perfect all-or-none, there are some gradations:

[Demonstration - show all-or-none and determine a threshold

value; use the light spring]

frequency => 1 event/sec

duration => 0.40 ms

stimulus => start at 40 v

sweep speed => 15 sec/sweep

Turn voltage up beyond threshold.

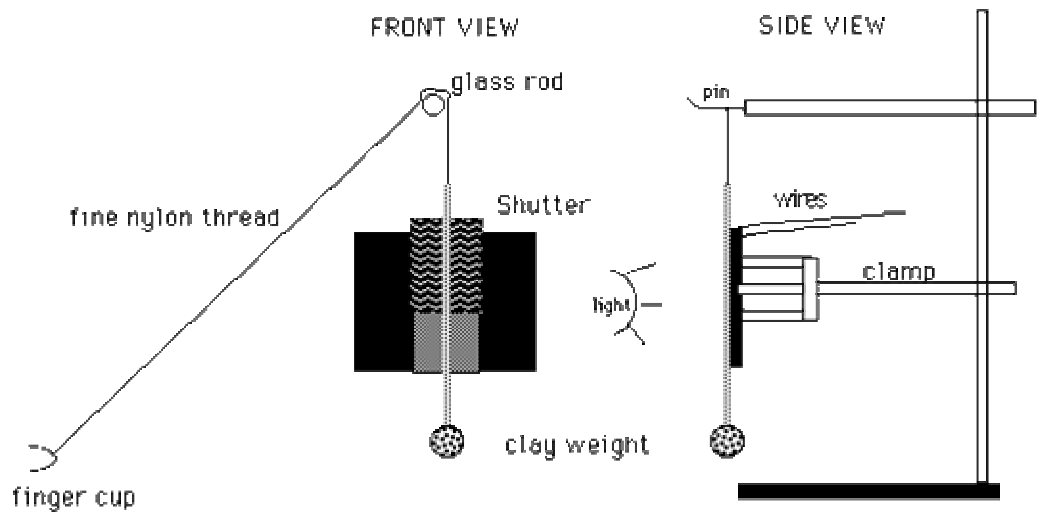
Turn voltage back down below threshold.

Review data.

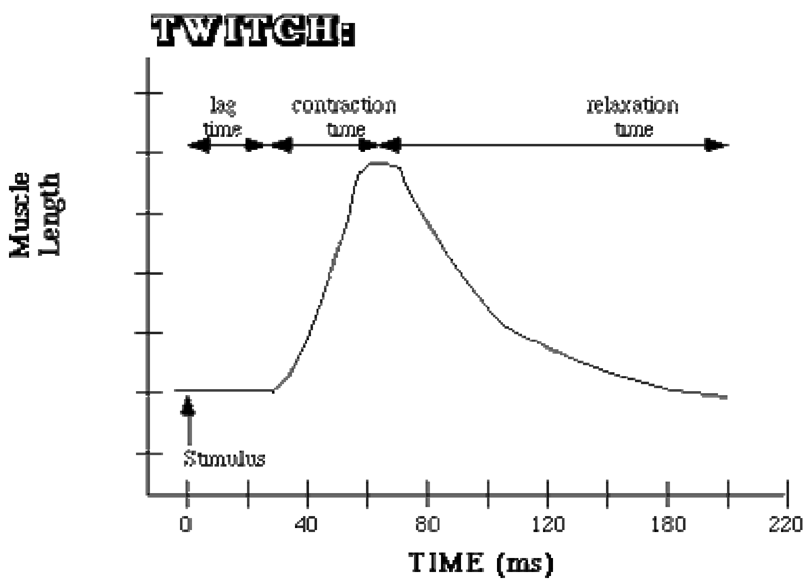
Initial experiment with muscle: Time 30 sec Rate: 30 pts/sec

Tetanus: Time 300 sec; Rate 15 pts/sec

Twitch: Time 2 sec; Rate 1000 pts/ sec



C. Timing details of a twitch.



1. **LAG TIME** - about 4 ms; due to all of the things that must happen before the sarcomeres actually start to contract.

2. **CONTRACTION TIME** - actual myosin-actin interactions.

3. **RELAXATION TIME** - the time to remove all of the cytoplasmic calcium, etc. The relaxation time is always slower than the contraction times.

