



Early Ideas about Muscular Contraction

Hippocrates thought that the tendons caused the body to move (he confused tendons with nerves, and in fact used the same word, neuron, for both).

Aristotle compared the movements of animals to the movements of puppets and thought that the tendons played the role of the puppet strings, bringing about motion as they were tightened and released.

Muscles themselves were not credited with the ability to contract until the third century BC when Erasistratus suggested that the animal spirit flows from the head through the nerves to the muscle. He thought the nerves were hollow tubes, through which the muscles could be filled with pneuma, causing them to expand in breadth but contract in length, thus moving the joints. Actually, muscles don't increase in volume as they contract!

Jan Swammerdam in the early 1660's showed that muscle contracts without changing its volume. Using a frog muscle in a sealed air-filled glass and preserving the length of a nerve, the nerve was stimulated mechanically (pulling on it with a fine wire). A drop of water in the small tube should have risen if the muscle volume increased, but it did not. Extended to human muscles by Francis Glisson in 1677 (arm in a water filled rigid tube, sealed at the elbow).

Most of what has been learned about muscle mechanics is from whole muscles removed from the animal. Many of the most important experiments being performed between 1910 and 1950 by A.V. Hill and his collaborators at University College, London. Isolated from muscle preparation (alive for several days in an oxygenated solution). When given a stimulus, the mechanical and thermal activation will not be synchronous at all points because the wave of electrical excitation is fairly slow (30-40 m/s in amphibian muscle).

The fact that muscle is turned on electrically is very interesting.

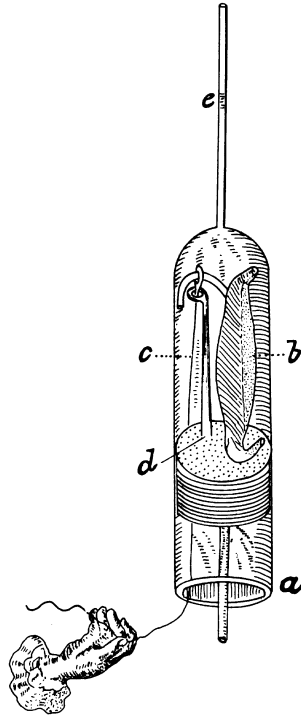


Figure 1. The experiment of Jan Swammerdam, circa 1663, showing that a muscle does not increase in volume as it contracts. A frog's muscle (*b*) is placed in an air-filled tube closed at the bottom (*a*). When the fine wire (*c*) is pulled, the nerve is pinched against the support (*d*), causing the muscle to contract. The drop of water in the capillary tube (*e*) does not move up when the muscle contracts. From Needham (1971).

Mechanical Events: Twitch and Tetanus

The first mechanical event it is possible to measure following stimulation is not the development of force, but the resistance to an externally imposed stretch. Even before the electrical action potential is over, about 3-5 msec after the stimulating shock, the contractile machinery feels stiffer to an external pull than it does when subjected to a similar pull without first being shocked.

There is latency for about 15 msec following the shock and the muscle produces no force (if stimulated under isometric = constant length conditions). Finally, the muscle responds, and if it was given a single stimulus, it produces a single transient rise in tension = TWITCH.

The strength of the stimulus must be strong enough to depolarize the muscle membrane - otherwise nothing happens. Over a limited range above the threshold amplitude, the peak force developed in the twitch rises with the strength of the stimulus, as more muscle fibers are recruited into the force-generating enterprise. Once the majority of muscle fibers become active there are no further increases in force.

If a train of stimulations is given, the force has a steady magnitude with a little ripple at the stimulation frequency = Unfused Tetanus. As the frequency is raised, mean force rises and the ripple finally reaches a very low level (about 30 shocks per sec). Further increase in freq. produce no further increases in mean force = TETANIC FUSION (mammalian muscle at body temp. 50-60 shocks per sec).

