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MUSCULAR ACTIVITY AND ITS RELATIONSHIP TO BIOMECHANICS AND HUMAN PERFORMANCE

O Investigator, do not flatter yourself that you know the things nature performs for herself, but rejoice in Knowing the purpose of those things designed by your own mind.

Leonardo Da Vinci (118)

INTRODUCTION

The purpose of this manuscript is to address the issue of muscular activity, human motion, fitness, and exercise. Human activity is reviewed from the historical perspective as well as from the basics of muscular contraction, nervous system controls, mechanics, and biomechanical considerations. In addition attention has been given to some of the principles involved in developing muscular adaptations through strength development.

Brief descriptions and findings from a few studies are included. These experiments were conducted in order to investigate muscular adaptation to various exercise regimens. Different theories of strength development were studied and correlated to daily human movements. All measurement tools used represent state of the art exercise equipment and movement analysis.

The information presented here is only a small attempt to understand the effects of exercise and conditioning on Earth with the objective of leading to greater knowledge concerning human responses during spaceflight.

What makes life from non living objects is movement which is generated and controlled by biochemical substances. In mammals, the controlled activators are skeletal muscles and this muscular action is an integral process composed of mechanical, chemical and neurological processes resulting in voluntary and involuntary motions. The scope of this discussion is limited to voluntary motion.

HISTORICAL CONSIDERATIONS

The phenomenon of muscular contraction as a prime mover of animal motion has fascinated men for many centuries. In the fifth century B.C., the Hippocratic collection of writings on medicine and its philosophy, consisted of various treatises of the corpus. It is interesting to note that in these early Greek works the tendons were confused with nerves (320). Today, confusion between tendons and nerves no longer exists. However, there is no precise understanding of the activation of the elastic component of the connective tissue nor their contributions to the total muscular contraction.

Skeletal muscles usually originate on a skeletal segment, span one or more joints, and insert onto another bone. Human motion is composed of the coordinated contraction of these voluntary skeletal muscles. This coordinated movement can be conceptualized as consisting of several components. One of the most basic structural components is the cell. Within the human muscular system these cells include bone, muscle, nerve, and brain. Although these four types of cell make up different appearing structures, they have many common features which all cells posses, eg. protoplasm, mitochondria, membranes, etc. The cells are the components of each organ and the organs constitute the system's production of motion. The coordination of these individual blocks is necessary to create coordinated movement. The movement process, intensity, displacement, speed, and acceleration can be executed by various controlled interactions between the organs.

Aristotle (384 to 322 B.C.), considered animal motion to be caused both by the power of the nerves and with the spirit. He wrote:

> *The movements of animals may be compared with those of automatic puppets which are set going on the occasion of a tiny movement; the levers are released, and strike the twisted strings against one another... Animals have parts of a similar kind, their organs, the sinewy tendons to wit and the bones; the bones are like the wooden levers in the automation, and the iron; the tendons are like the strings, for when these are tightened or released movement begins... Now experience shows us that animals do both possess conatural spirit and derive power from it ... And this spirit appears to stand to the soul-center or original in a relation analogous to that between the point in a joint which moves, and that which is unmoved. Now since this center in a joint which moves, and that which is unmoved. (160).*

Circa 1650, Giovanni Alfonso Borelli (75) showed that the muscles act on the limbs with short lever arms, whereas the part of the body carrying a load utilized a longer lever arm. Consequently, Borelli concluded that the joints transmitted forces which are several times the weight of the supported part of the body.

Borelli's contemporary, Descartes, the mathematician and philosopher, related the muscular action to the nerve which inserted into them. Descartes believed that "spirts" entered the brain, passed into the pores of the substance, and from these pores into the nerves. The "spirits" of Descartes then had the power to change the shape of the muscles in which these nerves were inserted and by this means to make all the limbs move.

Today, there are thousands of research articles dealing with understanding of muscular contraction and many of the mysteries continue to allude investigators. There are more then 600 muscles in the human body. In each movement, even the simplest one, groups of muscles work together to achieve the voluntary task. The intensity of the muscular action can be controlled by neural, chemical and biomechanical coordination.

The goal of efficient movement is to accomplish that action with the minimal amount of energy. For example, an Olympic shotputter tries to throw the longest distance by coordinating all internal and external forces in order to generate maximum velocity on the shot at the proper angle with minimal effort. If the movement is not efficient, energy will be wasted in the wrong direction.

Efficiency of motion obviously incorporates activities within the nervous system. In 1883, Yale College received eighty thousand dollars to investigate and lecture on the subject of "Electricity and Matter". Parts of these lectures were devoted to Charles S. Sherrington (410), who studied the role of electricity in the human body. In his book, "The Integrative Action of the Nervous System", Sherrington wrote that:

> *in the multicellular animal, especially for the higher reactions which constitute it's behavior as a social unit in the natural economy, it is the nervous system and its reaction which 'par excellence' integrates it, welds it together from its components, and constitutes it from a mere collection of organs.*

According to Sherrington, the integration of the animal organism was obviously not the result solely of any single agency at work within it, but of several. Thus, Sherrington believed that the mechanical combination of the unit cells of the individual were not independent but functioned as a single unit.

In muscles, this mechanical integration of the organ may produce a single "cord tendon" by which the tensile stress of myriad contractile cells can be additively concentrated upon a single place of application. Sherrington measured forces at the muscle rather than externally as some subsequent investigators have done.

In addition, Sherrington believed that the integrative action of the nervous system is different from other bodily systems. He believed that connective tissue was merely intercellular material and that the circulation system transferred material in mass. On the other hand, the nervous system worked through living lines of stationary cells along which it "despatches waves of physico-chemical disturbance, and these act as releasing forces in distant organs where they finally impinge." Sherrington described the foundation of reflex activity in the human body and established the knowledge of the integrative mechanisms of muscular activity.

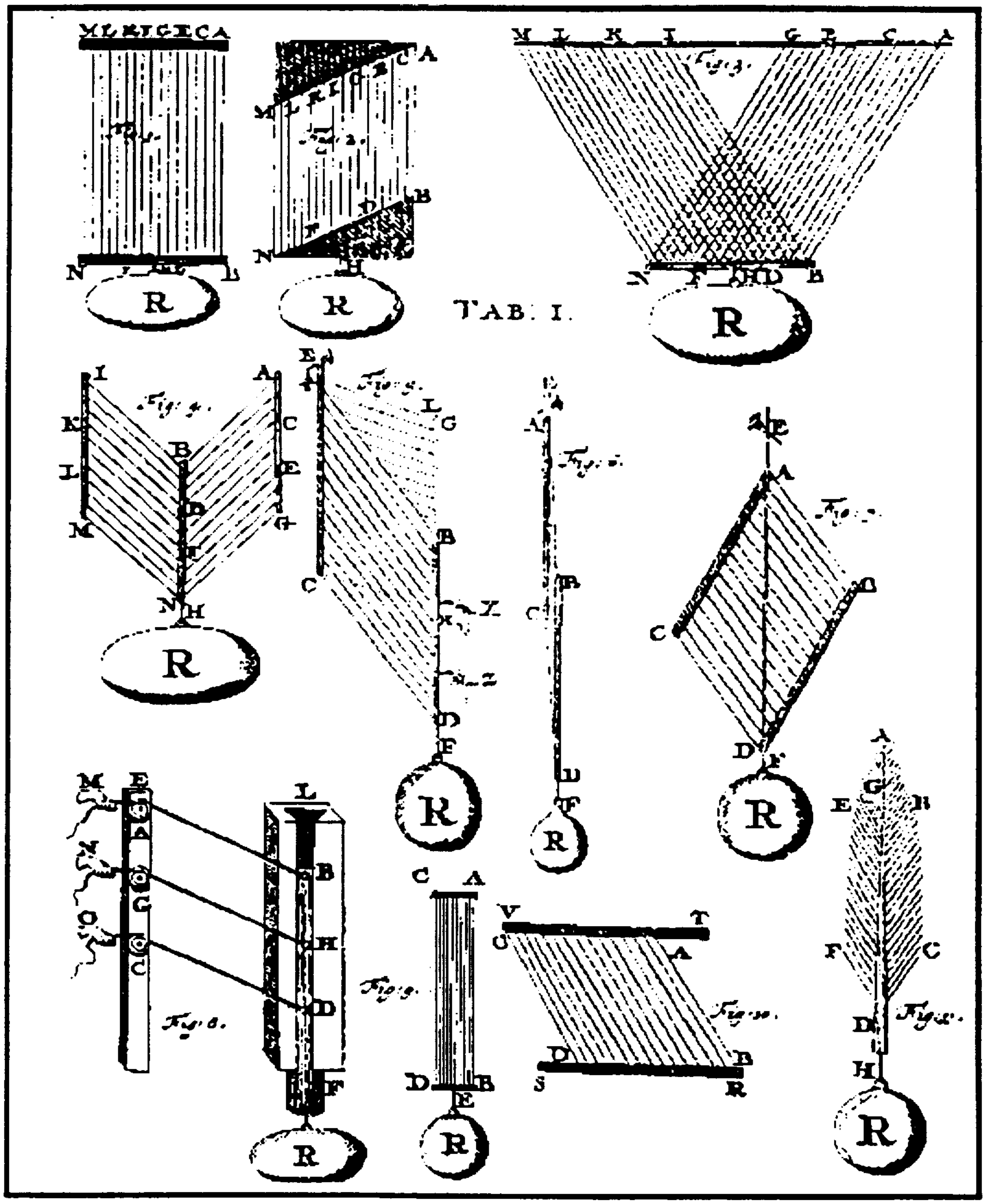

Figure 1

MUSCLE STRUCTURE

Learning about muscular function requires the knowledge of the structure of muscles themselves. Muscular structure can be divided into Macroscopics, which relates the muscle connection to the bones which serve as levers in the different skeletal structure, and Microscopics, which relates the cellular structure and the micro structure of the muscular cell within the fibril structure.

Macroscopic Structure:

In the 1600's, Borelli (75) described the macroscopic structure of the muscular system in his book, "On the Movement of Animals", and presents an exceptionally detailed description. Until some of the recent discoveries in the twentieth Century, there were no other works which provided such detail on muscular function based on mathematical and geometrical relationships. Borelli observed that muscle fibers do not always run parallel to the force which they transmit. This has significant implication for the muscle's internal biomechanics since the resultant force depends on the geometrical relationship of the muscle fibers.

Muscular structure is designed to allow movement and the cell itself is a mechanical structure which causes movement. Borelli (75) stated in his Proposition IV: "Muscle acts by contracting". His illustrated Table (Figure 1) which present the various structures of muscles is amazingly accurate particularly when one realizes that the information dates from the 17th century not the 20th century. His Proposition stated that:

in muscle we see that only the fleshy threads AB, CD, EF and C in the figures 1,2,3 and 4 in Table I contract when the muscle acts. The tendons at the extremities BH to which the fleshy fibers are attached do not contract but retain their initial length. Consequently, only the fleshy fibers AB, CD, EF, GH and C exert a force by contracting when they carry considerable weights. The tendons BH are subjected to a force when moved by the contraction of the fleshy fibers. They undergo this force like a handle to which the fibers are attached.(75)

Hundreds of years after Borelli's pioneering work, the Nobel laureate, Albert Szent Gyorgyi (440) from Hungary, stated that these fleshy parts described in the 17th Century are made of two types of proteins. Skeletal muscle fibers are elongated cylinders containing several nuclei, originally belonging to smaller cells known as myoblasts that merge before birth. Since they are larger than other muscle fibers, many skeletal muscle fibers are visible to the naked eye. Some, like those in the thigh's sartorius muscle, are more than a foot in length and some individual fibers can extend the entire length of the muscle. Usually, however, one end of the fiber attaches to tendon which is the tough tissue that binds muscle to bone while the other end attaches to connective tissue in the muscle.

