

VII. CONTRACTION--MECHANICS OF WHOLE MUSCLES

A. General

1. **Opposing forces**

- a. **Tension**--the force produced by a muscle's contraction.
- b. **Load**--the force exerted against a muscle at its insertion (i.e. the resistance to the opposing tension).

2. **Results**

- a. **Isotonic**--this occurs when the tension is greater than the load, resulting in movements at the insertion and a shortening of the muscle(s).
Literally this means "constant tension."
- b. **Isometric**--this occurs when the tension is just equal to the load, resulting in the forceful maintenance of the insertion's position and no shortening of the muscle(s). This is generally produced by the simultaneous contraction of two (or two sets) of antagonistic muscles; this causes each to pull upon the other, thus stretching the muscles and preventing them from shortening. The physical basis for this ability of a muscle to remain unshortened while its fibers (cells) are contracting is within the elastic elements, which will be explained later.
Literally isometric means "constant length."

B. All-or-none law

1. **Concept**--this is a statement of the fact that a muscle cell will contract to its maximum ability when stimulated to a minimum or threshold level, or it will not contract at all.
2. **Fibers only**--this law applies only to muscle cells (fibers), and not to whole muscles. Whole muscles do contract to varying degrees.
3. **Threshold depolarization**--to produce all-or-none contraction, a muscle fiber is stimulated via its motor end plate by transmitter from its axon ending, to a particular minimum amount--this is called its threshold. Any amount of stimulation above threshold will result in no greater degree of

contraction. Any stimulation below threshold will result in no contraction at all.

C. **Twitch**

1. **Concept**

- a. **Meaning**--this is the all-or-none contraction produced by a single threshold (or above) stimulus. It is descriptive of the appearance of the muscle, since it is rather jerky.
- b. **Application**--a single fiber or an entire muscle can exhibit this phenomenon. The reason for a muscle "twitching" would be that one or more of its contained fibers has twitched--remember, it is a muscle's individual fibers which are obeying the all-or-none law.
- c. **Time**--the entire twitch cycle takes from 130-220 milliseconds (msec.). Examples--the external eye muscles would be the fastest, the gastrocnemius is intermediate, and the soleus would be the slowest.

2. **Phases**

- a. **Concept**--the twitch cycle includes three coordinated, sequential phenomena.
- b. **Latent period**--this occurs during the first 2-8 msec., during which the motor end plate depolarization is being conducted over the sarcolemma, down the T-tubules, causing the terminal cisternae to release calcium which then binds to troponin of the thin filaments.
- c. **Contraction**--this is the next 10-100 msec., during which the actual filament sliding is occurring, and tension is developing.
- d. **Relaxation**--this is the final 120 msec., during which the sarcoplasmic reticulum's pumping of calcium back in causes the thick filament heads to lose their active binding to the actin molecules of the thin filaments. This allows the muscle or muscle fiber to relax and an automatic lengthening to occur; the elastic elements are responsible for this latter phenomenon, as will be explained later.

3. **Fiber variations**

- a. **Fast (White)**--the muscle cells given this name exhibit the

following characteristics:

Largest diameter.
 Develop the greatest tension.
 Twitch very fast.
 Fewest capillaries in their endomysium.
 Highest glycogen content.
 Low myoglobin content.
 Respire "anaerobically" (fermentation).
 Fatigue the fastest.
 Their controlling motor nerves conduct impulses
 the fastest.

b. **Slow (Red)**--the characteristics of this fiber type are as follows:

Smallest diameter.
 Develop the least tension.
 Twitch the slowest.
 Many capillaries.
 Lowest glycogen content.
 High myoglobin content.
 Respire aerobically.
 Fatigue the slowest.
 Controlled by motor nerves which conduct the
 slowest.

c. **Intermediate**--the characteristics of this fiber type are as follows:

Medium in diameter.
 Develop intermediate amount of tension.
 Twitch rather rapidly.
 Have many capillaries.
 Medium in glycogen content.
 High in myoglobin.
 Respire aerobically.
 Fatigue in a medium amount of time.
 Controlled by motor nerves whose conduction
 speed is intermediate.

d. **Other types**--the above three types of fibers are not absolute, since there are many others in existence, which range in varying categories between fast and slow. Therefore, "intermediate" actually should be interpreted as meaning a number of different types, of faster and slower tendencies and appropriate variations in characteristics.

e. **Distribution**--most muscles will contain more than one fiber type; often all three will be present, or more when considering the vague intermediate category. One will usually predominate, though. Besides the various muscles in one person being different, it is possible for the same muscle to be of diverse

proportions in different people.

