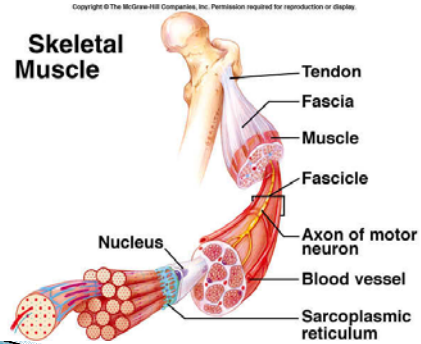
Lecture #2: Working of muscle
IE 665: Applied Industrial Ergonomics

Review



Review – U-tube video

- http://www.youtube.com/watch?v=EdHzKYDxrKc&feature=player_embedded

Review

TABLE 9.1 Muscular Contraction and Relaxation

Muscle Fiber Contraction	Muscle Fiber Relaxation
1. The distal end of a motor neuron releases acetylcholine.	1. Acetylcholinesterase decomposes acetylcholine, and the muscle fiber membrane is no longer stimulated.
2. Acetylcholine diffuses across the gap at the neuromuscular junction.	2. Calcium ions are actively transported into the sarcoplasmic reticulum.
3. The sarcolemma is stimulated, and a muscle impulse travels over the surface of the muscle fiber and deep into the fiber through the transverse tubules and reaches the sarcoplasmic reticulum.	3. ATP causes linkages between actin and myosin filaments to break without ATP breakdown.
4. Calcium ions diffuse from the sarcoplasmic reticulum into the sarcoplasm and bind to troponin molecules.	4. Cross-bridges recock.
5. Tropomyosin molecules move and expose specific sites on actin filaments.	5. Troponin and tropomyosin molecules inhibit the interaction between myosin and actin filaments.
6. Actin and myosin filaments form linkages.	6. Muscle fiber remains relaxed, yet ready until stimulated again.
7. Actin filaments are pulled inward by myosin cross-bridges.	
8. Muscle fiber shortens as a contraction occurs.	

Review: Conversion of chemical to mechanical energy

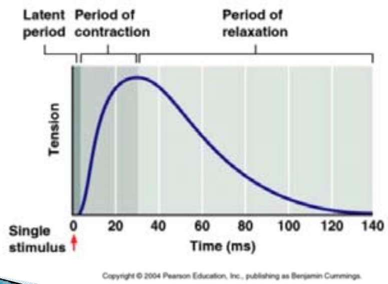
WATCH HOW MUSCLE CELLS CONTRACT

- http://www.youtube.com/watch?v=gJ309LfHQ3M&feature=player_embedded#!
- http://www.mmi.mcgill.ca/mmimediasampler/

Topics

- Force regulation by muscle
- Isometric and isotonic contractions
- Length tension relationship
- Energy consideration of muscle contraction
- Types of muscle cells
- Cellular respiration – static and dynamic muscle contraction.

Single Muscle Twitch– isometric tension from a single action potential



Single Muscle Twitch- tension from a single action potential

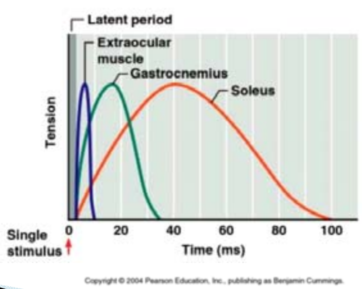
The muscle twitch is a single response to a single stimulus.

Latent period - the period of a few ms for the chemical and physical events preceding actual contraction.

Contraction period - tension increases as action potential is spreading along the length of the muscle tissue.

Relaxation period – muscle relaxes, relieves tension or comes back to its original length. Since it occurs due to passive tension from the connective tissues, takes more time than the contraction phase.

Velocity of contraction is different for different muscle types: Fast twitch, slow twitch and intermediate types.



