Space Biomedical Engineering
& Life Support

Muscle Mechanics, Reflexes and Motor Control

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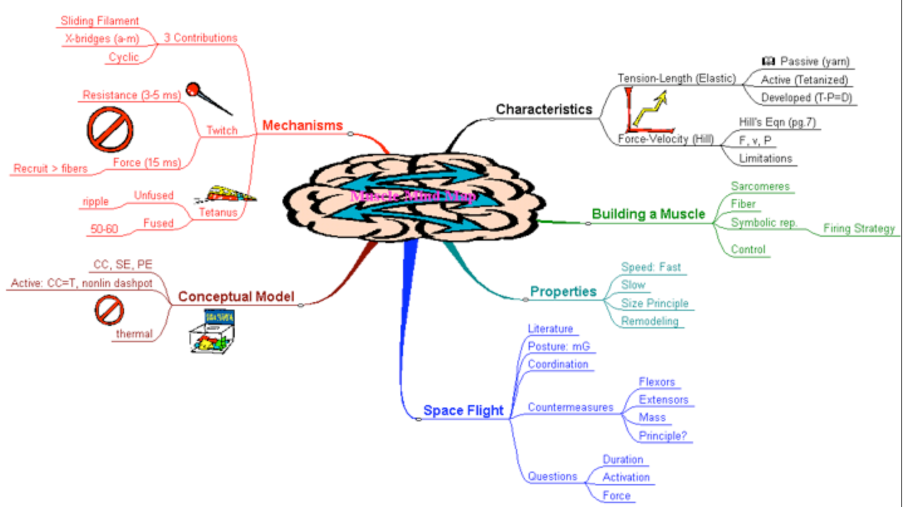
Muscle - Summary



Muscle Strength Loss in Microgravity

Strength loss over time

- Reported 40% lower at 6 months, 60% at 12 months
  - 21% lower peak activate force 17-day flight [Widrick, 1999]
  - 120 days HDT bed rest [Koryak 1999]
    - 44% / 33% (M/F) decline in isometric max. voluntary contraction (MVC)
    - 36% / 11% (M/F) decline in isometric twitch contraction
    - 34% / 24% (M/F) decline in tetanic contraction force
  - Maximal explosive power (MEP) reduced to 67% after 31 days, 45% after 180 days of space flight [Antonutto et al., 1999]

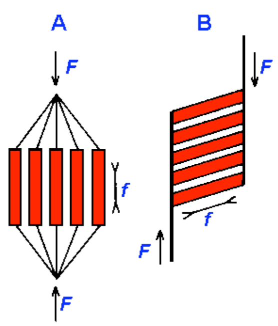
Muscle Mechanics

- Musclemechanics2006.pdf
  (Stellar course website)

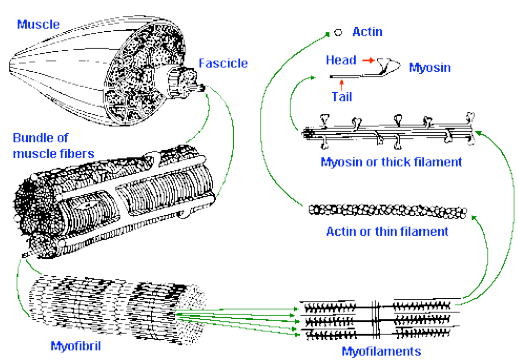
Effectors of the Motor System

- The major output of the elaborate information processing that takes place in our brain is the generation of a contractile force in our skeletal muscles.
- Muscle fasciculus
  - Muscle fiber
    - Myofibril
      - Sarcomere
- Each muscle fiber is innervated by only one motor neuron, although each motor neuron innervates a number of muscle fibers
- The motor neuron and all the fibers it innervates is called a motor unit (the smallest functional unit controlled by the motor system)

Skeletal Muscle



Two arrangements of muscle fibers within a muscle. A. Parallel arrangement: Tendons are lines radiating from rectangles (muscle fibers) at each end. B. Pennate arrangement: Tendons are vertical lines extending from the two sides of the parallelogram. (Zierler KL: Mechansims of muscle contraction and its energetics. In: Mountcastle VB [ed]: Medical Physiology. 13th ed, Vol. 1. St. Louis, C.V. Mosby, 1974).