Borelli (75) believed that when a muscle contracted moving a bone, it created a spherical or circular movement as described in his Table II (Figure 2). It is a humbling experience to realize that, in 1630, Borelli stated what remains as the modern foundation of the relationship of bones, as levers, and the muscles to which they are attached:

But, although the movements of the limbs are circular, the position of the center of rotation of the limbs and bones is not obvious and must be found. If the bones of the limbs were solid lines their contact would be a point which should be considered as the center of fulcrum. However, since the bones have some thickness their extremities cannot easily contact and articulate at one point to rotate about this point of contact. This would be possible if the extremity of one of the bones was pointed, like the apex of a cone or of a pyramid, and if this tip was attached to the cavity of the opposite bone which would be immobile. Then the point of contact would be the fulcrum and the center of rotation. But this would be very inconvenient and fragile. If indeed the ulna ended in a *conical apex and if this conical extremity of the humerus, such a pointed protuberance could easily be crushed and broken and the joint could not be linked strongly enough to avoid unsteady contact at the apex and deviation. Actually, foreseeing and wise nature, to avoid these inconveniences, created a joint which is easy, safe, stable, resistant, and minimally liable to dislocation. She shaped the ends of the bones round, one convex, the other concave so that contact does not occur at one point but over a wide area. This avoids crushing and fracture. This does not give a center of rotation but rather a cylindrical fulcrum over which the bone moves. Any point in which the moving bone rests over the immobile bone is not a fixed or stable point and, therefore, there can be no center of rotation.*

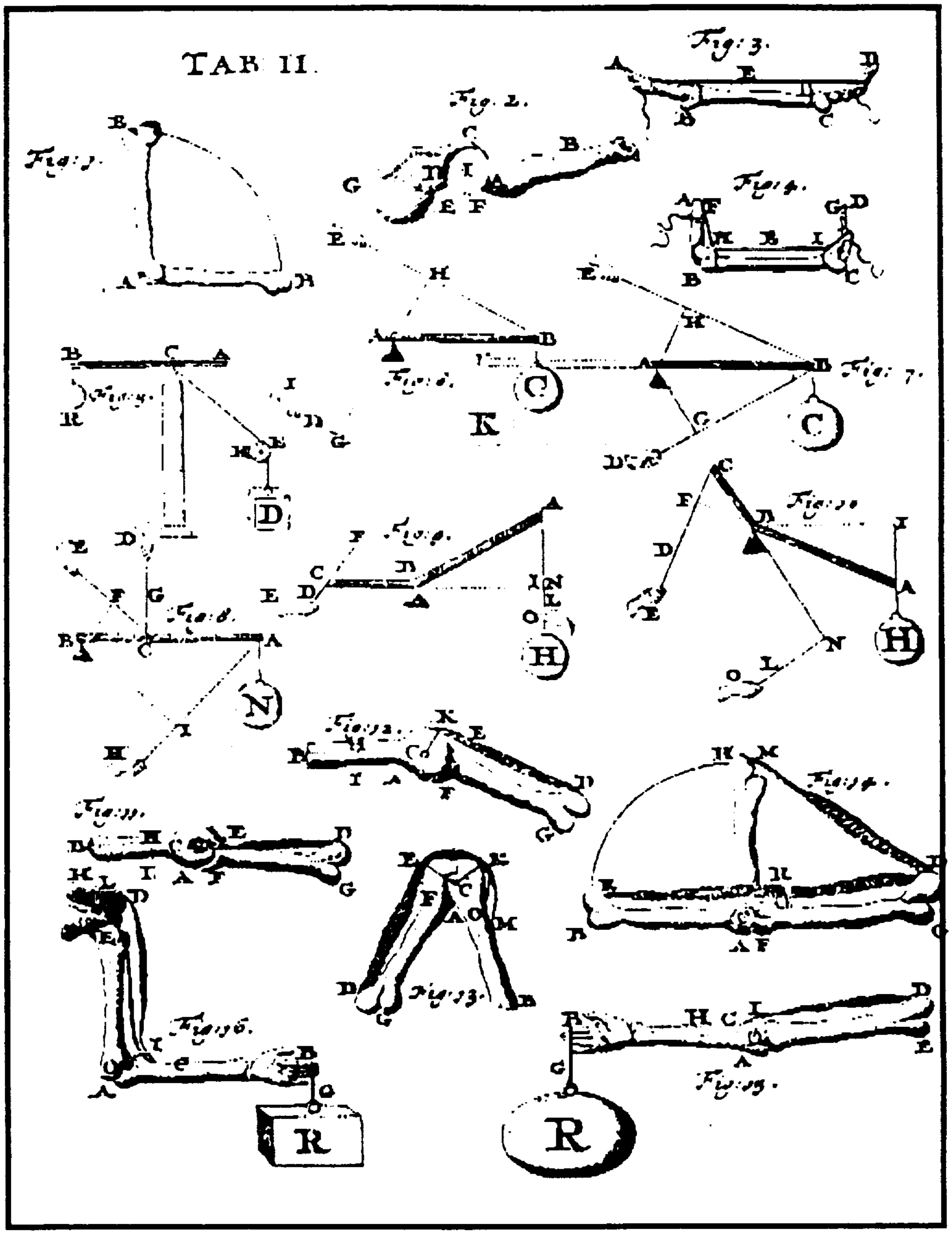

Figure 2

Unfortunately, this explanation from the 17th century has been overlooked by many in our time. The fact that the external force is measured at different angles and at different moment arm lengths is significant in interpreting the muscular force. This concept will be discussed subsequently. Even earlier than Borelli, in the 15th Century, Leonardo Da Vinci (118) wrote: "You may not be versed in geometrical exposition or in the method of calculating the forces and energy of the muscles". Leonardo warned that simple conclusions based on simple assumptions could result in erroneous conclusions.

Another foundation for muscular activity proposed by Borelli, (Proposition VIII) stated:

It is commonly thought that Nature raises considerable weights by using the machines of the muscles with a weak moving force.

The magnitude of the vital force of the muscles must be measured. This force sustains, raises and moves not only an arm or a leg, but the whole animal machine, enabling it even to dance. Besides the mass of the animal, heavy enough by itself, this, this force carries, pulls and pushes considerable weights. Aristotle above all dealt with this matter. He did not recognize the muscles but imagined spirits which pull and push the limbs. This perspicacious author sensibly remarked how difficult it would be for the huge mass of an elephant to be moved and pushed by tenuous spirit or wind. He met the difficulty by saying that Nature moves the joints and limbs of the animal by using very small force. He said that this results from the work of the machine by which motions initially small soon lead to large and multiple displacements. Similarly, small and easy motion of a pole or of the rudder provokes large displacements of the bows and of the boat. Then he considered the nature of a pole from a mechanical point of view and said that the operation is carried out by way of a lever. Therefore, it is not surprising that huge weights can be moved and displaced by a small force. Lucertius used the same example: 'Using pulleys and winding-drums it moves many heavy things and the machine raises them with little effort'.(75)

Despite the antiquity of the statement, the facts are correct. Forces measured at the limbs are related to the muscular force but the relationship is not linear. There is an integration of neuromuscular activity at the muscular site but it does not have a linear relationship to the application of force. It is for this reason that repeating an experiment at different limb positions does not produce the same results in spite of exposure of the segments articulations to the same forces. This calls attention to Borelli Proposition XV which stated:

If two opposite forces are applied at two points of the same lever and have equal moments, their magnitudes are inversely proportional to the distances of their lines of action from the fulcrum (Table II, Fig.8).

The fulcrum of the lever AB is B. Two opposite forces H and E are applied at points A and C in such a way that the lever remains immobile. In other words, the moments of the forces are equal. Their lines of action are AH and CF. Two perpendiculars BI and BF are drawn from the fulcrum to these lines of action. I claim that the magnitudes E and H are inversely proportional to the lever arms BI and BF. Two opposite forces D and N are applied at points C and A. Their lines of action AN and CG are at right angles to the lever BCA. The moment of force D is equal to the moment of force N, to the moment of force H and that of force E. The ratio of the magnitudes D/N is equal to AB/BC. At the end C of the lever BC the fulcrum of which is B, two forces of equal moments are applied, one D at right angles, the other E obliquely. Therefore the ratio of the magnitudes of the forces E/D is equal to BC/BF. Hence, exchanging the terms of the equations, the ratio of the magnitudes E/N is equal to BA/BF. Similarly, the ratio of the magnitude of force N pulling at right angles to the magnitude of force H pulling obliquely is equal to IB/AB. Consequently, exchanging the terms of the equations, the ratio of the magnitudes of the forces E/N is equal to the ratio of the lever arms IB/BF.

Borelli was one of the first mathematicians to reduce the laws of motion into objective, quantifiable relationships. In other words, Borelli was an early pioneering biomechanist. His explanation of fulcrums and levers demonstrated that muscular forces measured at the point of application will not produce the same force quantity at the site of insertion.

Human movement, however, is normally more complicated than a single lever. Most actions involve multiple lever systems with one bone attached to another bone creating a common angular focal point which moves about another angular attachment. These levers are moved by the interaction among different muscle groups. It would be naive to describe muscular activity by considering an isolated joint. Such reality was perceived in the 17th Century as Borelli expressed in his Proposition XVI, which stated (75):

> *if two opposite forces are applied at the extremities of an angulated balance the fulcrum of which is at the apex of the angulation and if these two forces have equal moments, their magnitudes are inversely proportional to the lengths of their lever arms. Reciprocally, if two forces are inversely proportional to the lengths of their lever arms, their moments are equal (Table II Figs. 9 and 10) (75).*

Because of the lever structure of the human skeleton, Borelli evaluated the relationship of muscular force to the external force. He found that different positions of the forearm relative to the upper arm produced different forces applied by the elbow flexors. The various Tables by Borelli III, IV, V and VI (Figures 3, 4, 5, and 6) illustrates the relationships of muscular forces at different body parts. One can observe the complexity of mechanical arrangement and should never forget that these elementary Propositions were proposed in the 17th Century.

In our more modern age, with the advent of sciences and sophisticated instrumentation, it became possible to examine the anatomical structure of the joints and the muscle.

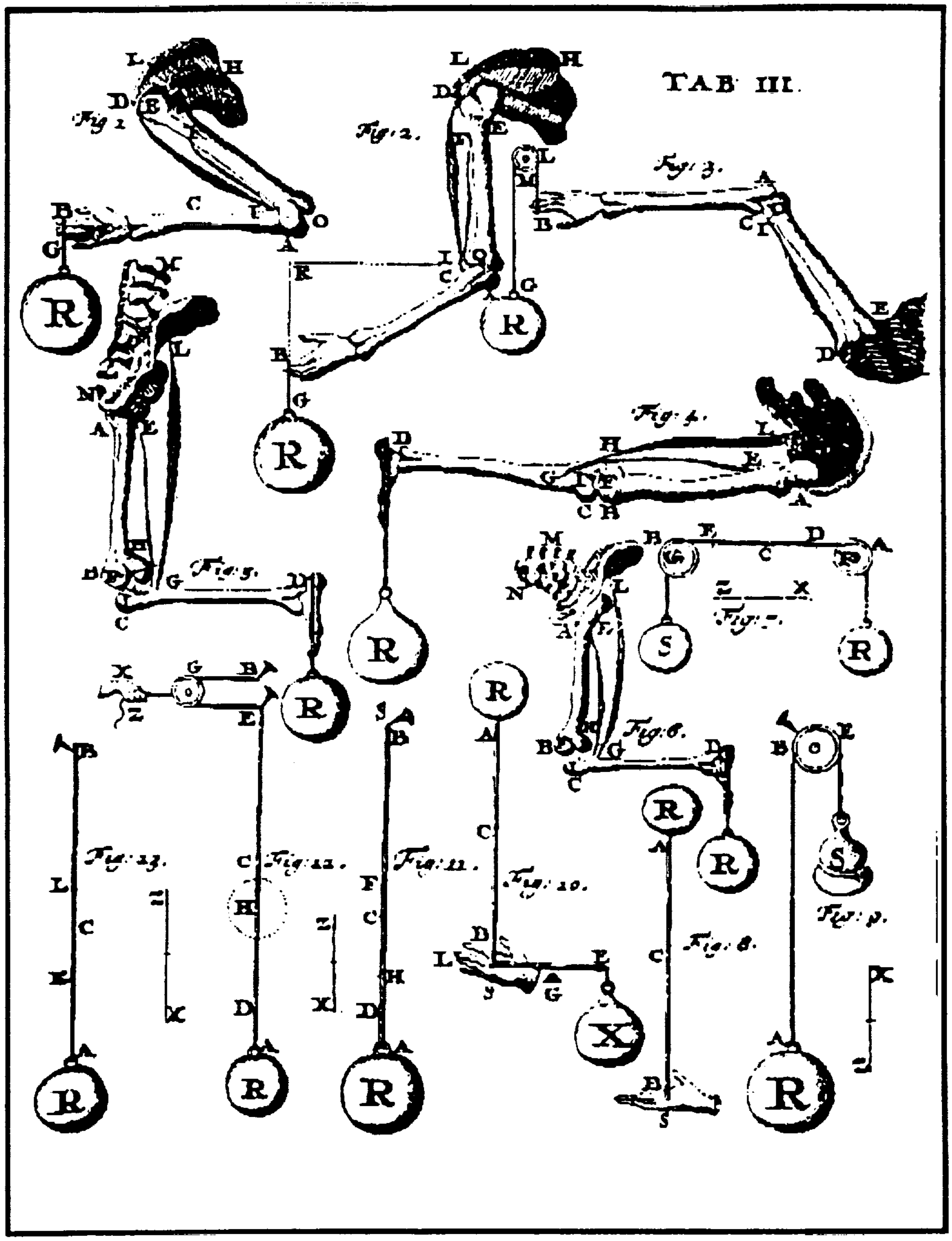
TAB III.
Fig. 1
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Figure 3