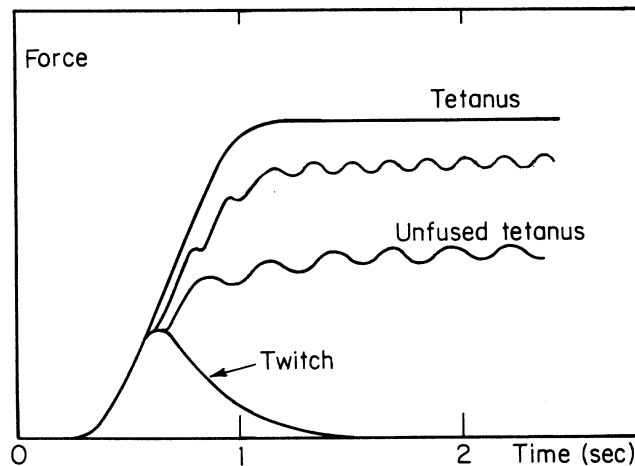


Figure 2. Twitch and tetanus. When a series of stimuli is given, muscle force rises to an uneven plateau (unfused tetanus) which has a ripple at the frequency of stimulation. As the frequency is increased, the plateau rises and becomes smoother, reaching a limit as the tetanus becomes fused.

Tension-Length Curves: Passive and Active

Marey knew that somehow the elasticity of muscle must be one of the features that determine how the separate effects of a sequence of shocks coalesce in a tetanus. There are 2 separate elements of elastic behavior: one due to PASSIVE and one due to ACTIVE properties.

Passive properties:

Force is recorded as the muscle is stretched to a number of constant lengths, with no stimulation. Curve gets progressively steeper with larger stretch, same reason that a piece of yarn gets stiffer as it's extended - fibrous elements which were redundant at low extension become tensed at high extension, thereby adding their spring stiffness in parallel.

The derivative of stress with respect to strain, $d\sigma/d\lambda$, is shown to be a linearly increasing function of the stress ($\sigma = F/A$)

$$1 \quad \frac{d\sigma}{d\lambda} = \alpha(\sigma + \beta)$$

where λ is the Lagrangian strain, ℓ/ℓ_0 , when a muscle of rest length ℓ_0 is stretched to a new length ℓ . Integrating,

$$2 \quad \sigma = \mu e^{\alpha\lambda} - \beta$$

where μ is the constant of integration (rabbit heart muscle, many collagenous tissues - tendons, skin, resting skeletal muscle obey similar exponential relationships between stress and strain. No plausible derivation of this form from first principles has yet been given!

When the muscle is tetanized, the tension at each length is greater than it was when the muscle was resting (some show a local max.)

Developed tension (difference between the active (tetanized) and passive curves) is greatest when the muscle is held at a length close to the length it occupied in the body. The maximum developed stress is almost a constant, about 2 kg/cm² (in mammalian muscles taken from animals of a wide range of body sizes). Noteworthy, because many other parameters (shortening speed, activity of enzymes controlling metabolic rate) are very different in animals and even between muscles. Cross-sectional area of muscle doesn't have a unique meaning in muscle which tapers down into a tendon on either end, so divide the weight in grams by the length in centimeters (assuming muscle density ~ 1 g/cm³).