Skeletal muscle organization: CCW whole muscle and fascicles, bundles of muscle fibers, myofibrils, thin and thick filaments, and myosin and actin molecules. (Warwick R, Williams PL [ed]: Grays' Anatomy. 35th British ed, Edinburgh, Churchill Livingston, 1973; modified from a drawing by Professor D Fawcett)

http://www.unmc.edu/Physiology/Mann/mann14.html

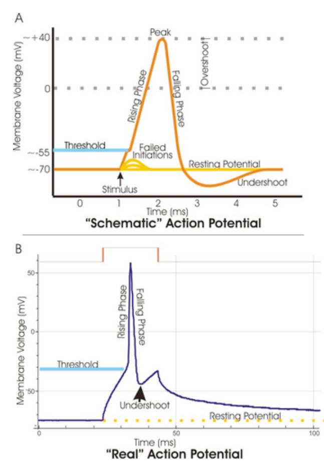
Innervation, Size and Force

- The number of muscle fibers innervated by one motor neuron is called the innervation ratio. The innervation ratio can vary between 10 and 2000
- A low innervation ratio indicates a greater capacity for finely tuning the muscle total force
- Size Principle [McMahon, 1984 and before him Henneman]

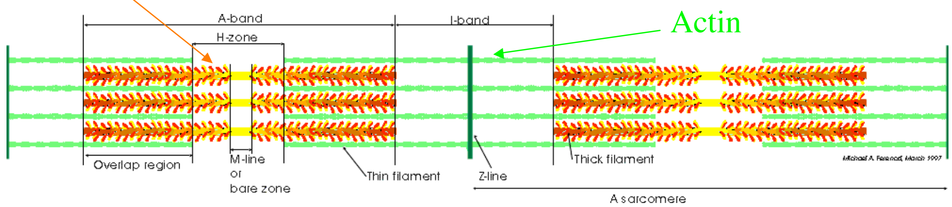
  Large motor units require the greatest amplitude of stimulus to become active. The smallest and most excitable neurons are turned on at a low level of stimulus strength, with the consequence that the muscle force may be finely tuned at low levels through small adjustments in the number of muscle fibers active. The larger motor units come in only at high levels of force.

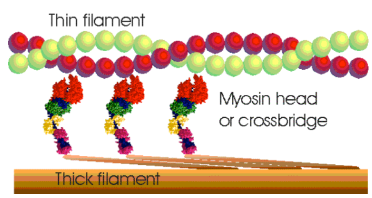
From Action Potential (AP) to muscular contraction

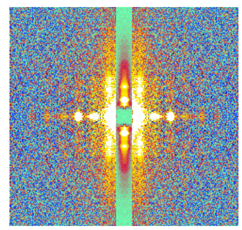
- Motor neuron fires an action potential
- It propagates down the motor axon until it reaches the neuro-muscular junction
- It triggers an AP in the muscle fiber
- This AP is propagated rapidly over the surface of the fiber and conducted into myofibril by the T-tubule system
- This in turn releases Ca^{++} from the Sarcoplasmic Reticulum (SR)-the SR serves as a store of Ca^{++}
- This in turn triggers the cyclic motion of Myosin heads, attaching and detaching on the Actin filaments, thus forming cross-bridges and generating the pulling force
- Ca^{++} are pumped back to the SR



Sliding Filament Model







Cross-Bridge Theory

- The cross-bridge theory says that sliding is produced by physical attachment of myosin heads to actin and by rotation of the heads.

• Assumes that the force generated by the muscle is proportional to the number of cross-bridge linkages formed

• Probability of formation of a cross-bridge is proportional to the speed of shortening, i.e., the probability is great when attachment sites move slowly past one another, small when they move rapidly.

• If tension is a function only of the number of cross-bridges, then there should be a linear relationship between length and tension such that tension increases with decreasing length because of the greater overlap of thick and thin filaments at shorter lengths.