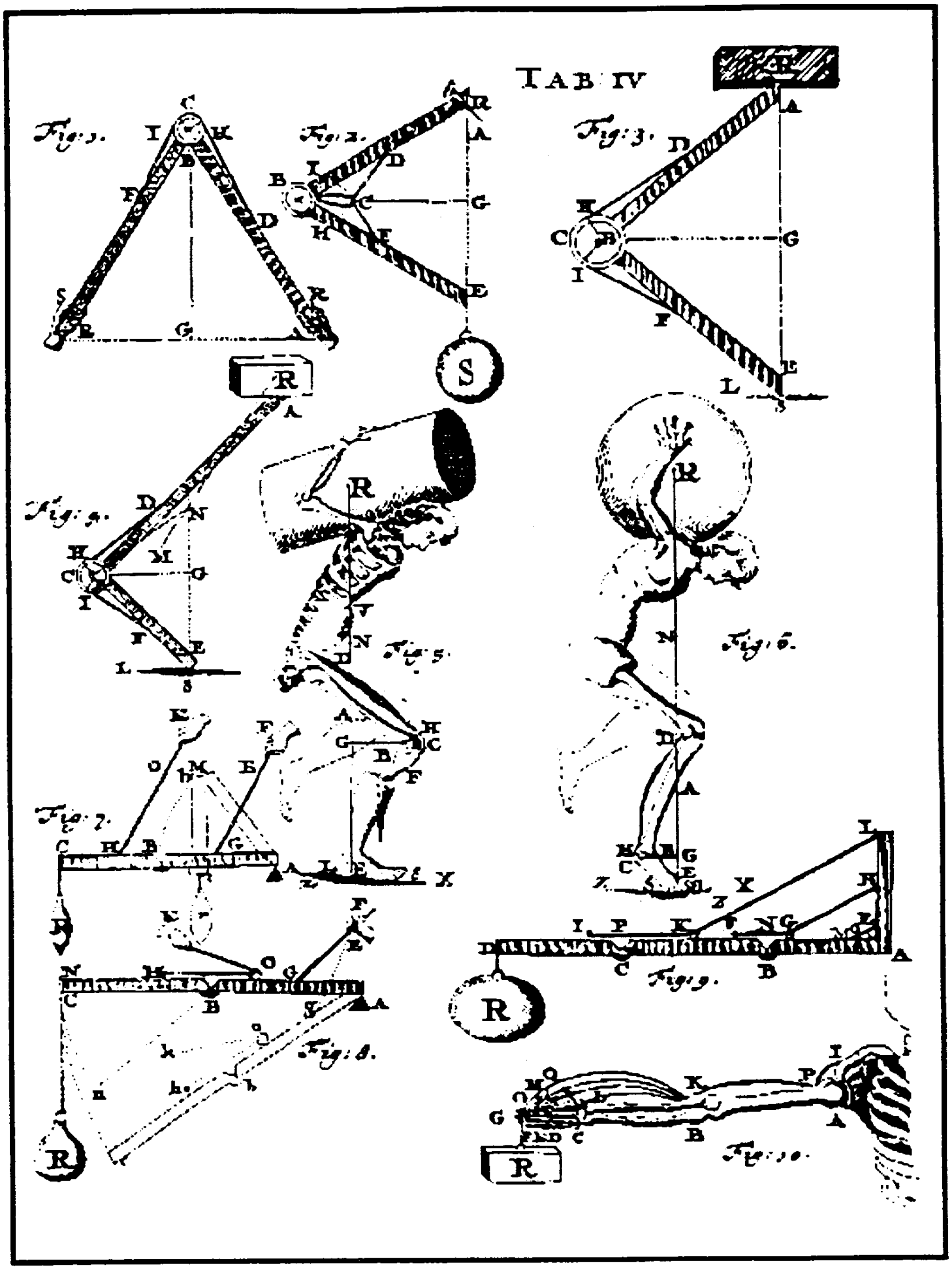
TAB IV
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Figure 4

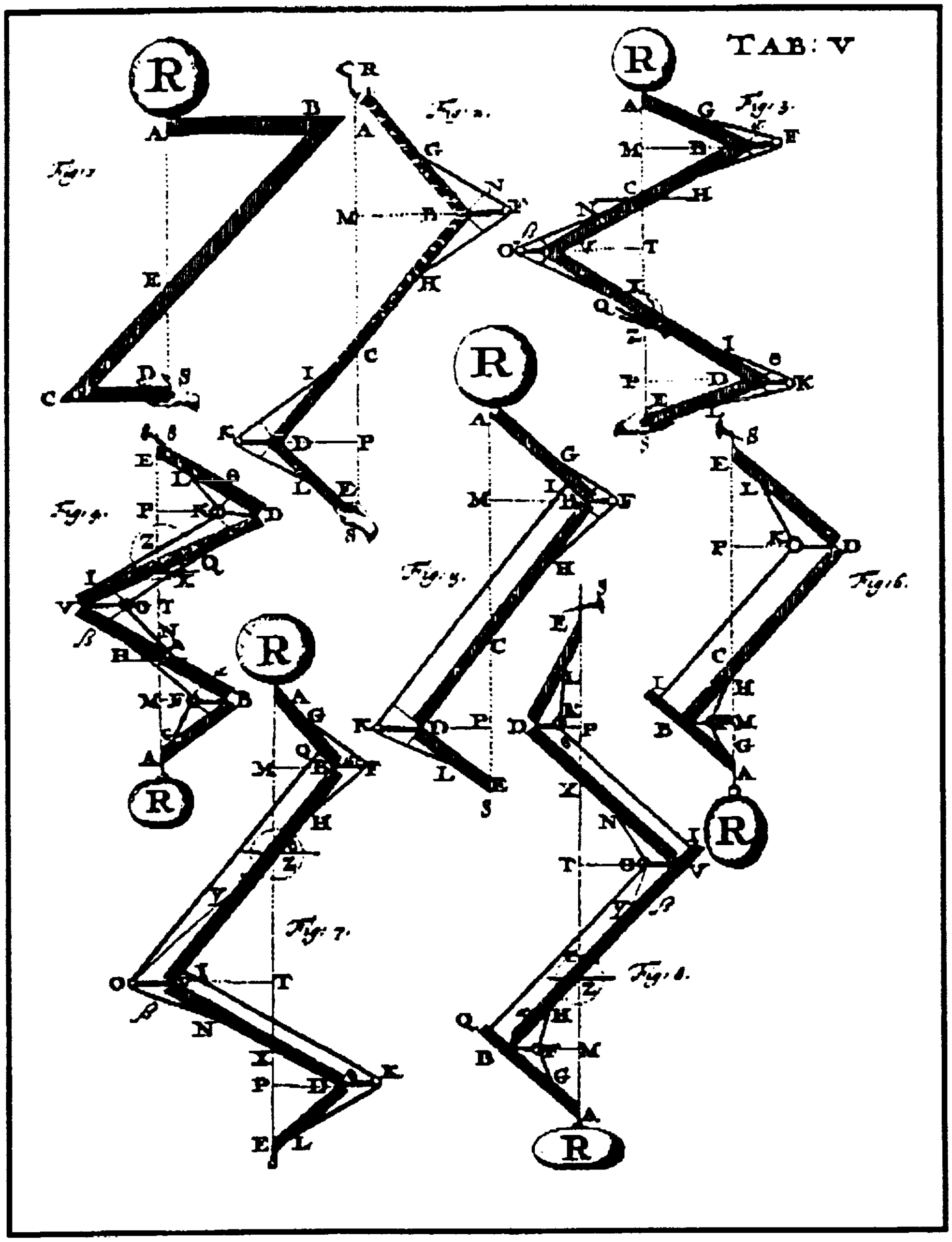

Figure 5

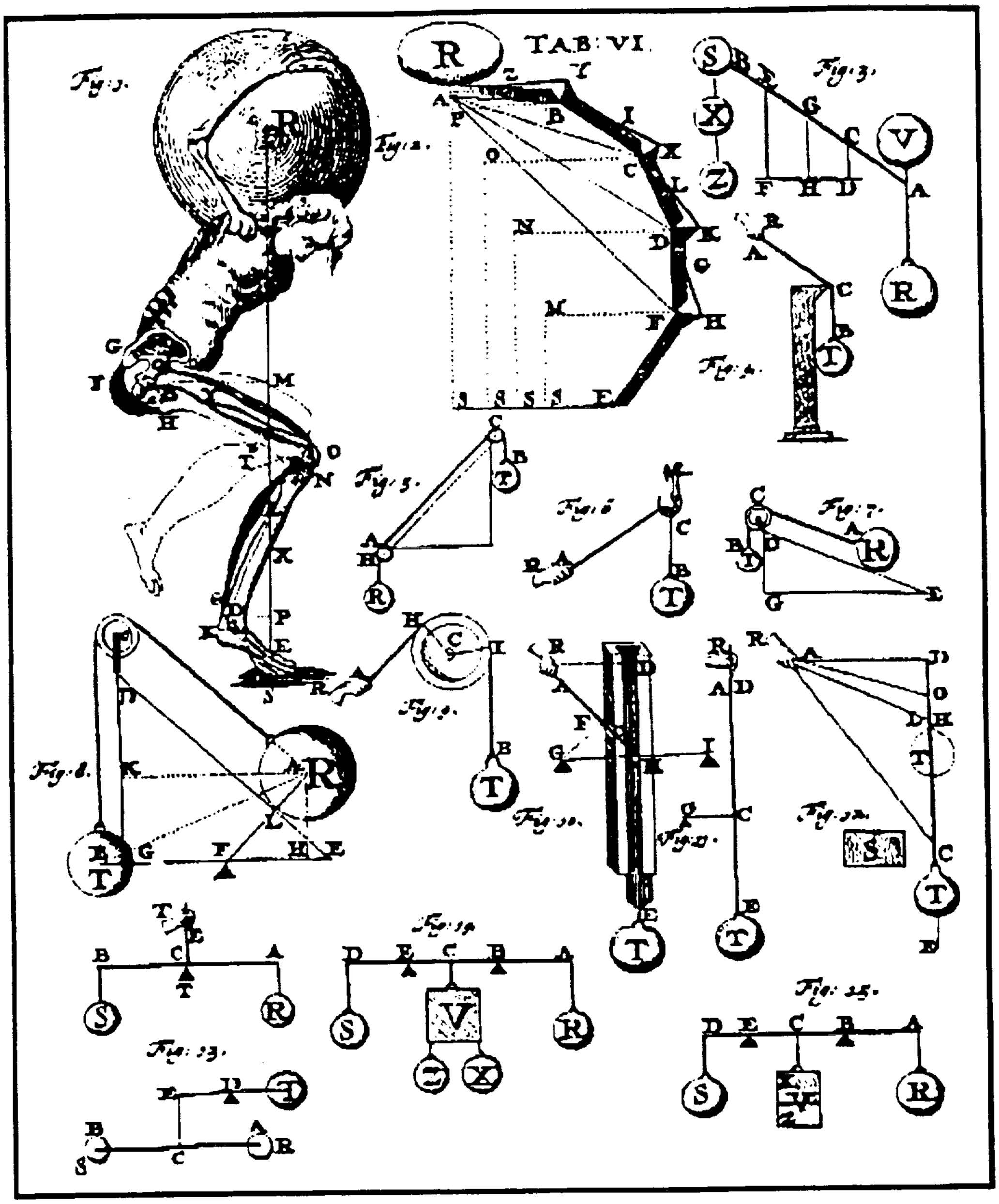
TAB: VI.
Fig. 1.
Fig. 2.
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Fig. 10.
Fig. 11.
Fig. 12.
Fig. 13.
Fig. 14.
Fig. 15.
R
S
X
Z
V
T

Figure 6

Microscopic Structure:

At approximately the same time that Borelli postulated biomechanical descriptions of motion, a Danish anatomist, Nicholas Stensen, described the motor fibers of the muscles with such detail that one imagines that he had microscopic abilities. Stensen determined that the fibers rather than the tendons were responsible for the muscular contraction.

It is now known that skeletal muscle fibers are elongated cylinders containing several nuclei which developed from cells, known as myoblasts, that merged before birth. In most skeletal muscles, one end of the fiber is attached to a tendon and this tendon is connected to the bone. The other end of the muscle is attached to connective tissue in the muscle itself. This connective tissue, originating in the tendon, spreads into the core of the muscle. However, the materials of which the muscle and the material consist are different from each other. The muscle belly is surrounded by a tissue called endomysium, which is a thin sheath of connective tissue. Another connective tissue is the internal perimysium which bundles the specific muscle into groups which called fasciculi. These bundles are themselves bound together by another layer of connective tissue called the external perimysium or epimysium.