- f. **Importance**--it should be obvious that these different fiber types in varying distributions permit a tremendous range of muscle actions. Following are examples:

>Ocular muscles--white, contracting in 10 msec.; they permit the rapid eye responses for this vital sensory function.

>Soleus--red, contracting in 100 msec. Though slow, it permits sustained contractions due to its high myoglobin content and extensive blood supply.

>Gastrocnemius--white, specializing in power and speed. Its low oxygen supply (little myoglobin to carry it) causes the resulting fermentation to limit endurance, with fatigue ensuing rapidly.

D. Varying Degrees of Contraction

1. Recruitment

- a. **Concept**--this is a descriptive term, from the observation that varying contractions will fundamentally be produced by the choice of which and how many of a muscle's fibers will be recruited into action.
- b. **Multiple motor unit summation**--this is the way that varying degrees of tension can be produced in a muscle. It is simply due to a difference in the number of its motor units being activated at one time. The more motor units active at one time, the greater will be the tension produced. This is produced by varying amounts of motor nervous stimulation to the muscle. If more axons are carrying impulses then more muscle fibers will be contracting.
- c. **Different size motor units**--motor units can vary from two (maybe one) to over 2,000 muscle fibers each. Obviously, a muscle with smaller motor units is capable of much more precise variations in its tension. Eye muscles have an average of 23 fibers per unit, hand and laryngeal muscles from just a few to no more than 100, and the gastrocnemius has units ranging from 100-2,000⁺ fibers.
- d. **Fibers varied**--the proportion of fast, slow, and intermediate fibers will be a variable as well. Further, varying thresholds will

exist for different motor units in one muscle.

2. Treppe (staircase)

- a. **Concept**--a rested or "cold" muscle or single fiber, when stimulated at threshold or above repeatedly, but slowly enough to allow complete twitches, will show a gradual increase in tension until a maximum is reached.
- b. **Cause**--this would appear to be an exception to the all-or-none law, since an individual fiber will exhibit this phenomenon. However, a very rested muscle fiber will release increasing increments of calcium from its terminal cisternae for the first few repetitive contractions, until a critical maximum is attained. Therefore, the fiber is contracting to its maximum each time, but the extent possible is gradually increased by this residual calcium buildup until the fiber (or muscle) is "warm."
- c. **Importance**--the warming up of muscles is critical to get them past this period of treppe so that maximum contractions will then occur.

3. Wave summation

- a. **Concept**--with a constant amount of stimulation, but an increased frequency of stimulations, the total tension developed by a muscle will be greater than with a single twitch caused by a single stimulation. At approximately 10-25 stimulations/second a muscle should exhibit this phenomenon. Keep in mind that this is not recruitment, since the number of motor units active will not vary with the constant amount of stimulation.
- b. **Cause**--most simply this is from the addition of partial contractions to each other, producing an almost sustained contraction. This can occur because the twitch cycle is interrupted, so that before complete relaxation can occur from one contraction another stimulation has arrived at the motor end plates--this causes a second, though individually weaker, twitch to be added (kind of "piggyback" fashion) to the first. The same summing of partial twitches would occur for the third and subsequent stimulations. The total amount of contraction is greater because many partial twitches added together will have more tension than a single complete twitch.
- c. **Importance**--this is mostly of theoretical and clinical significance, since smooth, gradual contractions require phenomena such as asynchronous motor unit summation and tetanus (discussed below).

4. **Incomplete (unfused) tetanus**

- a. **Concept**--at about 35 stimulations/second, at a constant amount, the degree of wave summation will be at its peak, almost producing a true sustained contraction with no wavering from slight relaxations between stimulations.
- b. **Cause**--[explained above in "Concept"]

5. **Tetanus**

- a. **Concept**--this is a maximum sustained contraction.
- b. **Cause**--at about 50 or more stimulations/second there is no degree of relaxation allowed between stimulations. This produces a maximum summation of sorts, so that the tension is the most possible from a muscle at that time; different metabolic conditions could inhibit or enhance its maximum.
- c. **Importance**--this intense type of contraction can be appreciated by picking up something heavy enough to offer a challenging load, then trying to just hold it at one position. Eventually one's muscles involved will begin to shake from the effort of a tetanic contraction, because some motor units will be fatiguing while others are maintaining the tetany. Soon all motor units will fatigue and the load must be dropped.