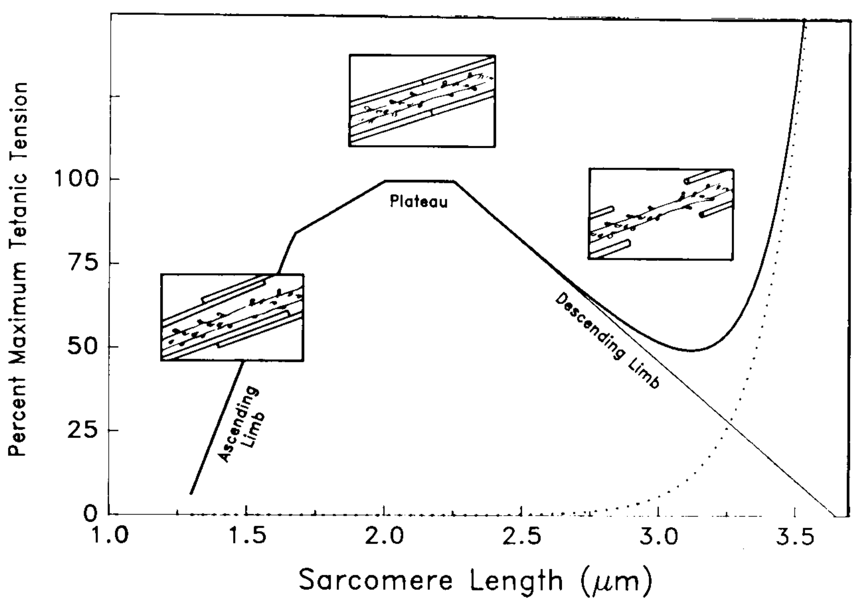
• The force required to stretch the muscle at any time is therefore also proportional to the number of cross-bridges-it is the force required to break the actin-myosin bonds.

Summary: 1.Tension is developed by physical bonds between thick and thin
2.Tension depends upon the degree of overlap between thick and thin filaments.
3.The cross-bridge originates at the thick filament and terminates at the thin filament.

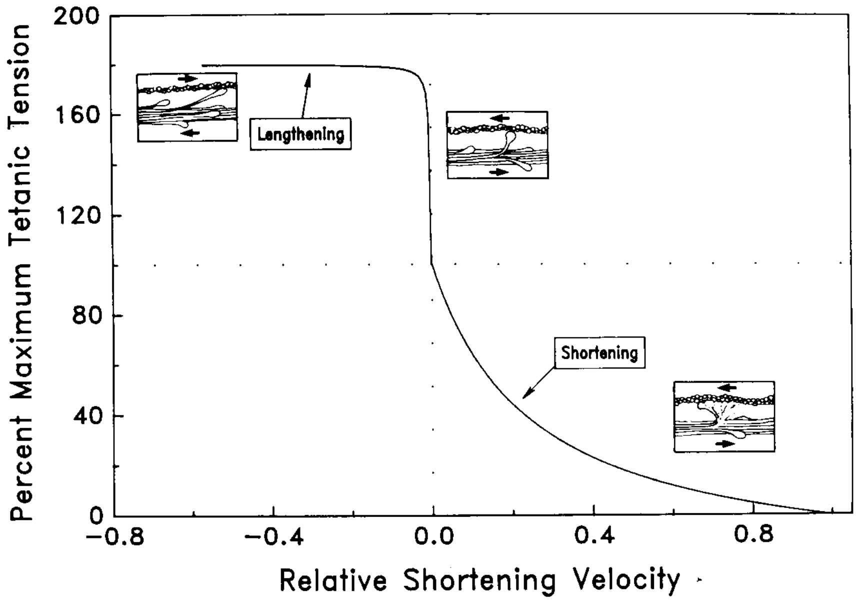
Muscle Contraction

- The force of contraction depends on the length of the muscle (length-tension relationship)
- The force of contraction also depends on the relative rates of movement of the Actin and Myosin filaments (tension-velocity relationship, Hill's curve)
- Motor units are recruited in a fixed order from the weakest to the strongest (Henneman size principle): The weakest inputs recruit the slow units which generate the smallest force and are most resistant to fatigue. The fast fatigue-resistant are recruited next, followed by the fast fatigable units which generate the strongest force.