These various connective tissue types and the muscle itself constitute the macroscopic structure of the muscle. However, the dynamics of muscle action is locked within the basic component, the cell. Each individual fiber is surrounded by a thin plasma membrane called the sarcolemma. Figure 7 illustrates these structures. The muscle fiber is filled with tiny fibrils, known as myofibrils, and a jelly-like material called sarcoplasm. Most current scientists agree

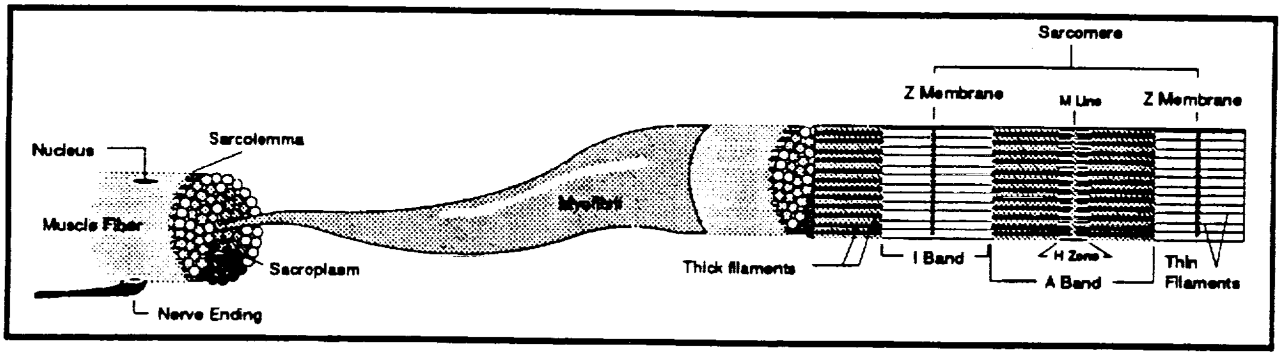


Figure 7

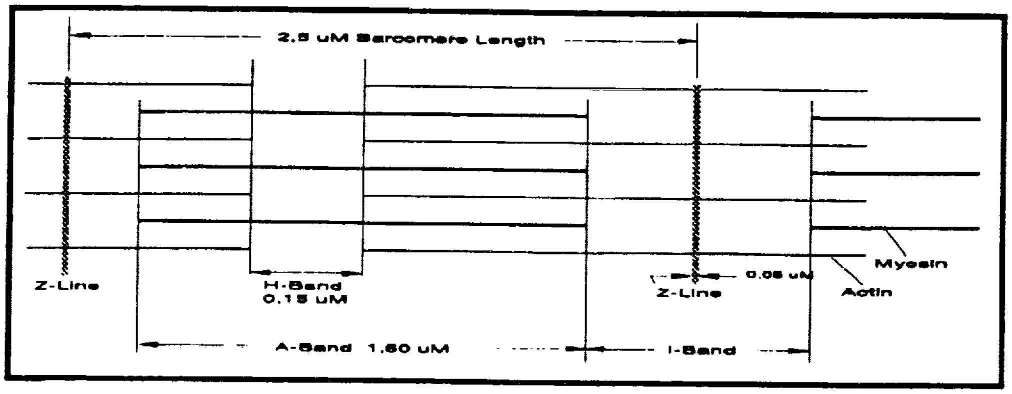


Figure 8

that the fibers contain bundles of fibrils. Each fibril has a diameter of about .5 microns and comprises the hexagonal array of the protein filaments which are directly responsible for the contractile process. Figure 8 illustrates the relative dimensions of the sarcomere. When the fibrils are investigated under the electron microscope, a peculiar structure is evident. In fact, these myofibrils produce the skeletal muscle's striations and cause it to appear striped. It was a seventeenth-century Dutchman, Anton van Leeuwenhoek, who was the first to observe a muscle fiber's striations utilizing a microscope. He predicted that the mechanism of muscular contraction would be in these structures. Leeuwenhoek even entertained the possibility that the striped elements themselves might be enclosed in another membrane and continue into incredibly smaller and smaller filaments.

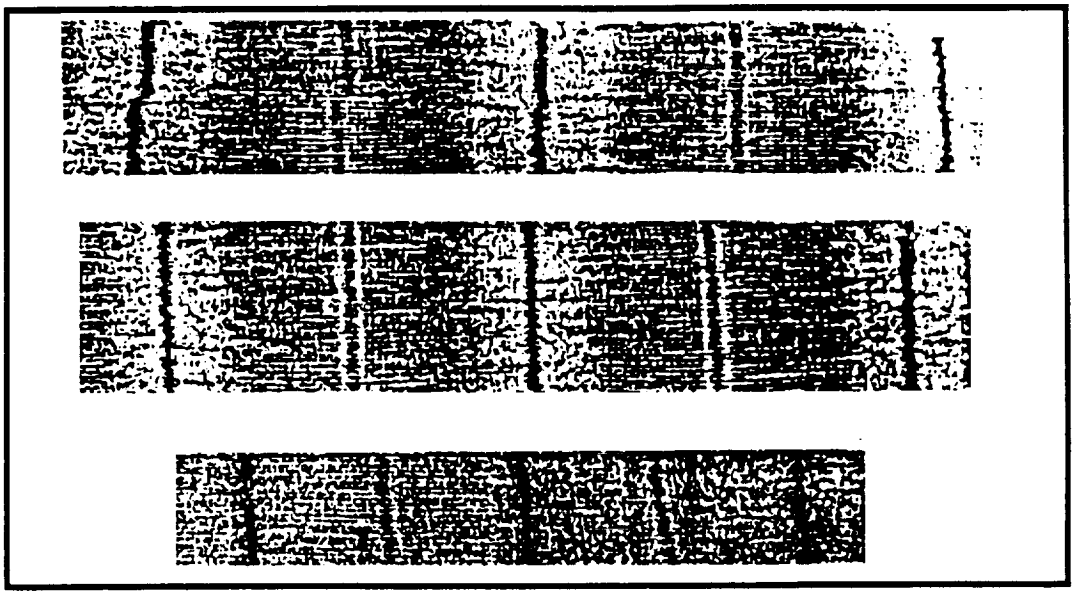


Figure 9

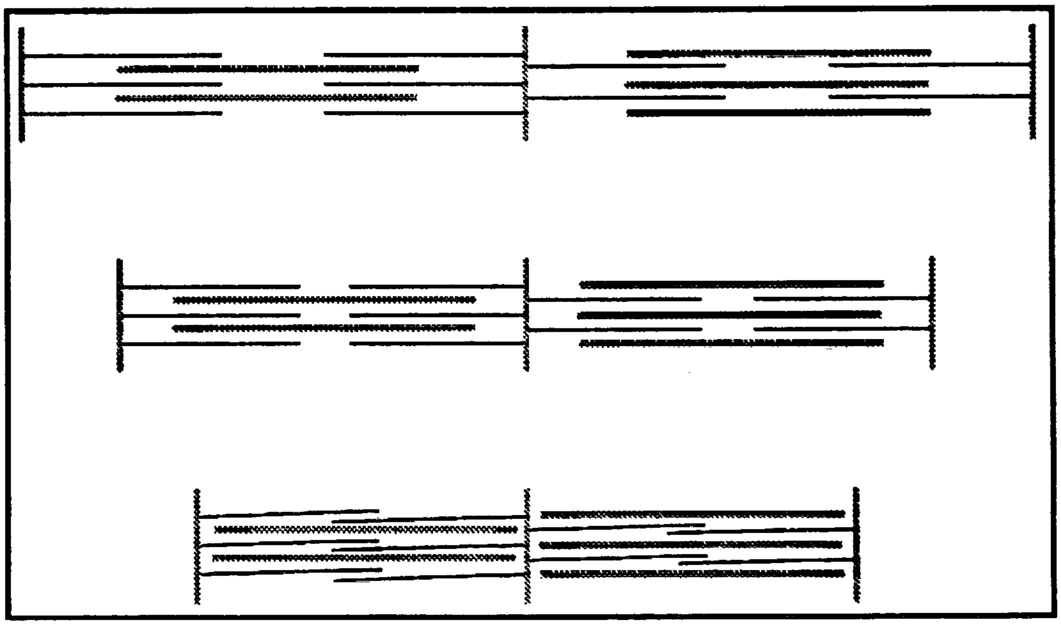


Figure 10

Leeuwenhoek's speculations were not, however, accurate. The striations caused by the myofibrils are subdivided to a unique microscopic structure. The striations are optically made by a dividing band called the Z-line or Z membrane from the German word "Zwischenscheidung". When photographed, the Z-lines appear as dark lines (Figure 9). Two Z lines form a unit of the contractile element and this unit is called a Sarcomere. The Sarcomeres are the basic units of the muscle's contraction. Beside the Z membrane are light regions which are called the I bands. A darker band forms the middle section of the sarcomere and is called the A band. The A band is composed of lighter bands in the middle and darker bands on either side. The lighter center is called the H zone. In the middle of the H zone there is a dark line called the M line (Figure 10). This pattern is repeated throughout the entire length of the fibril.

These striations, then, are due to the composition of the Sarcomeres which are made of thick filaments composed of the protein myosin and thin filaments formed from the protein actin. It is the location of the actin and the myosin which results in the appearance of striations, since the thick filaments originate from the dark regions of the sarcomere and the thin filaments originate in the light areas. The A band, which is darker, consists mostly of the myosin filaments. These filaments are anchored in the middle of the sarcomere in a line called the M line. The actin, the thin filaments, are anchored on the other side, which is the Z membranes. On both sides of the Z membrane, the actin is extended to produce the I band. The thick filaments, the myosin, do not stretch all the way to the center of the sarcomere and, for this reason, the H zone appears lighter in color.

In spite of Leeuwenhoek's discovery of these striations, it was nearly three centuries before the modern knowledge of muscular contraction was postulated. Until the middle of the twentieth century, scientists had assumed that when a muscle shortened, its components also shortened. The theory was that the filaments folded or coiled during contraction. With the invention of electron microscopes and biochemical measuring devices, it became possible to examine muscle as they had never been seen. These 20th Century investigators found that when a fiber contracted, the length of its dark A bands remained constant. This means that the thick filaments, the myosin, do not change their length nor do they contract. However, the two light regions, the I band and the H zone did shorten when the fiber contracted. More evidence suggested that the thin filaments, the actin, did not contract per Se. This was evident from the fact that the Z membrane, where the light actin filaments are anchored, to the H zone where the actin met in the middle of the sarcomere, did not change during contraction. Figure 11 illustrates these relationships.

Investigators from both sides of the Atlantic Ocean independently arrived at the same conclusion, namely that the filaments were actually sliding into each other. M.I.T. scientists, Hugh Huxley and Jean Hanson (275), and Cambridge University researchers, Sir Andrew Huxley and Rolf Niedergerke (272), announced their findings in 1954. Each group postulated the Sliding Filament theory which has served the basic framework for other researchers. Still today, there are many unanswered questions with more mechanisms yet to be discovered. All recently advanced theories of muscular contraction confirm the likelihood that the actual contractile process takes place at the junctions between myosin and actin.

The sliding mechanism is triggered by chain of events which must start with the nervous system. The nerves which terminated near the muscle cell's membrane, secrete specific chemicals. These neurotransmitters start a wave of electrical activity that spreads through the whole fiber. This electrical activity, called the "action potential" causes the fiber's membrane to release calcium ions which initiates the process of contraction. The calcium ions spread throughout the fiber via a specific structure of tubules, diffuse into the myofibrils, and come into contact with the fiber's contractile proteins, the actin and myosin. Two additional types of proteins, Troponin and Tropomysin, work as a team to circle the thin actin filaments. The calcium

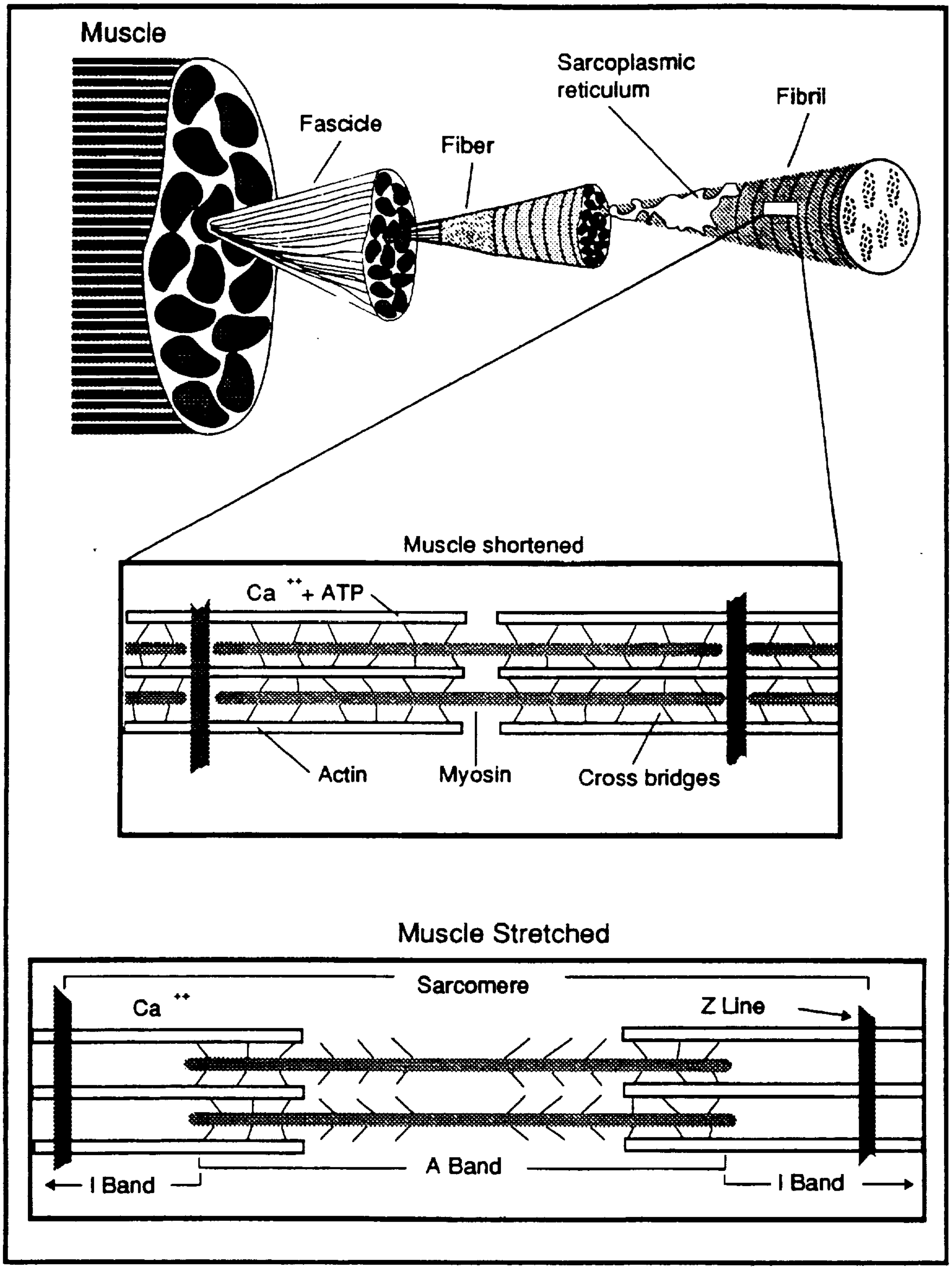

Muscle
Sarcoplasmic reticulum
Fibril
Fascicle
Fiber
Muscle shortened
Ca ++ + ATP
Actin
Myosin
Cross bridges
Muscle Stretched
Sarcomere
Ca ++
Z Line
A Band
I Band
I Band

Figure 11

chemically binds with the troponin and, in a way not yet understood, causes an interaction with the tropomyosin. The tropomyosin threads shift their hold on the actin filament and, with this process, reveal locations along the shaft of the actin filament that are receptive to binding with the myosin filaments. Pairs of rounded extensions, resembling buds are found on these myosin filaments. Each pair forms the head of a single myosin molecule. These buds form bridges to the actin filaments and, hence, these molecules are called "cross bridges" (Figure 12).