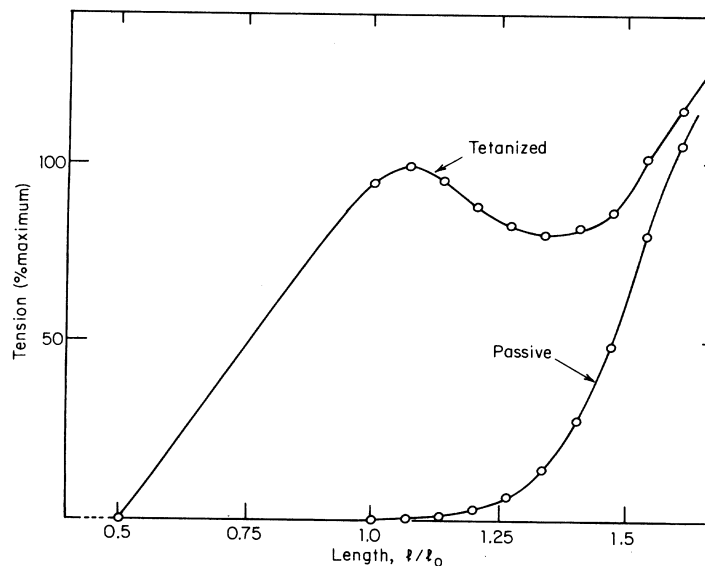


Figure 3. Tension-length curves for frog satorius muscle at 0°C. The passive curve was measured on the resting muscle at a series of different lengths. The tetanized curve was measured at a series of constant lengths as the muscle was

held in isometric contraction. The rest length, l_0 , was the length of the muscle in the body. From Aubert et al. (1951).

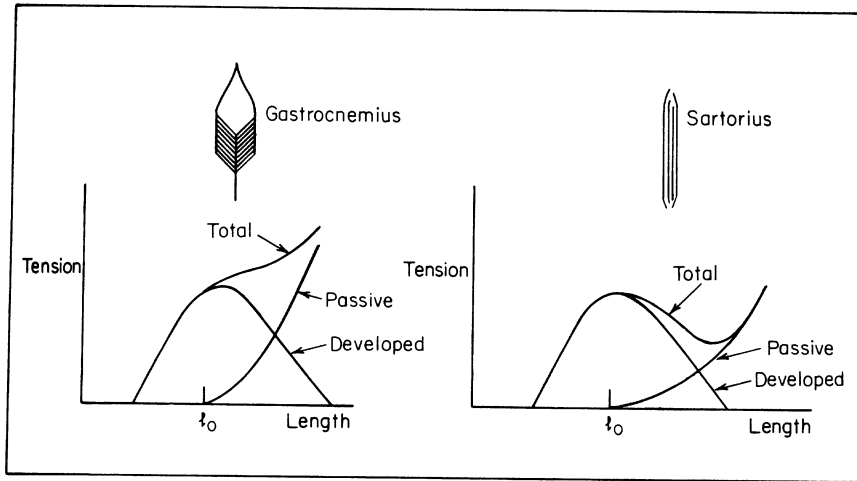


Figure 4. Schematic force-length curves. The pennate-fibered gastrocnemius (left), with its short fibers and relatively great volume of connective tissue, does not show a local maximum in the tetanic length-tension curve. By contrast, the parallel-fibered sartorius (right) does show a maximum.