Length Tension Curve



Force-Velocity Curve (Hill's Curve)



Dark (red) meat or Light (white) meat?

Motor Unit Properties	*Red Muscle Fibers*	*White Muscle Fibers*
Number of motor units	many	few
Number of muscle fibers per motor unit	few	many
Axon diameter	small	large
Tetanic tension	small	large
Contraction speed	slow	rapid
Fatigue	slow (difficult)	rapid (easy)
Metabolism	aerobic	anaerobic
Blood supply	rich	sparse
Twitch contraction time	slow, 100-200 ms	fast 50-80 ms
Minimum tetanic frequency	16/sec	60/sec
Nerve fiber activity	Continuous, low freq.	Intermittent, high freq.
Muscle Fibers	***Slow Oxidative (SO)***	***Fast Glycolitic (FG)***
	Contract rapidly, oxidative, & glycolitic (FOG)	

Although a motor unit consists of only 1 kind of muscle fiber, most muscles are mixture Of all 3. Soleus=red= 87-100%SO Gastrocnemius=white FG 41-66%, FOG 14-38%, SO 5-45%

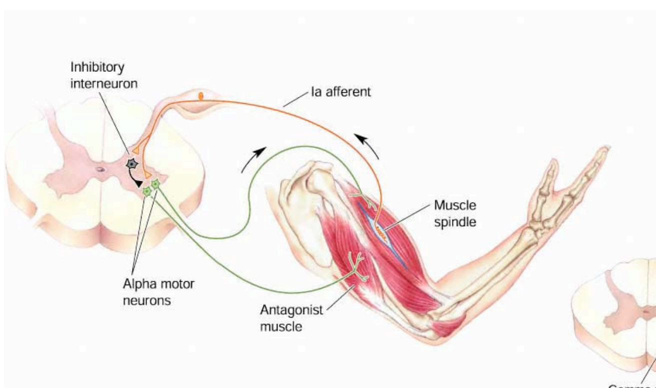
Muscle Proprioceptors
(Spindles and Golgi tendons)

- Muscle Proprioceptors (Spindles and Golgi tendons)

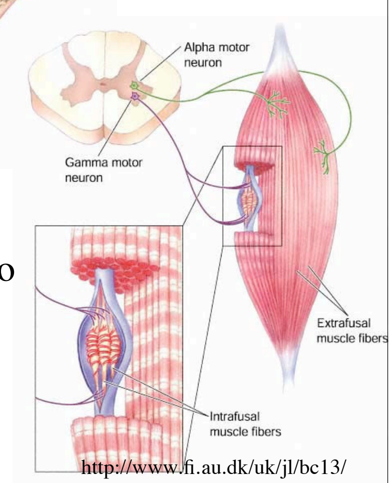
  There are different types of receptors which respond to light, sound, odor, heat, touch, pain, etc. The receptors which lead to conscious sensations are called **exteroceptors**, those that are not responsible for conscious sensation are called- *primary in motor functions*- are called **proprioceptors**

  – **Spindle organs**: Stretch receptors scattered deep within all muscles. They are usually attached in parallel with a muscle fiber, and therefore experience the same relative length change. Spindles give information about muscle **length** and **rate of change** of length

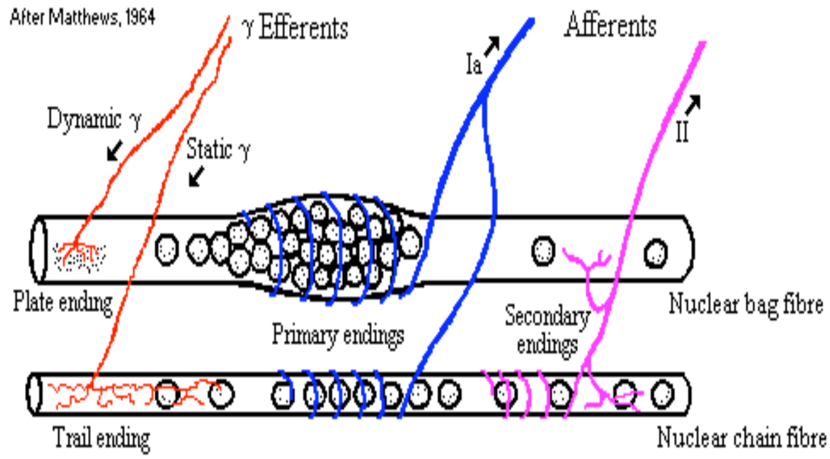
  – **Golgi tendon:** are found very close to the junction between tendon and muscle fibers. They are placed in series with the muscle fibers and respond to the tendon stretch which accompanies a muscle tension. Thus they are **force transducers** for the muscle.