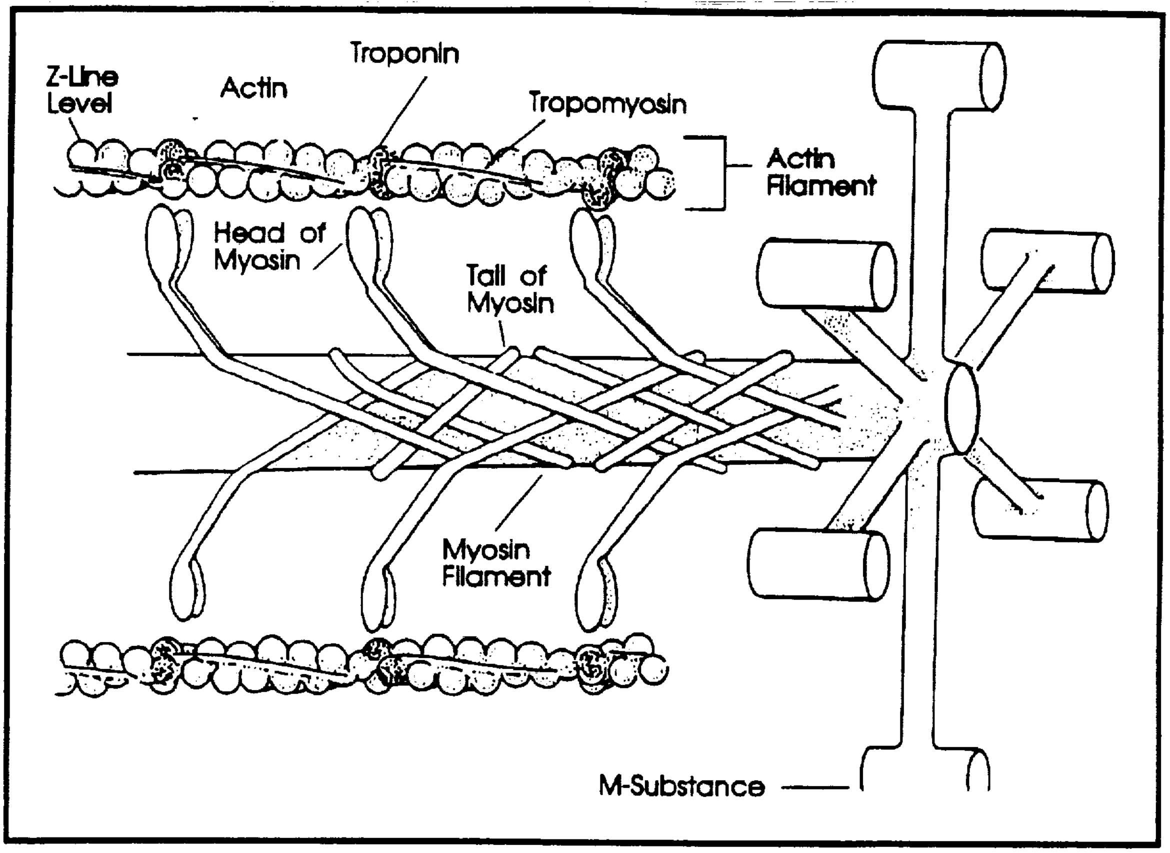


Figure 12

Cross bridges are crowned with a remarkable substance, adenosine triphosphate, or ATP. The ATP molecule is the bases for generating energy for life. In fact, ATP can be referred to as the "Molecule of Life". Reducing the ATP molecule by one phosphate element results in adenosine diphosphate, or ADP. This molecule is able to release energy responsible for muscular contractions as well as many more processes in the human body. Looking at this mechanism from another perspective is that the energy lost in the splitting of the ATP molecule into two lower energy products, the energy lost in the split is then available for use in the body's metabolism.

The ATP molecule has a great affinity to the myosin molecules. Therefore, many of the ATP molecules in the vicinity of the contractile mechanism "choose" to sit on the myosin filament. The higher the number of ATP molecules, the greater the potential for energy requirement during contractions.

The discovery of the enzyme ATPase by Engelhardt (151) gave new light to the research on muscle contraction. Engelhardt proposed a possible mechanism of contraction such that ATP, which is bound in resting muscle to some protein complex, combines with myosin on stimulation. An as yet unknown process within the myosin is initiated and contraction ensues. During this process, the ATP molecule becomes dephosphorylated and yields energy for muscular contraction and ADP, which has a lower affinity for myosin than ATP.

Current theory holds that this "sitting" site of the ATP is comprised of two buds and each bud has a different function. One bud is made of ATPase which is an enzyme responsible for the splitting of the ATP molecule. The other bud is attached to the actin with the ATP molecule. This means that the actin and myosin filaments are "bridged" together with a structure consisting of the enzyme ATPase and the ATP molecule connected with an electrical bond. The bond, by itself, has a unique strength to maintained its position. Figure 13 illustrates schematically these bindings.

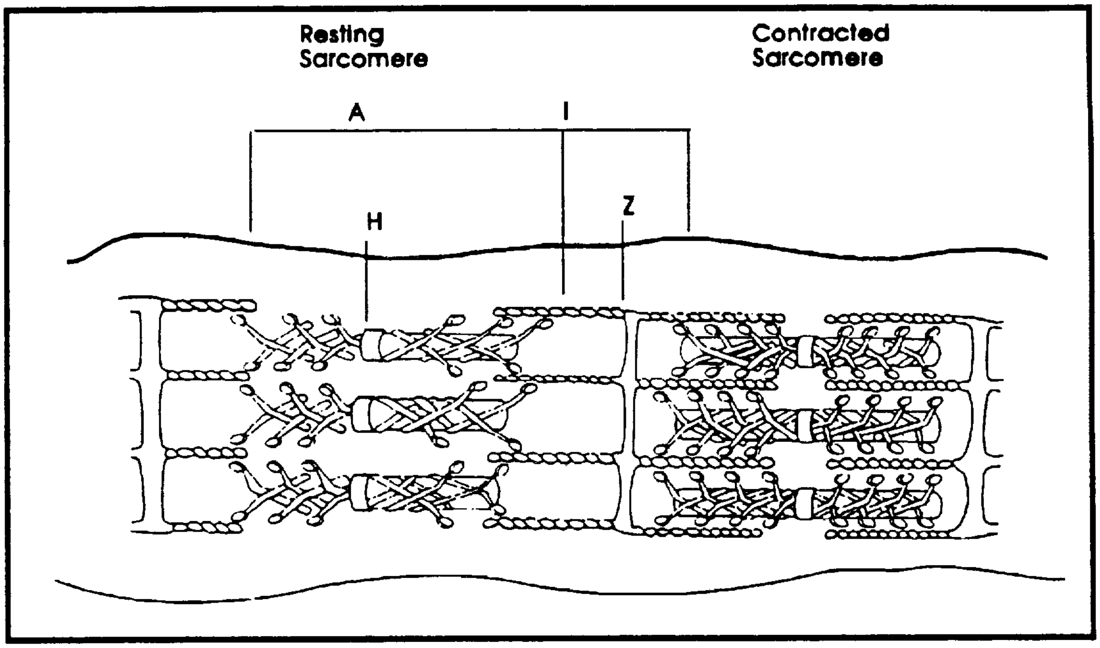


Figure 13

Huxley's model (275), although exceedingly successful at the time of its creation, has lost its attractiveness in the light of more recent experimental evidence. Barany (56) studied the ATPase activity of myosin and found that the rate limiting factor was the ATP splitting. This contradicted Huxley's assumption that one of his rate constant, the constant f, was responsible for the limitation of the reaction rate. Lowey et al. (325) have clearly demonstrated that the side-pieces emerging from the myosin backbone consist of two identical rods of light-metromyosin (LMM) which are connected to two pieces of heavy-meromyosin subfragment.

H.E. Huxley (274) provided electron microscopic proof for the existence of structures linking the myosin and actin molecules. These structures were termed cross-bridges and Huxley suggested in his paper influenced by works of A.G. Szent-Gyorgyi (440), that these bridges consisted of the heavy meromyosin parts of the total myosin molecule. This would mean that the location of the ATPase activity and the site of the contact with actin had been found. This was a tremendous step forward and all subsequent theories had to take this finding into account.

Muscular contraction begins when the tropomyosin shifts away from the binding sites on the actin filaments and the two arms of the myosin filament immediately link with the actin. The ATPase enzyme splits the ATP, liberating energy which provokes cross bridge actions resulting in muscular contraction. In muscular contractions, this activity is continuously repeated with the cross bridges forming and splitting from the actin, causing the actin filament to slide over to the myosin filament, thus, making the sarcomere smaller. The breaking and reattaching of the actin-myosin filaments is, currently, the most accepted hypothesis of muscular contraction. Each sarcomere acts as a distinct unit and the combination of many sarcomeres produces contraction of the whole muscle which pulls on the tendon and its associated bone. Hugh Huxley calculated that the cross bridges would have to execute 50 to 100 cycles per second to accomplish efficient contraction. Other investigators have found that, indeed, the muscle ATP utilization support this rate.

In general, muscular contraction follow the following sequence:

1. The depolarization of the sarcolemma by nervous impulse.
2. The impulse is conducted down the length of the sarcolemma and through the T-tubules.
3. The calcium ions are released from the Sarcoplasmic Reticulum.
4. The calcium ions bind with troponin which stimulates a release of tropomyosin causing inhibition.
5. Actin and myosin interact.
6. Activation of ATPase.
7. ATP is broken down and energy is released.
8. Conformational changes occur at the head of the myosin molecule.
9. Cross bridges are formed.
10. Conformational changes occur at the actin-myosin linkage.
11. The muscle shortens.

The amount of linkage between the cross bridges and the actin relates to the amount of muscular force. The steps listed above allow each sarcomere along the full length of the myofibril to contract. For example, if a muscle is stretched beyond its normal length, there is less overlap between the actin and the myosin resulting in reduced muscular force. On the other hand, when the muscle is compressed or over-contracted, the myosin overlaps itself which reduces muscular force. There appears to be an optimal actin-myosin relationship at which the amount of cross bridges achieves the highest muscular force per sarcomere. However, force in a muscle depends on many factors in addition to the internal sarcomere filament arrangement.

The status at the cross bridges were described by Davies in 1963 (121) such that the cross-bridges were imagined to exist in two different states. In the inactive state, the bridges consist of extended polypeptide chains with fixed negative charges at their bases. One ATP molecule is bound to the top of each bridge in a way which results in a negative unit net charge. The repulsion between the two negative charges, the base and top, keeps the bridge extended. If the muscle is stimulated, calcium moves from the sarcoplasmic reticulum and one calcium ion then provides a link between the ATP ion on top of the cross-bridge and the ADP ion situated on the actin filament. The negative charge on top of the bridge is neutralized, active repulsion no longer exists, and the extended polypeptide chain transforms into a helix-coil. It is believed that contraction is produced by this process. Davies's theory has been challenged by newer studies. Ebashi and Endo (136) have shown that calcium acts indirectly by combining with the troponin-tropomyosin complex.

Based on the preceding information concerning the biochemical and cellular understandings and speculations, the author postulates the following:

Postulate I

Chemical reaction of phosphate molecules result from the splitting of ATP and energy regeneration of these phosphate molecules occurs in the sarcomere. There is, however, no relationship between the chemical processes and the direction of any subsequent limb motion. That is to say, sarcomere activities and the direction of limb movement are independent. Activation levels depend on many external effects such as motor recruiting, motor programming, and the interaction of different muscles. However, the elementary unit of muscular function is the sarcomere and the activity which causes the filament to slide is independent of the external movement.

The sarcomere is the basic functional unit of muscular contraction. However, other factors are associated with the activity of contraction. For example, after the motor unit fires in its motor preprogramming fashion, many sarcomeres contract causing the total fiber to shorten and pulling various connective tissues both internally and externally to the muscle.

This process can be equated with an engineering model. In its simplest form, the model would consists of three-components. A simple model would assume linearity for each component. However, in real life these components are not linear. There are two models which are commonly used to describe these relationships: the Voigt model and the Maxwell model Figures 14 and 15. These models incorporate three distinct elements: elastic, serial and parallel, and damping. Williams and Edwin (473) employed such models in the electronic simulation of frog muscle responses to pulse trains at various selected frequencies of stimulation.