Graded Contraction

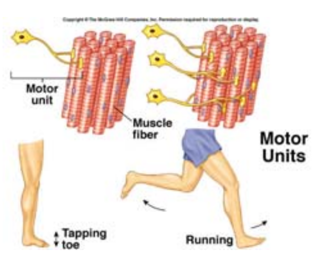
We do not use the muscle twitch as part of our normal muscle responses. Instead we use graded contractions, contractions of whole muscles which can vary in terms of their strength and degree of contraction. In fact, even relaxed muscles are constantly being stimulated to produce muscle tone, the minimal graded contraction possible.

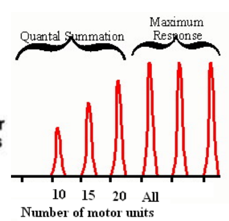
Muscles exhibit graded contractions in two ways:

(1) Summation/Recruitment/Quantal Summation: Increasing numbers of motor units to increase the force of contraction. (Quantal, because individual muscle cells cannot be recruited).

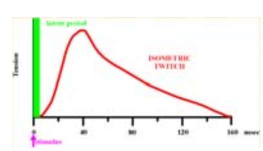
(2) Frequency Summation/Rate coding & Titanization: This results from stimulating a muscle cell before it has relaxed from a previous stimulus by increasing the frequncy of nerve stimulation. This is possible because the contraction and relaxation phases are much longer than the refractory period.

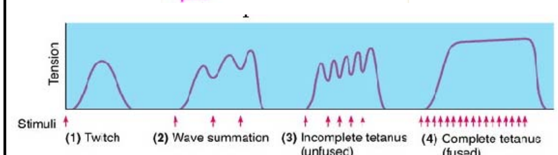
Quantal Summation/Recruitment



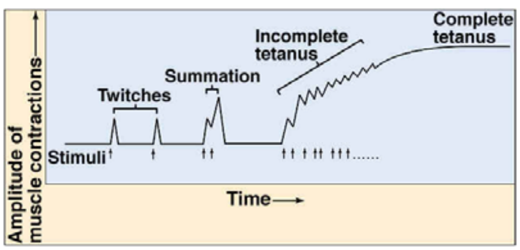


Frequency Summation or Rate coding



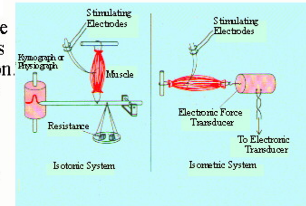


Muscle Stimulation Pattern



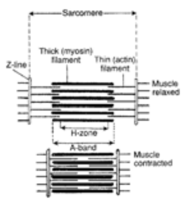
Isometric and Isotonic Contractions

Most muscle contractions are isotonic, the muscle shortens to establish a constant tension. In isometric contraction the muscle does not shorten appreciably, contracting against a heavy load for example, or maintaing static position.



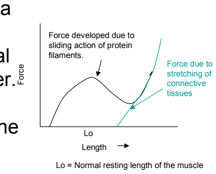
Length-Tension Relationship

With the change of length of a muscle fiber from its resting or optimum length, the number of cross bridges between actin and myosin filaments decreases. As a result of this, the force developed for an action potential decreases as it is stretched or shortened from its normal resting length.



Length-Tension Relationship

The graph shows the force developed in a muscle fiber for a single twitch, when it is kept at various lengths. Lo is the normal resting length of the muscle fiber. The black line shows the contractile force generated by the action of myosin sliding over actin filaments. After sufficient stretch, the elastic contractile force from the connective tissues adds a passive tension.



Implication of Length-Tension Relationship

When the joint angle changes, length of muscles spanning the joint also changes.

Thus,

- the maximum torque that can be developed at a joint varies with joint angle.
- strength depends on posture

Energy consideration for muscle contraction

Muscle contraction needs energy for myosin-actin sliding, transport of Na out of plasma membrane, transport of Ca molecules back to SR etc. all of which are energy intensive.

Muscle cells, like all other cells, use ATP (adinosine tri-phosphate) as their energy currency.

ATP↔ADP + Energy

Each muscle cell stores some ATP, which can sustain contraction for 1 to 2 seconds. To continue contraction, other high energy particles are broken down and the energy liberated from these reactions is used to re-synthesize ADP back to ATP to sustain contraction.