Conceptual Model of Muscle

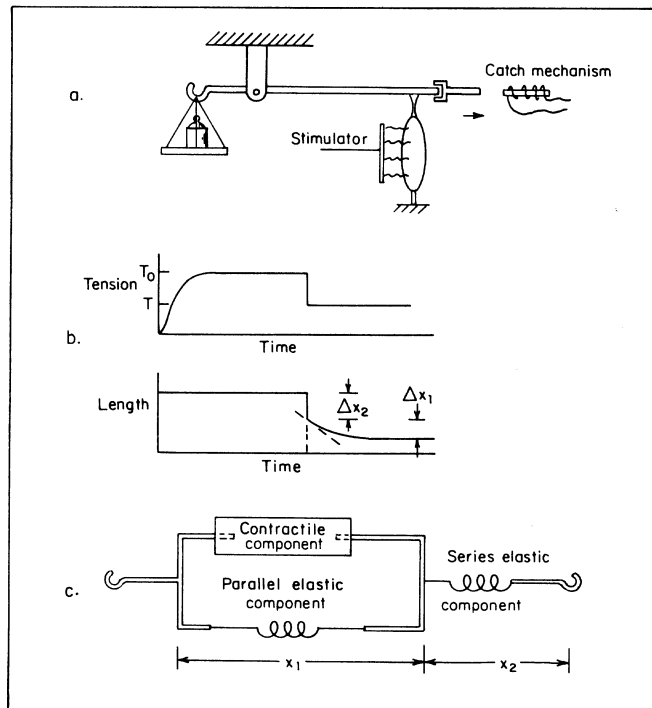


Figure 5. (a) Quick-release apparatus. When the catch is withdrawn, the muscle is exposed to a constant force determined by the weight in the pan. (b) The muscle is stimulated tetanically. Upon release of the catch, the muscle shortens

rapidly by an amount Δx_2 which depends on the difference in force before and after release. (c) A conceptual model of muscle.

Series elastic component in this diagram is in the tendons, since they must ultimately transmit the muscle force to bone. The parallel elastic component acts in parallel with the part of the muscle which generates the force - contractile component.

Together, parallel and series elastic components account for the passive tension properties of muscle. This model only represents the gross features of whole muscle mechanics. (single muscle fibers, without tendons, requires more advanced models, Ch 5).

Series Elastic (SE) Component

Quick release experiments provide direct evidence of a series elastic component. The rapid change in length which accompanies the sharp change in load is consistent with the mechanical definition of a spring, which has a unique length for every tension but is entirely indifferent to how fast its length is changing. Series elastic element for both skeletal and cardiac muscle has been shown to fit the same exponential form [2. $\sigma = \mu e^{\alpha x} - \beta$ (tension=y vs. extension=x) found for the parallel elastic element].

Force - Velocity Curves

All of this assumes that the contractile component (CC) is damped by some viscous mechanism and cannot change its length instantaneously. You've probably all experienced that muscles shorten more rapidly against light loads than they do against heavy ones. (lift a light or heavy weight from the floor). Inertia, yes, but main cause it that muscles which are actively shortening can produce less force than those which contract isometrically.

Suppose that the CC is not capable of instantaneous length change. Then all the rapid shortening in the quick release experiment is taken up in the SE component. Further length changes must now be attributed to the CC alone since the tension, and thus the SE length, is held constant.

Particularly important is the rate at which the CC shortens before it has time to move very far from its initial length (broken line tangent to the length-time curve just after the rapid shortening phase, 1.8b). When this initial slope is plotted against the isotonic afterload, T, a characteristic curve is obtained which shows an inverse relation between force, T, and shortening velocity, v. A.V. Hill (1938) proposed an empirical relation which emphasized the hyperbolic form of the curve,

$$3. \quad (T + a)(v + B) = (T_o + a)b$$

This is a rectangular hyperbola whose asymptotes are not $T=0$ and $v=0$ but $T=-a$ and $v=-b$. The isometric tension T_o defines the force against which the muscle neither shortens nor lengthens, and the speed $v_{\max}=bT_o/a$ is the shortening velocity against no load. Hill's Equation is found to describe nearly all muscles thus far examined, including cardiac and smooth muscle as well as skeletal muscle (even contracting actomyosin threads, more on that later, read Chapters). Only insect flight muscle seems to be an exception, and this muscle is extraordinary in many other respects, particularly in its very short working stroke. Hill's equation can be written in normalized form:

$$4. \quad v' = (1 - T') / (1 + T' / k)$$

where $v' = v / v_{\max}$, $T' = T / T_o$, $k = a / T_o = b / v_{\max}$. For most vertebrate muscles, the curve described by Hill's eq. has a similar shape. In fact, k usually lies within the range $0.15 < k < 0.25$.

The mechanical power output available from a muscle,

$$5. \quad Power = Tv = \frac{v(bT_o - av)}{v + b}$$

has a maximum when the force and speed are between a 1/3 and a 1/4 their maximum values. It is apparent that the speed of shortening controls the rate at which mechanical energy leaves the muscle. The peak in the curve corresponds to about $0.1 T_o v_{\max}$ watts. Bicycles have gears so that you can take advantage of this, by using the gears they can keep muscle shortening velocity close the maximum-power point.