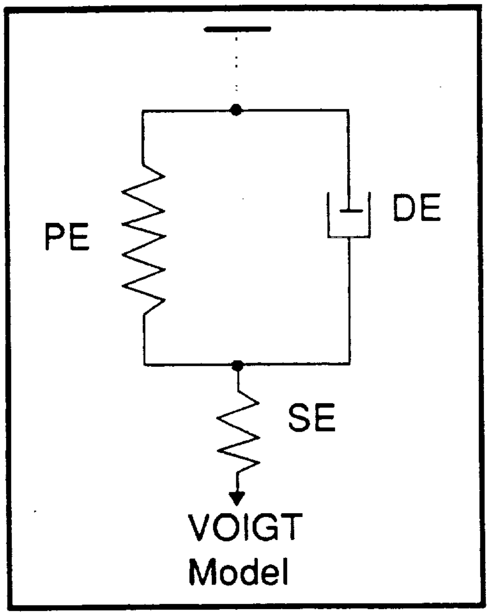


Figure 14

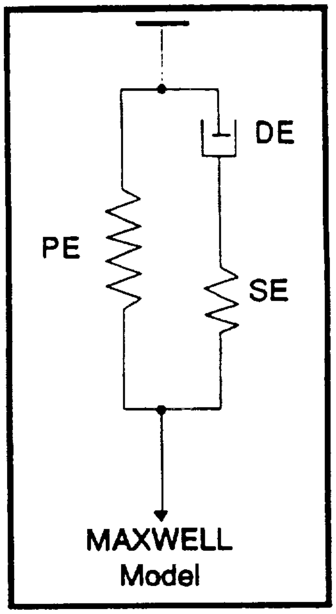


Figure 15

Crowe (116) incorporated the Voigt model to study the responses of intrafusal muscle fibers of mammalian muscle spindles to mechanical stretch and to fusimotor stimulation. In 1969, Green (208) also employed the Voigt version of the three-component model. He recognized the nonlinearity of all the elements involved, thus, accepting the concept that other factors which were not incorporated must ultimately be included.

Many more studies were conducted in order to find a model appropriate for muscular contraction. However, in all cases, the non linearity of the system and the complexity in behavior of muscular contraction precluded an ideal model which functioned properly under all conditions.

Bawa et al. (59) presented a model of muscle consisting of linear springs and a dashpot in parallel with a force generator. This force generator produced a contractile force of constant magnitude each time a stimulus was received. Immediately afterwards, the force was assumed to decay exponentially. According to the authors, the predictions of this model were in good agreement with experimental observations.

If the muscle was not stimulated, its internal tension due to filament binding was small. Therefore, if a muscle was stretched without neural stimulation, any tension must come from the elastic structures of connective tissue which are in parallel with the sarcomeres. At the time of stimulation, the contractile machinery produced tension which was transferred to the endpoints of the muscle. This transference of forces was through the connective tissue lying in series with the sarcomeres.

One can appreciate the mechanical complication associated with this structure and transfer of forces. For example, the system must be described with one type of connective tissue providing non linear resistance in parallel while another type of connective tissue gives non linear resistance at the end points of the muscle in series with the force generator mechanism. In addition to these non linear relationships, the fibrils themselves have specific geometrical relationships to the line of force which causes the contraction. The tendons, as well, have their own nonlinear elastic characteristics.

The concept associated with the "give in the system" provided by the various connective, muscular, and other soft tissues is known as compliance. Various locations for compliances were suggested by various investigators. Jewell & Wilkie (282) suggested various sites. Jewell & Wilkie and Szent-Gyorgyi (283) suggest that the Z-discs in the sarcomere allow a great deal of compliance in the muscular structure. Huxley & Simmons (270) propose that there are two elastic elements with one used as a damper and the other provides compliance for the sarcomere. They suggests that these elements are within the myosin molecule. Flitney and Hirst (170), and Morgan (361) provided conclusive evidence that part of the series elastic structure is indeed located within the cross-bridges. These researchers believe that this part depends on the active state of the muscle and the degree of filamentary overlap.

These research findings indicate that there are elastic elements within the sarcomere and at the end point of the fibers where connective tissues connect the muscle to the bone. The important factor is that when the sarcomere shortens, there is a short latency during which some energy is stored within the elastic components of the muscle. After this short latency, the force is applied at the end points of the muscle and the lever begins moving.

Based on the facts described previously, the author postulates the follows:

Postulate II

All mechanical movement originates at the sarcomere level. Regardless of the movement of any external lever, that is, the bone to which the muscle is attached, the specific chemical reactions within the sarcomere begin the shortening or contracting process. The ATP activity, the ATPase reaction, and the calcium ion flow are independent of the external lever movement. The sarcomeres shorten as the actin filaments are pulled by the myosin cross bridges. Sarcomere activity can only produce contraction. However, bone movement can be either in the direction of the contraction or, if there is a sufficiently large load to overwhelm the contractile strength of the sarcomeres, in the direction opposite to the contraction.

Functional Characteristics and Mechanical Properties of the Muscle:

Skeletal muscle is composed of three distinguishing components: contractile, serial elastic, and parallel elastic. In addition, the muscle also has a blood supply and functions within a semi fluid environment. Attention will not be given here to the vascular factor.It is comparatively easy to determine the constants for the parallel elements of the muscular structure. This can be done by studying the relaxed muscle.

When considering the elastic elements in parallel, Yamada (479), demonstrated its characteristics by utilizing stress-strain curves for muscles and fascia. Figure 16 illustrates this relationship with different muscles having different curves. However, all muscles and fascia demonstrate non linear relationships. Examination of the curves readily confirms that muscles are much more compliant than fascia. This observation seems quite reasonable since fascia consists of connective tissue to transmit forces and for protection whereas muscles are the force generators. Other investigators, including Jewell & Wilkie (282) and Hefner & Bowen (236), have found similar results.

This stress-strain relationship demonstrates that beyond a certain stress level, the fascia will be damaged before the muscle is injured. However, the state of the muscle is the important factor. When the muscle is in a full contractile state, the stress-strain relationship can be shifted. Also, a state of muscular fatigue can bias the relationship resulting in an altered reaction to stress.

Whether a stress-strain relationship can be altered by the forces generated from a combined effort of the sarcomeres alone without external influence is doubtful. That is, it seems unlikely that muscle strength alone can injure the fascia or the muscle tissue themselves. However, high levels of force generated by external means due to gravity or to impact as well as a summation forces originated through movement produced by a combination of levers could exceed the compliance of the fascia or the muscle resulting in internal damage.

Postulate III

Injury to the skeletal system occurs due to external force which exceeds the maximal internal force. Under this condition of excessive external force, the stress-strain relationship may exceed the compliance capability of the connective tissue and, therefore, cause tissue damage.

Examination of the series elastic element in the muscular structure is a more complicated task. The reason is that the state of the muscle alters the relationships. The biological material of which the serial elastic component is composed is not different from the parallel elastic material which consists of elastin and collagen fibers in complex arrangements. Again, investigators such as Yamada (479), Wilkie (471), Hill (247), Bahler (52), Joyce & Rack (290) and others have defined the compliance characteristics of the serial elastic elements of the skeletal muscle. For example, Yamada (479) found that calcaneal tendon tissue ruptures at extensions exceeding a value of .1 relative to the tendon's resting length.

Again, the force generated by the combined sarcomere pool is insufficient to over stress the serial elastic component of the muscular system. Only an external force generated at the contact point of the connective tissue by a lever, such as bone on bone or bone and external object, could transmit a force which would exceed that produced internally. These facts lead to the Author's fourth postulate:

Postulate IV

The muscular system is exposed of two types of forces. The first type is the sum of the forces generated by the individual sarcomeres. The second type of force is generated from the lever through serial and parallel elastic connective tissue. The sarcomeres realize this force but do not contribute to it. The state of the sarcomeres is the determining factor as to the response to this force. If the force is greater then the binding force of the cross bridges, then either the actin filament will be stretched away from the myosin filaments or internal damage will occur in a tissue which is weaker then the binding chemical force occurring at the cross bridges level. The only force generator in the contractile system is the contractile element. The connective tissues, such as the fascia or the tendon, cannot generate force but can only absorb energy and return it to the system in a form of elasticity.

The behavioral characteristics of the contractile element is extremely complicated. Some of the nonlinear factors affecting its force generation capabilities depend on its length, fatigue, the rate of length change, the degree of stimulation, and its temperature. Each of these factors affect the level of force that the contractile element can produce. In physiological terms, these factors can reduce to the active-state function, the filamentary-overlap, and the velocity-dependence functions.

As was discussed previously, the contractile element produces the force due to the actin-myosin cross-bridges. Detailed examination reveals that the cross-bridges are part of the myosin filament, being the heavy-meromyosin subunits projecting out of the light-meromyosin assemblage which constitutes the backbone of the myosin filament. The heavy-meromyosin subunits consist of two rod-like subunits, each of which carries a globular head subunit (325). It is to these globular heads that the energy-providing ATP molecules are presumed to bind in the presence of calcium ions and are thought to provide the direct link with the actin filaments.

The internal source of force by the muscle, therefore, is equal to the sum of the forces produced by all the cross-bridges in one half-sarcomere of the fiber, at any instant of time. Since it was found that the propagation velocity of the calcium ions moving from the terminal cisternae into the sarcoplasm is finite (284), the onset of the contractive cycle of different sets of cross-bridges along the myosin filament upon stimulation will be successive. This fact was verified by Huxley and Taylor (271).

It should be remembered that the appearance of force, measured by an external transducer or calculated from the movement, is not equal to nor does it correlate highly with the internal force. One reason is that in living human subjects, it is impossible to know the number of sarcomeres, fibers, or activation levels within the studied muscle. Another factor is that the leverage system changes during movement as does the interaction between different segments in the body. Inertial forces act on each body segment due to the acceleration of the different segments. Co-activation of antagonistic muscles also plays a major role in producing the net moment around a particular joint.

The force in the skeletal muscle is generated within the sarcomere and is equal to the sum of the forces generated by the cross bridges. The force is equal to the sum of the forces produced by all the cross-bridges in one half-sarcomere of the fiber.

Any attempt to relate the sarcomere force to the force generated by a limb movement will yield a low correlation since the force measured at the force application point depends on the lever arm, the amount of antagonistic muscular co-activation, and the inertial forces due to the movement. The appearance of force on the load arm, such as the hand, wrist, ankle, or at the joints, such as the elbow, knee, etc, does not correlate highly with the forces generated at the sarcomere level.

As early as 1940, Ramsey and Street (396) demonstrated the existence of an internal force tending to extend the fiber and, therefore, presumably removing whatever tension was developed by the filaments during contraction (202). These authors also suggested that this internal force may be attributed to the deformation of the sarcolemma accompanying the increase of the fiber diameter during shortening. Therefore, the amount of force needed for shortening will be smaller on the external measuring device than the amount actually generated at the sarcomere level. The sum of forces generated by the cross bridges is at least 10 times the amount shown on the force application. The efficiency of the force at the point of external application depends upon the position of the lever, the position of the body, the technique in executing the movement, and the utilization of energy derived from other body segments toward the desired movement.

Therefore, the ability to carry a greater load at a particular movement in a specific direction has no bearing on the ability of a single cross bridge at the sarcomere level to produce more force. The sarcomere can only contract and is not effected by the direction of limb movement regardless of the number of cross-bridges which are active at one time.

Training methods were and can be devised to increase the number of active cross bridges needed for a particular movement which would, therefore, increase the force generated for a specific action. However, the net force at the application point might not correlate with the number of cross bridges active at the prime mover muscle.

The number of cross-links formed is a function of the active state of the fiber as well as the degree of filamentary overlap (202) and, presumably, the velocity of shortening or lengthening of the contractile element (273). In addition, the average force output of the cross-bridges is postulated to depend both on the velocity of the interfilamentary movement and on certain intermolecular forces. These intermolecular forces were shown by Huxley (272) to exhibit a cyclic behavior the attachment-detachment-reattachment cycle of the cross bridges. Because this cyclic behavior is asynchronous, individual force fluctuations do not appear externally. Thus, the average force output of an activated cross-bridge becomes a function of the velocity of the interfilamentary movement only.

Therefore, the force output of the contractile proteins of a typical muscle fiber is equal to the average force output of a typical cross-bridge, multiplied by the number of cross-links active in a half-sarcomere, at any instant of time. As a formula this fact can be illustrated by the following equation:

$$F = N(E) * A(L) * L/t$$

F is equal to the force output of the contractile proteins of a typical muscle fiber.

N is equal to the total number of cross-bridges present in a half sarcomere, in a particular state of activation E.

E is equal to the state of activation.

A is equal to the average force output of a typical cross-bridge, at a particular length L.

L is equal to the instantaneous length of the sarcomere.

L/t equal to the Length of the sarcomere per unit of time t, which represents the change in length per unit of time or the velocity of sarcomere contraction.

It is important to realize that it is very unlikely that external conditions of the force application on a particular body segment would effect these relationships in most conditions. Of course, the speed of segment movement and the joint angular changes are directly related to the speed of sarcomere shortening and, therefore, the factor L/t in the sarcomere. If, for example, the elbow joint were restricted, such as in a isometric contraction, then the sarcomeres would remain in a state of unchanging length and, in that state, would function according to the formula. If the elbow joint were free to move, flexing or extending, the sarcomere would produce force regardless of the direction of movement according to the equation. In fact, sarcomere performance is unrelated to direction since there are no sensors of any kind within it to record or detect consequences.