- Extrafusal vs. Intrafusal fibers
  – Extrafusal - muscle fibers used to produce muscular contraction
  – Intrafusal - muscle fiber comprising the spindle



http://www.fi.au.dk/uk/jl/bc13/



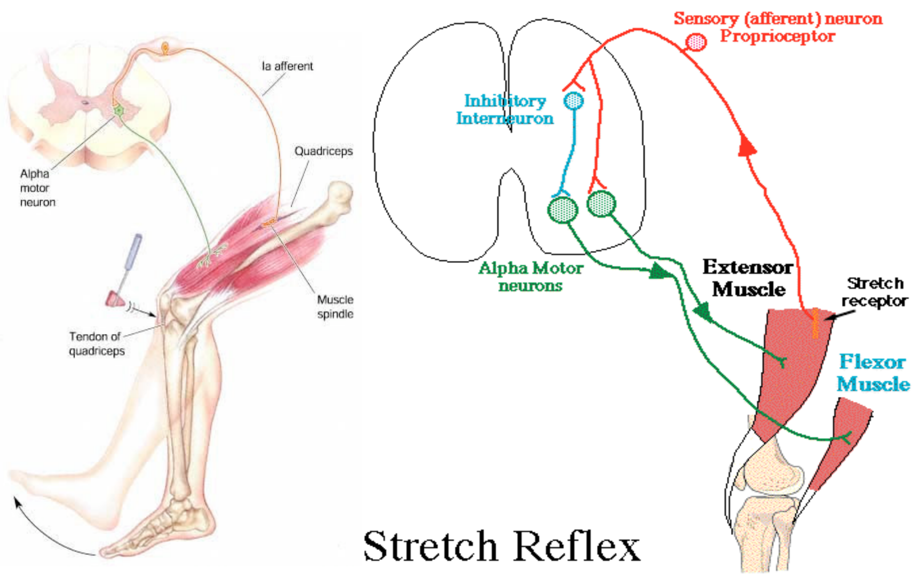
http://www.umds.ac.uk/physiology/mcal/spin1.html

Muscle Contraction: Afferent and efferent axons

- The nerve axons which run out of the spinal cord are called **efferent**, the ones that carry information to the cord are **afferent**
- Group I afferent fibers have large diameters therefore relatively high conduction velocities. They bring information from the spindle (Ia) and the golgi (Ib) to the cord
- The efferent which innervate the main muscle mass are the α, and those that serve the intrafusal fibers within the spindles are called γ
- The stretch reflex, co-activation of α-mn and γ-mn

Stretch reflex stiffness

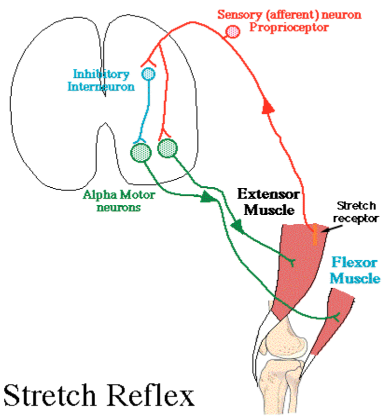
- Until recently, it was supposed that the tendon organ served as a sensor that turned off muscle activity (inhibited α-mn) when muscle force rose beyond safe levels
- Afferent activity from both spindles and Golgi tendons balance in such a way that neither muscle force nor muscle length should be considered as controlled quantity, rather their ratio (the stiffness or change in force per change in length) appears to be fixed by the stretch reflex