Active State

The fact that muscle develops its greatest force when the speed of shortening is zero led AV Hill (1922) to suggest that stimulation always brings about development of this maximal force, but that some of the force is dissipated in overcoming an inherent viscous resistance if the muscle is shortening. Thus he proposed representing the contractile element as a pure force generator in parallel with a nonlinear dashpot element (defined in a minute, Fig. 6). Pure force generator="active state" and proposed that it could develop a force T_o which rose and then fell after a single electrical stimulation. In a tetanus, this active state force would rise to a constant level numerically equal to the

developed isometric tension. The active state force was therefore a function of the length of the contractile element, x_1 , as was the tetanic developed tension.

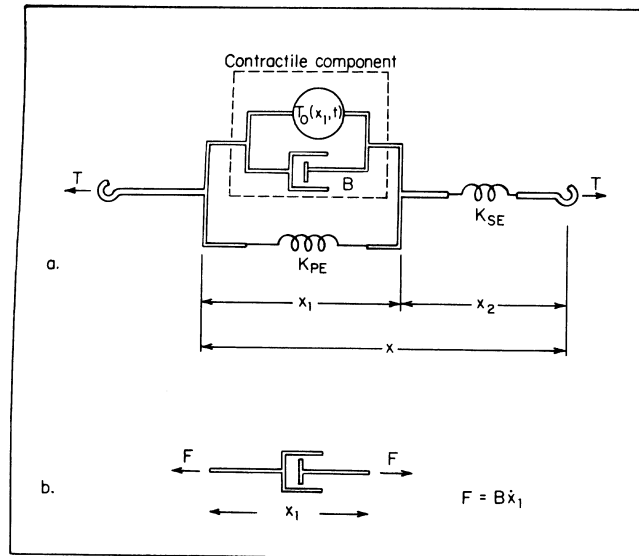


Figure 6. (a) Active state muscle model. The active state $T_0(x_1, t)$ is the tension developed by the force generator in the circle. (b) The dashpot element resists with a force proportional to the velocity.

Dashpot elements develop 0 force when they are stationary, but resist length changes with a force $F = B \dot{x}_1$, where B may be either a constant or a function of \dot{x}_1 (Fig. 7b; dot $\dot{}$ denotes $d()/dt$)

Isotonic contractions (i.e., muscle is shortening against a constant load) were first investigated by Fenn and March (1935). They found (Hill did later, 1938) that the relation between developed force and shortening velocity is nonlinear, therefore that the dashpot element has an acutely velocity-dependent damping.

As the mechanical circuit element suggests, engineering dashpot elements can be made by fitting a piston into a cylinder with enough clearance to allow fluid to escape past the piston as it moves. Since muscle contains a lot of water, the dashpot model suggests that the viscosity of water ultimately determines the viscous property of active muscle. But water is a Newtonian fluid; its viscosity is not a function of shear rate, provided laminar flow is maintained. A non-Newtonian liquid would have to be postulated in order to explain the velocity-dependent damping in muscle.

By contrast the damping factor B for muscle was shown to be strongly dependent on shortening speed (Hill curve) and temperature. In order for muscle to suffer

such a large change in internal viscosity temperature, it would have to be filled with a viscous fluid with the properties similar to castor oil.

It may have been these thoughts which led Fenn to doubt that anything as simple as a dashpot was responsible for the force-velocity behavior of muscle. He proposed, correctly, that a biochemical reaction controlled the rate of energy release and therefore the mechanical properties.

Nevertheless, the model (Fig. 6) has proven enormously useful in calculating the purely mechanical features of skeletal muscle working against a load. If T_0 is specified as a function of time, and if $B(x_1)$, $K_{PE}(x_1)$, and $K_{SE}(x_2)$ are given as empirical relations, then the overall length x and tension T of the muscle can be calculated.