Therefore, the relative number of active cross-links is a function of the active state, the degree of filamentary overlap, and the velocity of shortening or lengthening of the contractile element. This means that there is a condition in which the sarcomere length is optimal and the active state is at maximum stimulation. The sarcomere is in isometric state when this optimal length does not change. At that point the force output will be maximally. However, this optimal state is rarely achieved since the number of cross links varies as well as the distortions caused by the collision between Z-lines and myosin filaments at very short sarcomere lengths and the overlap of actin filaments at intermediate sarcomere lengths (202). In any case, the force output of the contractile element is not identical with the force output as observed externally. Clearly, the force output of the contractile machinery will be reduced by internal resistance, and the externally observable contractile force will be lowered as well. The parallel elastic connective tissue is a main factor in this reduction.

Neuromuscular Dynamics:

The active state of the filaments is one of the factors in the force production formula. Hill (250) reported and defined the active state of the muscle. Hill pictured the active state as some operational ability of the muscle which abruptly appeared when the muscle was stimulated and then slowly disappeared when the stimulus ceased. Gonzalez-Serratos (201) described the events leading to the onset of the contraction with the sequence beginning with the arrival of a nerve signal at the motor end plate of the fiber and the subsequent propagation of the fiber action potential along the fiber surface and down the transverse tubular system. The transverse tubular system which is called the T-system, located at the Z-discs, converts the action potential into a depolarization signal which acts across the walls of the tubular network (10,159). Immediately upon the arrival of the action potential, depolarization of the T-membranes causes the release of calcium ions from the sarcoplasmic reticulum. This phenomenon is described in detailed by Inesi (277). At the instance the calcium ions penetrate the membrane, ATP hydrolysis is initiated and, simultaneously, calcium ions bind to the calcium-binding subunit of the troponin molecule. This cause the myosin head to bind to an actin monomer which caused the shortening (138,222, 386). Simply, the active state relates to the amount of calcium ions bound to troponin. If the maximum number of potential interactive sites on the actin filament are made available by the action of calcium, then the maximal force will be produced by the contractile elements.

It appeared that the number of free calcium ions and the amount of binding is independent of both the external force requirements and the direction of movement. However, neural programming is involve in the recruitment phenomenon to be discussed later.

The amount of calcium ions bound to troponin relates to the amount of contracting elements which are in an active state. If, for some reason, the stimulus is such that the calcium ions do not combine with troponin, there will be a less than active state in the contractile element. In the presence of calcium ions, this binding depends on many factors and one of the most important is the amount of neural stimulation. The amount of calcium concentration varies under different conditions and is the "bottle neck" for the contraction mechanism. Without the process of the binding of the calcium ions to the troponin-tropomyosin complex, there would be a specific contractile force for a given sarcomere length. This does not occur since the rate of supply of calcium ions varies depending on the amount released from the sarcoplasmic reticulum. Depolarization of the membrane of the sarcoplasmic reticulum results from the depolarizing potential of the T-tubular system.

There is no research to show that the direction of the lever movement or the amount of external load in either direction affects a given sarcomere length or the level of calcium ions. Rather it is the level of electrical stimulation which causes the mobility of calcium ions. With regards to the electrical signal in the interior of the T-system, it was found by Huxley and Peachey (269) that this is due either to direct conduction of the action potential of the surface membrane or to an electronic spread of the surface potential down the T-system. This electrochemical transmission of the nerve impulse arrives at the motor endplate of the fiber to a neuromuscular junction and the T-system. These comprise a very complex electrical networks.

At the motor endplate, Eccles (141) reported that in mammalian muscle the nerve stimulation results in liberation of an acetylcholine transmitter substance. Each stimulation liberates a certain amount of this chemical. The frequency of stimulation varied depending upon the fiber type and ranged from approximately 100 c/s to about 25 c/s.

Needless to say, these activities do not occur simultaneously and various latencies exists. For example, the active state of the contractile element reaches its peak in 10 to 12 milliseconds. The decay of the active state also requires a few milliseconds. Therefore, the dynamics of the contractile element of a muscle fiber is dependent on velocity and the filamentary overlap.

Force Output:

The number of active cross-links in the interfilamentary space and the degree of filamentary overlap are the basic factors which generate force at the fiber. The other factors which effect the force output is the velocity of movement between the actin and the myosin filaments. There is virtually no relationship between the velocity of movement and the force production, however, it should be remembered that only the effect of velocity at the sarcomere level is important. Velocities of levers involve mechanical relationships and inertial forces are external factors which can affect the internal contractile element forces but cannot alter its physiological elements.

All these mechanisms contribute to all body motions. When training for improved movement or for enhanced athletic achievement, muscular activity is the predominant factor for increasing efficiency and optimizing skill.

Muscular Activity in Exercise:

Exercise can be define as physical activity utilized to generate body responses to demands. Exercise enables the body to adapt to certain demands and, therefore, increase or alter the performance capabilities.

There are various factors that affect the type of exercise. These are:

1. Speed of exercise
2. Duration of exercise
3. Resistance

The relationships between these factors determine the various adaptation characteristics of the body's physiological system.

Speed/Duration Factor:

The faster the speed, the shorter the time that exercise can be maintained. The slower the speed of movement, the longer the time the exercise can be performed. Figure 17 illustrates this effect. For example, sprinting can be performed for a short time, approximately 50 seconds, while jogging can continue for hours.

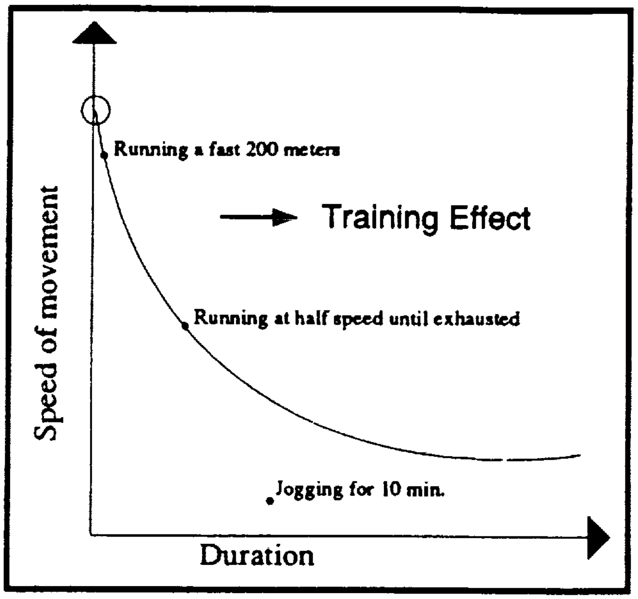


Figure 17

Speed/Resistance Factor:

The higher the resistance, the lower the speed of movement and with less resistance, the movement speed increases. In resistance training, the heavier the load, the slower the movement. Figure 18 illustrates this relationship.

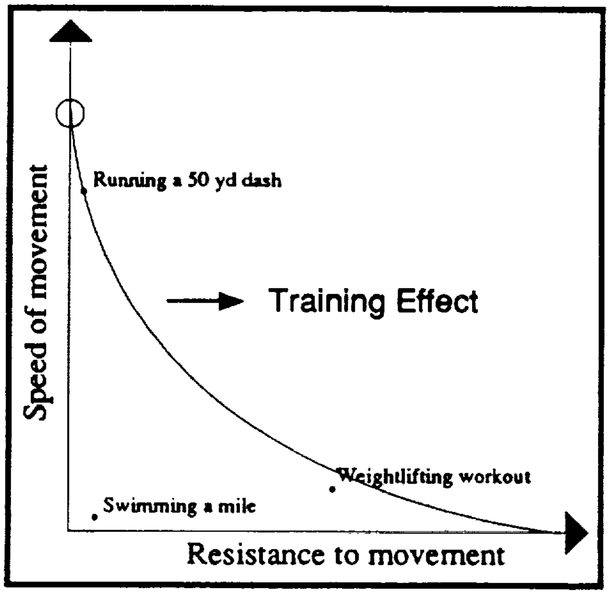


Figure 18

Resistance/Duration Factor:

The greater the resistance to movement, the less time the movement can be endured. Figure 19 illustrates this relationship.

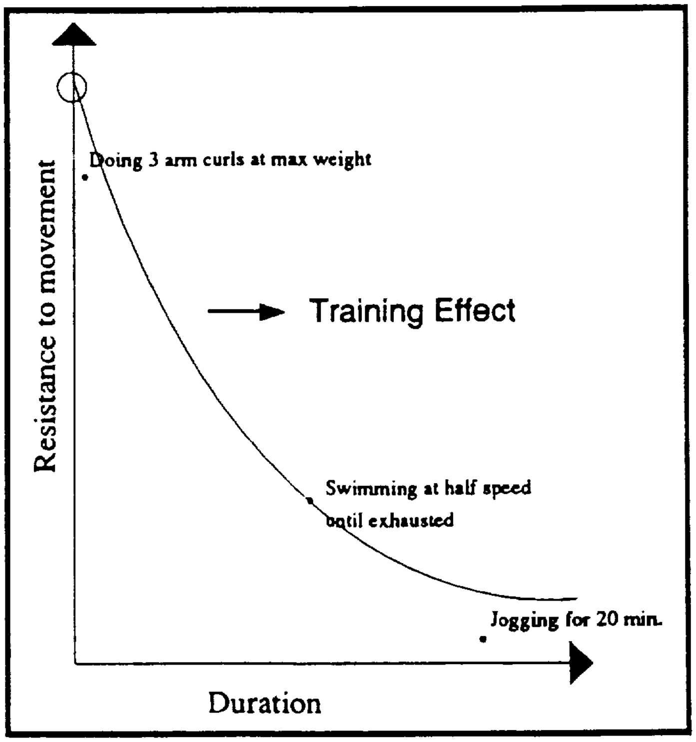


Figure 19

When combining these factors, one can consider the entity as a three-dimensional figure as in Figure 20. Exercises closer to the origin are the least strenuous while the further from the origin, the more difficult the exercise.

If one were to classify exercises for various physiological adaptations, they could be summarized in Figure 21 which shows that strength exercises, as in resistive training, and endurance exercises, such as in distance running.

Exercise is the act of performing a physical activity. In order to elicit specific training characteristics, one must exercise in repeated bouts. Repeated bouts of training will result in biological adaptations over a period of time. This time can vary from days to years.

Periodically repetitive performances of a sequence of exercises at increasing levels of intensity can cause physical adaptations. Adaptation takes place due to some unknown "set up" which occurs within the DNA-RNA protein mechanisms. Protein synthesis takes place during the training period and results in greater muscular strength and endurance. Subcellular components are altered during the training period and it is specific to the type of training regimen. In resistive training, the adaptations primarily occur in the contractile mechanisms on the myofibrillar protein. This results in increased size and number of myofibrils per fiber. On the other hand, endurance adaptations are observed in the enzymatic capabilities of the metabolic pathways. It is important to remember that specific exercises selectively alter specific subcellular compartments causing varying degrees of exercise capability and selectively altering the training adaptations. The training adaptations, therefore, are specifically related to the exercising conditions.