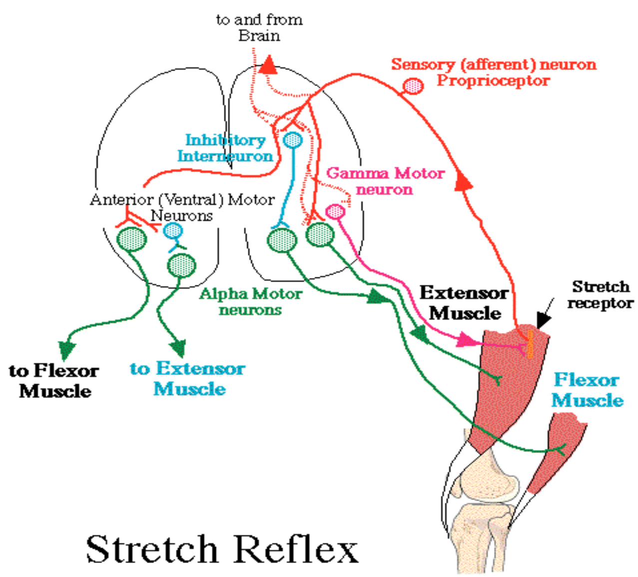
http://www.fi.au.dk/uk/jl/bc13/fig1317.jpg

Reciprocal Inhibition

- Complementary to Stretch reflex
- Inhibits antagonist muscles



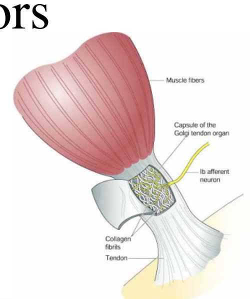
Stretch Reflex

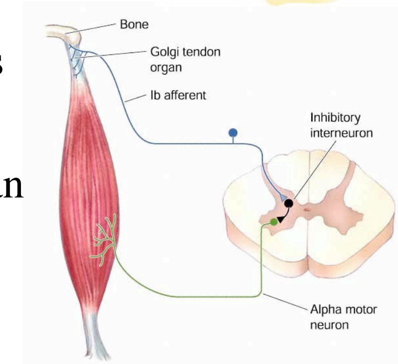


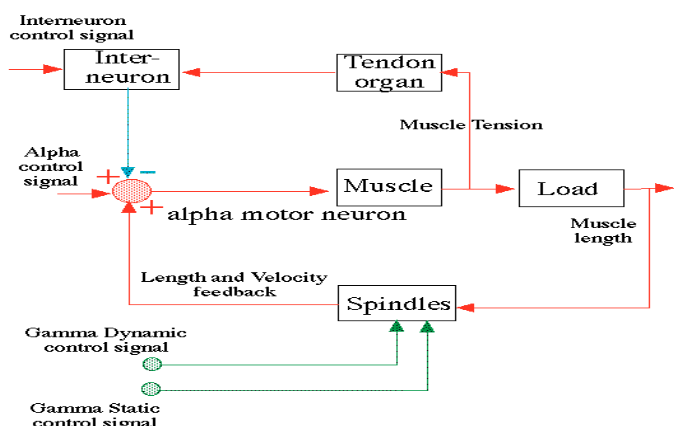
Stretch Reflex

Golgi Tendon Receptors

- Detect muscle tension
- Parallel to muscle fibers
- Produces muscle relaxation
- Less sensitive than spindles
- Override spindles
- More sensitive to active than tension







www.rpi.edu/dept/naturalsci/parsons/BIO4/BIO4J.html

See Lecture Notes on Proposed Enhanced Model

Saleh and Newman

Higher Level Control

- **The sensorimotor cortex** is at the top of the chain of command in the sensorimotor area of the cerebral cortex. There is a specialized area in the cerebral cortex devoted to movement of the limbs (1691, the case of a knight with a fractured skull and paralysis of the left side of the body)
  - The fraction of the cerebral cortex controlling each part of the body is by no means proportional to the size of that part
  - If the cerebral cortex is removed, the animal continues to display all the locomotion reflexes, but cannot learn new skills
- **Basal ganglia** are a set of specialized nerve cells in the brain stem.
- **Cerebellum** is a major focus of incoming sensory information. The information reaching the cerebellum has to do with length, force, velocity of muscles and position of joints.