Muscles Active While Lengthening

In ordinary tasks, such as running, muscle functions to stop the motion of the body as often as it does to start it. When a load larger than the isometric tetanus tension T_0 is applied to a muscle in a tetanic state of activation, the muscle lengthens at a constant speed. The surprise turns out to be that the steady speed of lengthening is much smaller than would be expected from an extrapolation of the Hill eqn. to the negative velocity region. In fact, Katz (1939) found that $-dT/dv$, the negative slope of the force-velocity curve, is about six times greater for slow lengthening than for slow shortening.

Another anomaly is that the muscle "gives" or increases length rapidly, when the load is raised about a certain threshold, as shown in Fig. 7, this "give" becomes a very large effect, almost as if the muscle had lost its ability to resist stretching, when the load is about $1.8 T_0$.

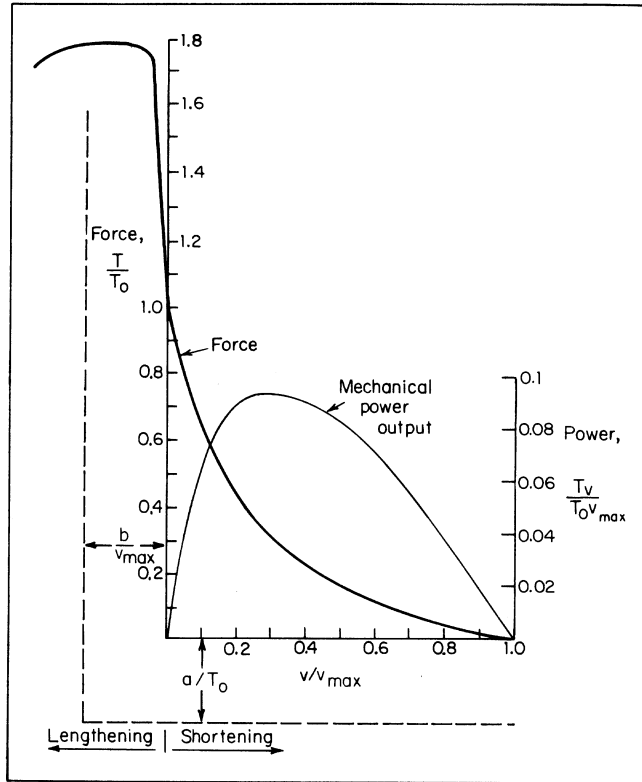


Figure 7. Hill's force-velocity curve. The shortening part of the curve was calculated from eq. (1.4) with $k = 0.25$. The asymptotes for Hill's hyperbola (broken lines) are parallel to the T/T_0 and v/v_{\max} axes. Near zero shortening velocity, the lengthening part of the curve has a negative slope approximately six times steeper than the shortening part. The externally delivered power was calculated from the product of tension and shortening velocity.

Summary and Conclusion

Introduce the schematic diagram of Fig. 7 whose parameters can be obtained empirically from mechanical experiments. Force-length of the parallel elastic spring KPE and active force generator T_0 can be found from passive and tetanic force-length experiments, respectively. Series elastic element KSE and the dashpot element $B(x_1)$ are determined from the initial (instantaneous) length change and early slope of the length record in the quick-release experiments.

Limitations: no one has believed in Fig. 6 as a comprehensive representation of the way muscle actually works since about 1924. Most notable among the failures of the "viscoelastic" model is its inability to account for the Fenn effect (not enough time to go into the metabolic properties).

Clarification on a 'muddy point' of the Force-Velocity relationship

Muscles Active while Lengthening

Consider the example of ordinary exercise, let's say one of the running events in the Olympics. Muscles function to stop the motion of the athlete as often as it does to start it. When a load larger than isometric tetanus tension T_0 is applied to a muscle in a tetanic state of activation, the muscle lengthens at a constant speed. The surprising thing is that the steady speed of lengthening is much smaller than would be expected from an extrapolation of the Hill equation (recall the empirical hyperbolic relation) to the negative velocity region. In fact, Katz (1939) found that $-dT/dv$, the negative slope of the force-velocity curve, is about six times greater for slow lengthening than for slow shortening.