Stored Energy: CP

Muscle cells store a high energy molecule, **Creatine Phosphate**, which can be readily decomposed to Creatine and phosphate to liberate energy, which then can be used to re-synthesize ADP to ATP. But this source of ATP can only supply a cell for 8 to 10 seconds during the most strenuous exercise.

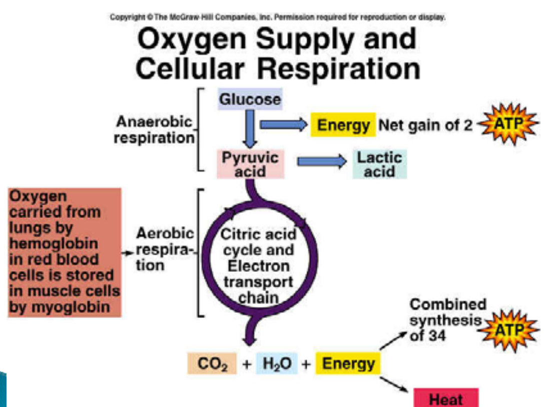
Creatine phosphate can be stored and is made from ATP during periods of rest.

Glycolysis

The bulk of the energy supply comes from metabolism (destruction) of glucose molecules, which is stored as glycogen (polymer of glucose) in muscle cells. Fat (and protein in extreme cases) molecules, supplied through blood are also metabolized in some cases. Glucose molecules can be metabolized in two ways:

Anaerobic: In the absence of oxygen (anaerobic glycolysis) – glucose molecules are broken down to pyruvic acid and each molecule produces energy equivalent to 2 ATP molecules. End product of anaerobic glycolysis is Lactic acid, which builds up in muscle cells causing local fatigue painful sensation.

Aerobic: In the presence of oxygen (aerobic glycolysis), glucose molecules break down to simpler molecules (CO2, H2O) and thus produces more energy, equivalent to 36 ATP molecules. This process of energy production can continue for long period of time as O2 can be made available through blood supply.



Anaerobic Glycolysis & Oxygen debt

Glycolysis is the initial way of utilizing glucose in all cells, and is used exclusively by certain cells to provide ATP when insufficient oxygen is available for aerobic metabolism. Glycolysis doesn't produce much ATP in comparison to aerobic metabolism, but it has the advantage that it doesn't require oxygen. In addition, glycolysis occurs in the cytoplasm, not the mitochondria. So it is used by cells which are responsible for quick bursts of speed or strength. Like most chemical reactions, glycolysis slows down as its product, pyruvic acid, builds up. In order to extend glycolysis the pyruvic acid is converted to lactic acid. Lactic acid itself eventually builds up, slowing metabolism and contributing to muscle fatigue.

Ultimately the lactic acid must be reconverted to pyruvic acid and metabolized aerobically, either in the muscle cell itself, or in the liver. The oxygen which is "borrowed" by anaerobic glycolysis is called oxygen debt and must be paid back. But mostly it is the amount of oxygen which will be required to metabolize the lactic acid produced.

Oxygen debt

- When body is moderately active or at rest, the cardiovascular and respiratory systems can usually supply sufficient oxygen to skeletal muscles to support the aerobic metabolism. However, when more strenuous activity is undertaken and muscle relies on anaerobic respiration to supply its energy needs, it incurs an oxygen debt, which requires the body to dispose off lactic acid and replenish the stored energy in the muscle cells in order to repay the debt.

Strength Training Effect

Strength training increases the myofilaments in muscle cells and therefore the number of crossbridge attachments which can form. Training **does not increase the number of muscle cells** in any real way. (Sometimes a cell will tear and split resulting in two cells when healed). Lactic acid removal by the cardiovascular system improves with training which increases the anaerobic capacity. Even so, the **glycolysis-lactic acid system** can produce ATP for active muscle cells for only about a minute and a half.