6. **Asynchronous summation**

- a. **Concept**--this is an alternation of motor units which are active at different times. This is sort of like a relay situation, described above in the example for tetanus as the shaking from the slight delay between the rested motor units replacing the fatigued ones.
- b. **Importance**--this is an important reason that smooth muscle contractions occur, despite the jerky twitching of individual fibers.

7. **Initial muscle length**--the stretching of a muscle prior to its contraction will produce more tension. Most muscles are at their optimum length normally, produced by stretch reflexes (to be discussed later). However, additional stretching will increase a muscle's potential. This is analogous to a rubber band, which will snap back harder when released if it was stretched beforehand.

E. Fatigue

1. **Muscle**

- a. **Lactic acid**--this eventual end product of fermentation will cause the tiring of muscles which are being contracted strongly for a sustained period. It does this by creating an oxygen deficit, which can only be made up by a relaxed muscle. All muscles can fatigue, but some will do this faster than others, since fermentation is utilized sooner (or exclusively) in certain ones which contain more fast fibers. Also, lactic acid is the cause of pain in muscles used strenuously, but later soreness is from other phenomena.
- b. **Blood supply**--if a muscle is being tetanized (for example) then its nutrient supply will also be a limiting factor in its speed of fatiguing, either exclusively or along with lactic acid buildup. Further, the blood supply will determine how quickly the oxygen "debt" (deficit) can be made up from lactic acid induced fatigue.

2. **Nerve**--depletion of transmitter or insufficient extracellular sodium for depolarization could cause a neuron to be unable to stimulate the muscle fibers of its motor unit. This would typically only occur during tetanus of a long duration.

F. Elastic Elements (Components)

1. **Concept**--these are parts of muscle cells and muscles which have the quality of elasticity.
2. **Types**
 - a. **Series component**--consists of the tendons, Z-lines, and cross-bridges. They are named due to their being positioned in line (series) with the sarcomeres.
 - b. **Parallel component**--consists of the sarcolemma, the sarcoplasm (its viscosity), and the connective tissues around the fibers (endo-, peri-, and epimysia). Note that these are all along side, that is parallel, to the sarcomeres.
3. **Functions**
 - a. **Stretched muscle force**--these elements are the cause of a stretched muscle contracting more forcefully than when unstretched or less stretched. The reason is that when stretched

there is less thin/thick filament overlap, which creates more bonding and swiveling opportunities during contraction--that is, there can be more room for acceleration.

- b. **Isometric/isotonic differences**--during an isometric contraction the muscle fibers do shorten (contract), however the entire muscle does not shorten. This seeming contradiction is solved by realizing that the elastic elements (primarily the series components) will give with the stretching effect of the antagonistic muscle's pulling, while simultaneously the parallel elements can exert a pull of their own from the tension they receive from the contracting fibers. Thus, an isometric contraction very definitely involves tension development, but of an opposing nature. It is good to think of the elastic elements as a stretchable harness attached to the fibers (the horse) pulling a bone (the wagon). Completing this analogy would be one or more other horses harnessed to the same wagon, passively allowing the first one to pull the wagon (isotonic), resisting the first one's pull (isometric), or assisting the first one (isotonic, as a synergist).
- c. **Relaxation**--when filaments cease sliding they are pulled apart by the tension still within the parallel elastic elements. The entire muscle will relax and lengthen by the same token.
- d. **Smooth tension development**--the elastic elements are much more capable of undergoing smooth tension changes than the muscle fibers' thick and thin filaments; despite cross-bridge asynchrony, there is still an abruptness to filament sliding. Thus, the tension is taken from the sarcomeres by these elastic structures which can pass it on to the insertion more gradually.

G. Tone (Tonus)

1. **Concept**--this is a condition of steady, continual, partial contraction of all healthy muscles, when a person is conscious.
2. **Stretch reflexes**
 - a. **Prestretching**--this involves the stretching of relaxed muscles by their antagonists, so that when contractions occur in the former they will be more efficient in tension production.
 - b. **Posture**--this involves the anti-gravity muscles--neck retractors, jaw elevators, back extensors, and knee and ankle extensors. They receive tonal nervous impulses to maintain the body's basic position. Their significance is dramatically appreciated when noting the loss of tone during unconsciousness.

- c. **Receptors**--there are special sense organs, the stretch receptors, located within a muscle's belly and tendons, which keep the nervous system informed of the degree of tone in order to make adjustments as necessary.