Another anomaly is that muscle 'gives', or increase length rapidly, when the load is raised above a certain threshold (the plateau and ultimate demise of the F-V curve). The 'give' becomes an overwhelming effect, almost as if the muscle had lost its ability to resist stretching, when the load is about $1.8 T_0$.

- McMahon, T.A. Muscles, Reflexes and Locomotion. 1984. taken from pp. 16-17.
- Katz, B. The relation between force and speed in muscular contraction. J. Physiol. 96:45-64. 1939.
- Hill, A.V. The maximum work and mechanical efficiency of human muscles, and their most economical speed. J. Physiol. 56:19-41. 1922.
- The heat of shortening and the dynamic constants of muscle. Proc. Roy. Soc. B. 126:136-195. 1938.

Prof. Newman
Summary

Muscle Performance Facts [McMahon, Muscles, Reflexes and Locomotion, 1984]

1. In shortening, the relationship between the Force and Velocity is (Hill's Curve - know this!!):

$$(T+a)(v+b) = (T_0+a)b \quad \text{Hyperbolic Form}$$

- muscles shorten more rapidly against light loads than they do against heavy ones
- muscles which are actively shortening can produce less force than those which contract isometrically.

2. There is a discontinuity in the slope of F-V curve at zero velocity.

3. Active muscle yields when the load exceeds about 1.8 T_0 (T_0 - Tetanus tension).

4. Hill's observations of the Fenn effect give a linear relation between total rate of energy liberation and tension.

Fenn = muscle produces a certain extra heat when it shortens a given distance, whether shortening velocity is fast or slow.

5. Muscle shortening should be based on the relative motion of sliding filaments because:

- A. A-band width stays constant during stretch and shortening
- B. A-band disappears when myosin is dissolved away
- C. Actin filaments begin at Z-line, run through I-bands into A-band, but stop before reaching H-zone (muscle at rest length)
 - I-band is entirely actin filaments
 - H-zone is myosin filaments

6. Muscular energy liberation should be based on the splitting of a high-energy phosphate as actomyosin attachments separate.

Robot / Human Comparisons (how inhumane)

Table I presents some of the elements of robotic and animal movement systems neatly compared for your viewing pleasure.

Table I. Comparison of Movement Control Systems in the Robot and Human

	<i>ROBOT</i>	<i>HUMAN</i>
<i>Communication</i>	wires	10 ⁵ -10 ⁶ axons
<i>Speed</i>	3 x 10 ⁸ m/sec	10-100 m/sec
<i>Control System</i>	computer	brain/spinal cord
<i>Effectors</i>	motors (linear)	400 ⁺ muscles (non-linear)
<i>Effector Directionality</i>	push or pull	pull only
<i>Transmission</i>	gears/linkages (precise geometry)	joints/tendons (nightmare geometry)
<i>Degree of Freedom</i>	<10	~100
<i>Control Design</i>	closed loop	closed loop
<i>Transducers</i>	position velocity acceleration	position (Muscle spindle) velocity (Muscle spindle) force (Golgi Tendon Organ)

Table II Motor Unit Properties (adapted from Henneman, 1980).

	<i>Red Muscle Fibers</i>	<i>White Muscle Fibers</i>
<i>Number of motor units</i>	many	few
<i>Number of muscle fibers per motor unit</i>	few	many
<i>Axon diameter</i>	small	large
<i>Tetanic tension</i>	small	large
<i>Contraction speed</i>	slow	rapid
<i>Fatigue</i>	slow	rapid
<i>Metabolism</i>	aerobic	anaerobic
<i>Blood supply</i>	rich	sparse