4. All of these times heavily depend upon the particular muscle in question.

[Demonstration - show twitch timing]

set up twitch mode

light spring

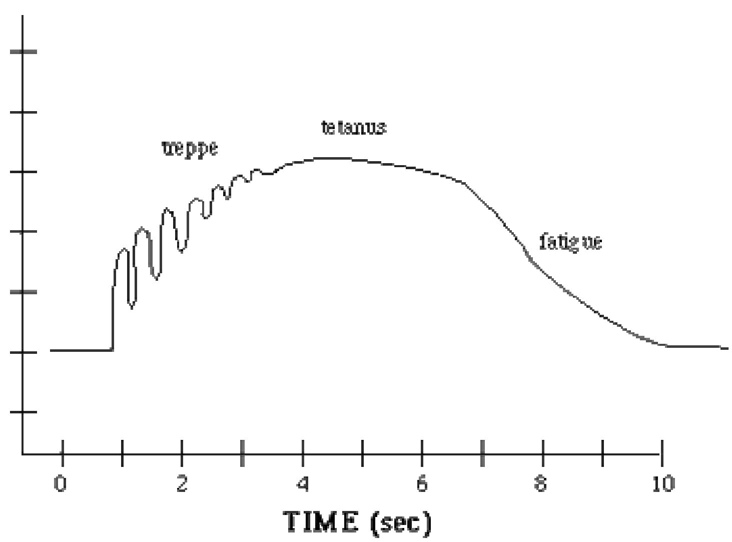
frequency => 1 event/sec

duration => 0.40 ms

stimulus => start at 40 v

sweep speed => 3 sec/sweep

D. **Summation** from frequent, multiple stimulations. Occurs when the next stimulation starts before full relaxation is allowed.



[Demonstration - show summation]

change back to regular mode

change to medium spring

frequency => 1 event/sec

duration => 0.40 ms

stimulus => 65 v

sweep speed => 3 sec/sweep

increase frequency to 50 events/sec

1. **TREPPE** - the gradual staircase increase in contraction due to repeated rapid stimulations.

2. **TETANUS** - the smooth, sustained, maximal contraction due to repeated rapid stimulations.

3. **FATIGUE** - loss in contraction ability; the magnitude decreases after several contractions.

VII. Two types of mechanical properties - force and kinetic.

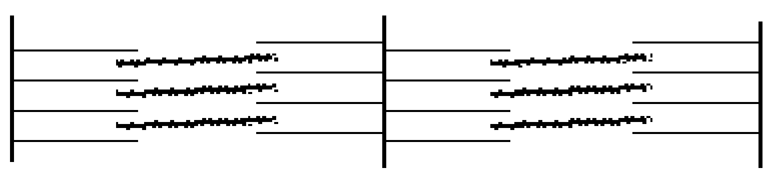
A. **Isometric** -> tension -> force of actin myosin bonds

B. **Isotonic** -> shortening -> sliding of myosin along actin.

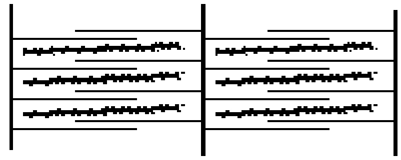
VIII. Strength and speed.

A. The strength of a muscle depends at what degree of extension it is in.

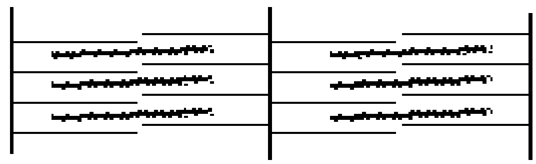
1. When the muscle is almost fully extended it has very little strength because the myosin can not make a lot of contract with actin



2. When the muscle is almost fully contracted it has very little strength because the myosin can not make a lot of contract with actin because the actin is overlapping itself:



3. When the muscle is at mid extension is when myosin and actin have maximal opportunity to interact and do something:



Demo : Use rubber bands hanging from a rod. Say one rubber band may be able to lift one Kg. The ask how many can a series of 4 lift? How much can a bunch of four lift? How about two bunches of two? How does speed work in each case.

Then continue with lever demo. Have the lever fulcrum attached toward the bottom of the ring stand. Put 500 g of weight on one end. Try to pull down the other end with the rubber band. Try this using different fulcrums and discuss.

B. Length versus cross sectional area of a muscle

1. Speed = distance over time. The time of each sarcomere contraction will not change. Putting many sarcomeres in series will increase speed because of the greater DISTANCE of shortening.

SPEED α LENGTH of muscle

2. Strength = the number of actin myosin interactions in a cross sectional area.

STRENGTH α CROSS SECTIONAL AREA of the muscle

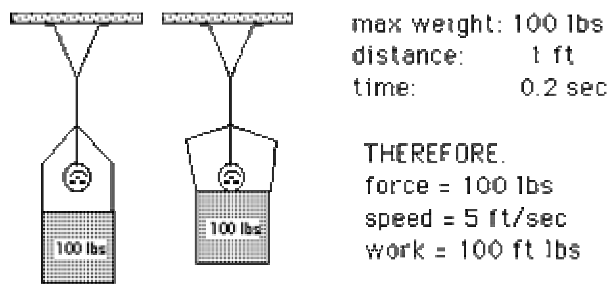
(Note that length of muscle has nothing to do with strength; e.g. a chain is only as strong as its weakest link, making it longer makes it no stronger)

3. Work = force X distance

Since force is proportional to the cross sectional area and distance is proportional to length, then force times distance will be proportional to volume or (mass).