Aerobic Glycolysis

Ultimately, the product of glycolysis, pyruvic acid, must be metabolized aerobically. Aerobic metabolism is performed exclusively in the mitochondria. Pyruvic acid is converted to CO2 and H2O and vast majority of ATP. The reactant other than glucose is O2. Aerobic metabolism is used for endurance activities and has the distinct advantage that it can go on for **hours**.

Training Effect:

Aerobic training increases the length of endurance activities by increasing the number of mitochondria in the muscle cells, increasing the availability of enzymes, increasing the number of blood vessels, and increasing the amount of an oxygen-storing molecule called myoglobin.

Types of muscle cells

Different types of cells perform the differing functions of endurance activities and **speed-** strength activities. There are three types, **red, white, and intermediate**. The main differences can be exemplified by looking at red and white fibers and remembering that intermediate fibers have properties of the other two.

White Fibers are fast twitch, large diameter, used for speed and strength, fatigable. Depends on the anaerobic energy metabolism, stores glycogen for conversion to glucose, Fewer blood vessels, Little or no myoglobin.

Red Fibers are slow twitch, small diameter, used for endurance. Depends on aerobic metabolism. Utilize fats as well as glucose. Little glycogen storage. Many blood vessels, mitochondria and much myoglobin give this muscle its reddish appearance.

Intermediate Fibers: sometimes called "fast twitch red", these fibers have faster action but rely more on aerobic metabolism and have more endurance.

Most muscles are **mixtures of the different types**. Muscle fiber types and their relative abundance cannot be varied by training.

Cellular Respiration

At the onset of muscular work, energy is supplied primarily from stored high energy particles and from anaerobic glycolysis. This is because circulatory system takes some time to catch up with the higher O2 demand at the muscle site.

CO2, and Lactic acid are built up (causing change in Ph level) in the muscle site triggering the CNS to initiates actions to increase cellular respiration (CO2 and O2 movement in and out of the cells). This is achieved in a combinations of ways (1) **Redistribution of blood** supply (dilating the arteries near the muscle and constricting arteries in skin and other organs), and (2) by increasing cardiac output and ventilation at lungs to maintain the O2 at the working muscle site. Heart rate, stroke volume, blood pressure and respiratory rate increase according to the intensity of the muscular work.

Effect of Muscle tension on Cellular Respiration

Cellular respiration is affected by constriction of the nearby arteries and blood capillaries by the mechanical force developed by the muscle itself.

The blood supply starts to decrease when the muscle contracts with an intensity of 15% of its maximum voluntary contraction (MVC) capacity.

The blood supply is completely occluded above 60% of MVC in most of the muscle cells. Reduction of blood supply means reduction of cellular respiration (O2--supply and CO2 removal).

Static muscular work

An activity which requires muscle to maintain contraction continuously it is called **static muscular work**.

Muscles that are maintaining a static body posture, or holding a hand tool are example of static muscular work.

As blood supply is impeded in this kind of muscle work, depending upon the contraction level, majority of the energy may be produced through anaerobic pathway. As a result, metabolite (Lactic acid) accumulates in the muscle cells and local fatigue of the muscles ensues quickly.

Typical endurance limits of skeletal muscles in static muscle contraction

% MVC	Endurance time for static muscle contractions
100	6 seconds
75	21 seconds
50	1 minute
25	3.4 minute
15	> 4 minute

Dynamic muscular work

In **dynamic muscular work** muscle contraction is followed by a muscle relaxation. **That is static tension interspaced with relaxation.** Work with rhythmic movement, such as walking, is an example of this kind.

During relaxation phase, the blood supply is restored which washes away the metabolite (waste byproducts) and supplies nutrients and oxygen. As a result, this kind of muscle work can be continued for long time without fatigue. The rhythmic movement also helps venous return of blood and thus is less taxing on heart performance.

In dynamic work, maximum intensity of work is determined by the circulatory systems capacity to supply O_2 which is determined by the Maximum heart rate capacity, or by Maximum O_2 (Max VO_2 in L/min) delivering capacity. Fatigue in this kind of work is primarily from the central fatigue, less blood glucose level, etc.