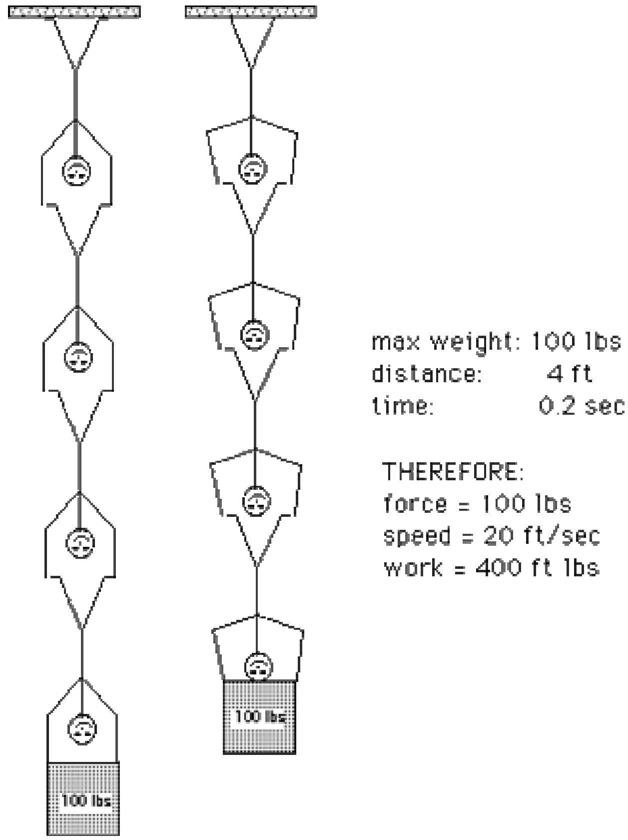
WORK α the MASS of the muscle

A weightless man can lift a maximum of 100 lbs in 0.2 sec a distance of 1 ft. Thus, his maximum force is 100 lbs, maximum work is 100 ft lbs (work = force x distance) and maximum speed is 5 ft/sec (speed = distance/time).

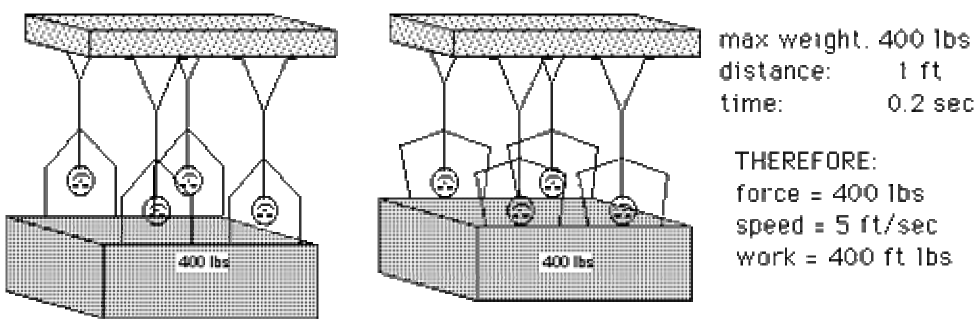


What can four such identical men do? Logically they can do 4 times the work (400 ft lbs) but is that due to more distance or more force? The answer depends on the arrangement:

If the four men are used to increase the length then the maximum weight that can be lifted will not be improved but the speed will increase by four:

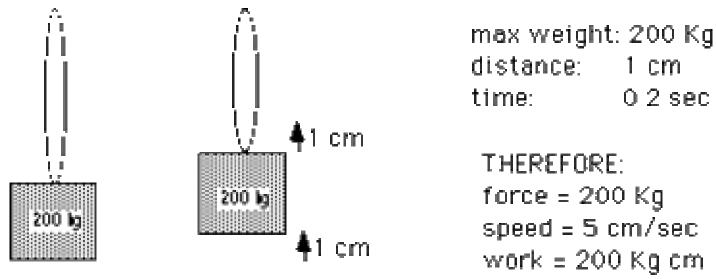


If the four men are used to increase the cross section area then the distance moved will be unchanged and thus the speed will be unchanged, but they can lift four times as much:



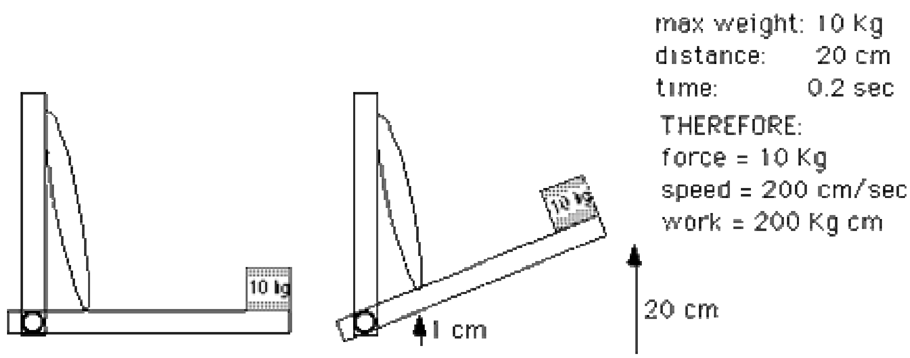
C. **Levers** due to muscular-skeletal arrangements can change the proportions to which a muscle is devoted to strength versus speed.

1. Consider a muscle that can do 200 Kg-cm of work, it takes 200 msec to contract and it can directly maximally lift 200 kg:

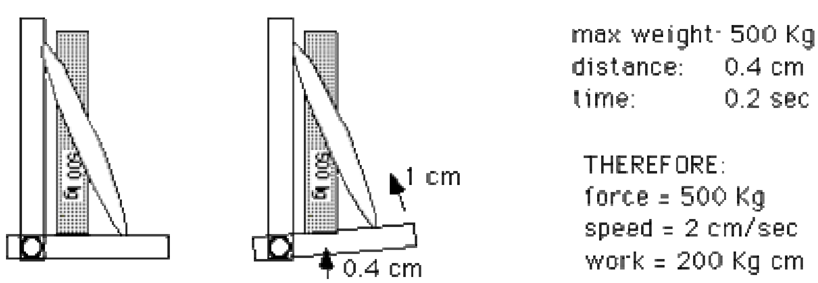


2. Levers can not change the amount of work a muscle can do (work = force times distance) but it can change the proportion that is devoted to distance verses force.

a. Consider the same muscle arranged as below (much like your biceps). The advantage is greater distance (which also translates into greater speed). The disadvantage is the amount of weight that can be lifted.

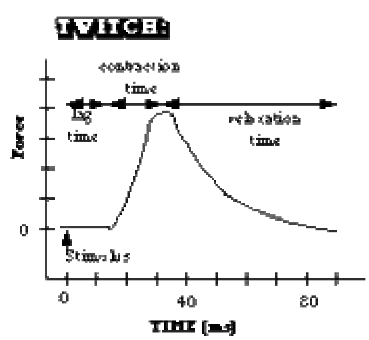
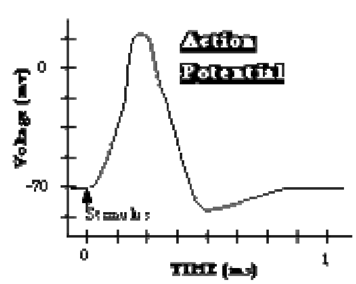


b. Consider the same muscle arranged as below (much like your the system that lifts your body when you stand on your toes).



Nerve activity and muscular contraction are two of the most important functions of the human body. It is very important to understand their basic characteristics. The phenomenon of an action potential (nerve and muscle) is very different than the concept of a twitch (muscle) -> <u>as different as night and</u>

day, as the cliché goes. Although some of the words used in describing each are the same, and some of the thinking is similar, it is very important not to confuse the understanding of an action potential versus a twitch.:

Characteristic	Twitch	Action Potential
Rough Definition	the resulting movement and/or force developed by a muscle as a result of a momentary above threshold stimulus.	the resulting voltage change developed by a nerve or muscle cell as a result of a momentary above threshold stimulus.
Outcome	Contraction/force.	Change in voltage
Body structures demonstrating phenomenon.	a single muscle cell or a whole muscle (i.e., group of muscle cells)	Only a single nerve cell or a single muscle cell
Timing	50 - 200 milliseconds (depends on muscle cell)	around 1 millisecond.
Laboratory stimulus	Voltage pulse (<1 ms)	Voltage pulse (<1 ms)
Graphical representation	note that: y-axis is contraction distance or force; the x axis is time with a twitch on the order of 100 ms. Note lag time, contraction phase & relaxation phase (the later being longer than contraction). 	note that: y-axis is voltage change across the membrane; the x axis is time with an action potential on the order of 1 ms. Note no measurable lag time, depolarizes above zero, and hyperpolarizes before coming back to the resting potential. 

All or none	Yes, but some gradations around threshold	Yes, never any gradations. It is very absolute.
Lag time	Yes (a few ms)	Virtually starts instantly
What happens if a second stimulus is applied while the phenomenon is happening.	Any above threshold stimulus applied during a twitch will initiate a second twitch on top of the first twitch resulting in a force stronger than a single twitch (Summation and treppe)	Any above threshold stimulus applied during an action potential will have no effect (this time of inability to restimulate is called refractory period). (note that if it did have an effect, we could not claim absolute all or none)

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