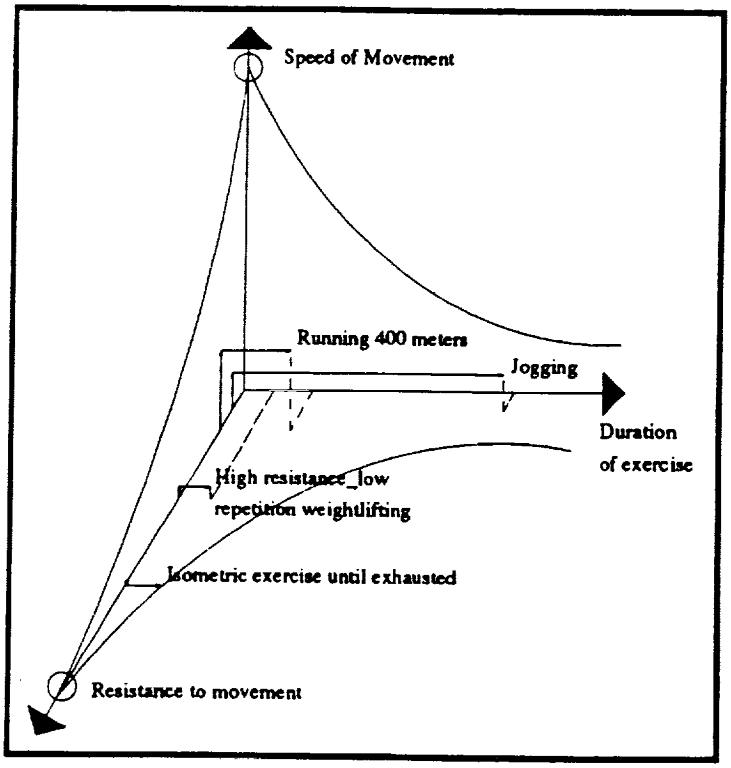


Figure 20

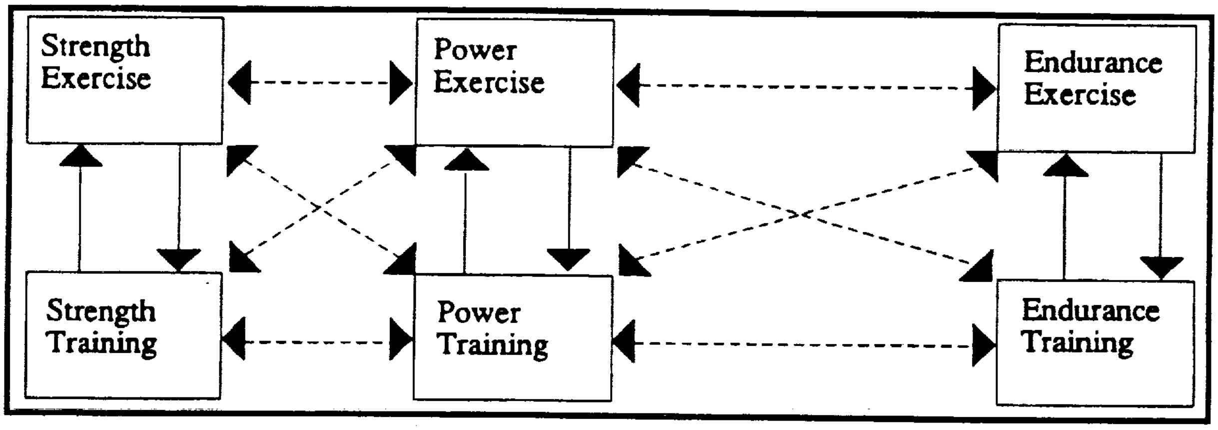


Figure 21

RESISTIVE EXERCISE

The relationship between resistance exercises and muscle strength has been known for centuries. In ancient Greece, Milo, the wrestler, used progressive resistance exercises to improve his strength. His original method consisted of lifting a calf each day until it reached its full growth, and this technique provides probably the first example of progressive resistance exercises. Today, it is well documented in the literature that the size of skeletal muscle is effected by the amount of muscular activity performed. Increased work by a muscle can cause that muscle to undergo compensatory growth (hypertrophy) while disuse leads to wasting of the muscle (atrophy).

This information has stimulated the medical and sports professions, especially coaches and athletes, to try many combinations and techniques of muscle overload. These attempts to produce a better means of rehabilitation or a physiological edge in sporting activities have only scratched the surface of the cellular mechanisms and physiological consequences of muscular overload.

Muscular strength may be defined as the force a muscle group can exert against a resistance in a maximal effort. In 1948, Delorme (125A) adopted the name "progressive resistance exercise" for his method of developing muscular strength through the utilization of counter balances and weight of the extremity with a cable and pulley arrangement and, thus, gave load-assisting exercises to muscle groups which did not perform antigravity motions. McQueen (344A) distinguished between exercise regimens for producing muscle hypertrophy and those for producing muscle power. He concluded that the number of repetitions for each set of exercise determines the different characteristics of the various training procedures.

Based on evidence presented in these early studies, hundreds of investigations have been published relative to "techniques for muscular development including isotonic exercises, isometric exercises eccentric contractions, the Oxford technique, the double and triple progressive super set system, and many others. Each system's effectiveness has been supported and refuted by numerous investigations.

Berger (61A) concluded that 6-7 repetitions three times a week was best for developing dynamic strength. Research conducted by Steinhause (432A) emphasized the need to increase the intensity, not the amount of work, in order to develop maximum strength.

In more recent studies pertaining to exercise, Pipes and Wilmore (388A) compared isokinetic training to isotonic strength training in adult men. According to their findings with isokinetic contractions at both low and high speeds, the isokinetic training procedure demonstrated marked superiority over the isotonic methods. In 1972, Ariel (29,30,31,32,33,34) introduced the Dynamic Variable Resistance exercise principles which resulted the variable resistance exercise equipment. For the first time biomechanical principles were employed in the design of exercise equipment.

Definitions of Terms:

Due to ambiguity in the literature of certain physiological terms and laboratory procedural differences, the following terms are defined:

1. Muscular strength: The contractile power of muscles as a result of a single maximum effort.
2. Muscular endurance: Ability of the muscles to perform work by holding a maximum contraction for a given length of time or by continuing to move a submaximal load to certain level of fatigue.
3. Isometric training: A muscular contraction of total effort but with no visible limb movement (sometimes called static training).
4. Isotonic training: Raising and lowering a submaximal load, such as a weight, a given number of times (sometimes called dynamic training).
5. Isokinetic training (Accommodating Resistance): Muscular contraction at a constant velocity. As the muscle length changes, the resistance alters in a manner which is directly proportional to the force exerted by the muscle.

6. Concentric Contraction: An isotonic contraction in which the muscle length decreases (i.e., the muscle primarily responsible for movement becomes shorter).
7. Eccentric Contraction: An isotonic contraction in which the muscle length increases (i.e., the muscle primarily responsible for movement becomes longer).
8. Muscle Overload: The workload for a muscle or muscle group which is greater than that to which the muscle is accustomed.
9. Repetitions: The number of consecutive times a particular movement or exercise is performed.
10. Repetition Maximum (1RM): The maximum resistance a muscle or muscle group can overcome in a maximal effort.
11. Sets: The number of groups of repetitions of a particular movement or exercise.
12. Variable Resistance Exercise: As the muscle contracts, the resistance changes in a predetermined manner (linear, exponentially, or in a user defined manner).
13. Variable Velocity Exercise: As the muscle contracts with maximal or submaximal tension, the speed of movement changes in a predetermined manner (linear, or exponentially, etc.)

In most existing exercise equipment today and in the previously cited research, resistive training was performed with "tools" which lack intelligence. That means the equipment was "unaware" that a subject was performing an exercise on it. For example, the equipment employed in the study conducted by Pipes and Wilmore assumed certain velocities on the isokinetic modality used. However, verification of the speed was impossible since a closed loop feedback and sensors were not used as they do not exist on the equipment employed. However, with the advent of miniaturized electronics in computers, it is possible today to join exercise equipment with the computer's artificial intelligence. For the first time it is possible for the equipment to adapt to the user rather than for the user to adapt to the equipment.

Another important consideration in both the design of equipment for resistive exercise and the performance of an athlete or a busy executive is that the human body relies on preprogrammed activity by the central nervous system. This control necessitates exact precision in the timing and coordination of both the system of muscle contraction and the segmental sequence of muscular activity. Research has shown that a characteristic pattern of motion is present during any intentional movement of body segments against resistance. This pattern consists of reciprocally organized activity between the agonist and antagonist. These reciprocal activities occur in consistent temporal relationships with the motion parameters, such as velocity, acceleration, and forces.

Hellebrandt and Houtz (236A) shed some light on the mechanism of muscle training in an experimental demonstration of the overload principle. They found that repetition of contractions which place little stress on the neuromuscular system had little effect on the functional capacity of the skeletal muscles; however, they found that the amount of work done per unit of time is the critical variable upon which extension of the limits of performance depends. The speed with which functional capacity increases suggests that the central nervous system, as well as the contractile tissue, is an important contributing component of training.

In addition to the control by the nervous system, the human body is composed of linked segments and rotation of these segments about their anatomical axes is caused by force. Both muscle and gravitational forces are important in producing these turning effects which are fundamental in body movements in all sports and daily living. Pushing, pulling, lifting, kicking, running, walking, and all human activities are results of rotational motion of the links which are made of bones. Since force has been considered the most important component of athletic performance, many exercise equipment manufacturers have developed various types of devices employing isometrics and isokinetics. When considered as a separate entity, force is only one factor influencing successful athletic performance. Unfortunately, these isometric and isokinetic devices inhibit the natural movement patterns of acceleration and deceleration.

The three factors underlying all athletic performance are force, displacement, and duration of movement. In all motor skills, muscular forces interact to move the body parts through the activity. The displacement of the body parts and their speed of motion are important in the coordination of the activity and are also directly related to the forces produced. However, it is only because of the control provided by the brain that the muscular forces follow any particular displacement pattern, and without these brain center controls, there would be no skilled athletic performances. In every planned human motion, the intricate timing of the varying forces is a critical factor in successful performances.

In any athletic performance, the accurate coordination of the body parts and their velocities is essential for maximizing performances. This means that the generated muscular forces must occur at the right time for optimum results. For this reason, the strongest weight lifter cannot put the shot as far as the experienced shotputter. Although the weight lifter possesses greater muscular force, he has not trained his brain centers to produce the correct forces at the appropriate time.

Because most athletic events are ballistic movements and since the neural control of these patterns differs from slow controlled movements, it is essential that training routines employ programmable motions to suit specific movements.

Resistive Exercising Methods:

There is a significant difference between various resistive training methods. When comparing isotonic and isokinetic exercises, for example, in the isotonic exercises the inertia, that is, the initial resistance, has to be overcome first and then the execution of the movement progresses. The weight of the resistance can not be heavier than the maximum strength of the weakest muscle acting in a particular movement or else the movement can not be completed. Consequently the amount of force generated by the muscles during an isotonic contraction does not maintain maximum tension throughout the entire range of motion. In an isokinetically loaded muscle, the desired speed af movement occurs almost immediately and the muscle is able to generate a maximal force under a controlled and specifically selected speed of contraction. The use of the isokinetic principle for overloading muscles to attain their maximal power output has direct applications in the fields of sport medicine and athletic training. Many rehabilitation programs utilize isokinetic training to recondition injured limbs to their full range of motion. The unfortunate drawback to this type of training is that the speed is constant and there are no athletic activities which are performed at a constant velocity.

In isotonic resistive training, is more than one repetition is to be used, one must use submaximal overload on the initial contractions in order to complete the required repetitions. Otherwise, the entire regimen will not be completed due to fatigue. Berger and Hardage (61B) studied this problem by training two groups of men with 10-RM. One group trained following the standard Berger Technique while the other group used on repetition maximum for each of the ten repetitions. This was accomplished by progressively reducing the weight for the next repetition in a manner which paralleled the fatigue of the muscle. The results showed that the intensity of the work seemed to be the important factor in strength increases, since the maximal overload group showed significantly greater strength gains than did the standard 10-RM group.

Based on these findings it would seem appropriate to assume that a modality which can adjust the resistance so that it parallels fatigue to allow the maximum RM for each repetition would be superior to the currently available equipment. Berger accomplished this function by removing weight from the bar while the subject trained. This is neither the most convenient nor the most practical method. With the aid of the modern computer, this function can be performed automatically.

Another drawback with current isotonic types of resistive exercises is that with the aid of inertia, due to the motion, the resistance changes depending on the acceleration of the weight and the body segments. In addition, since overload on the muscle changes due to both biomechanical levers and the length tension curve, the muscle can only obtain maximal overload in a small portion of the range of motion. To overcome this shortcoming in resistive training, several companies have manufactured strength training devices which have "variable resistance" mechanisms in them. However, these "variable resistance" systems increase the resistance in a linear fashion and this linearity does not truly accommodate the individual. When including inertial forces to the variable resistance mechanism, the accommodating resistance might be cancelled by the velocity of the movement.

There seem to be unlimited training methods and each system is supported and refuted by as many "experts". In the past, the problem of validly evaluating the different modes of exercise was rendered impossible because of the lack of the proper diagnostic tools. For example, in the isotonic type of exercise the investigator does not know exactly the muscular effort and the speed of movement but knows only the weight which has been lifted. When a static weight is lifted the force of inertia is a significant contribution to the load and cannot be quantified by feel or observation alone. In the isokinetic mode, the calibration of the velocity is assumed and has been very poorly verified. The rotation of a dial to a specific location does not guarantee the accuracy of subsequently generated velocity. In fact, discrepancies as great as 40 percent are found when verifying the velocity of the bar.

THE INTELLIGENT EXERCISE MACHINE

In all the previous descriptions of exercise equipment, the user has had to determine the amount of resistance and the number of repetitions desired. The reason the user made the choices was, of course, that the exercise equipment itself was inherently incapable of any intellectual participation. However, with the advent of computers, it became possible to design exercise equipment with artificial intelligence enabling the computerized machine to select the best exercise method based on each individual user. Thus, the user need not be an expert in any biological, physiology, or exercise area since the exercise machine is programmed with information from many scientific fields thus, correctly benefiting the different individual users.

The exercise machine described herein is the result of the application of many unique, innovative features and mechanisms to the long-established fields of resistive exercise or training for athletics, rehabilitation, and physical fitness. The underlying principle behind these innovations is that of a computer controlled feedback of servo-mechanism which is able to maintain any desired pattern of force and motion throughout the range of each exercise, regardless of the magnitude or rate of force applied by the person exercising. The advantages of an intelligent feedback-controlled mechanism over existing resistive exercise mechanisms are many.

First, all systems which employ weights as the mechanism for resistance have major drawbacks in four or more areas: (1) biomechanical considerations, (2) inertia, (3) risk of injury, and (4) unidirectional resistance. The biomechanical considerations are the most important for exercise equipment and have been previously explained. Inertia is the property of resisting any change in motion and, because of this property, it requires a greater force to begin moving weights than it does to keep them moving in a constant manner. Similarly, when the person exercising slows his motion at the end of an exercise movement, the weights tend to keep moving until slowed by gravity. This phenomenon reduces the required force at the end of a motion sequence. This property becomes especially pronounced as acceleration and deceleration increase, effectively reducing the useful range of motion of weight-based exercise equipment. The risk of injury is obvious in weight-based exercise equipment. When weights are raised during the performance of an exercise, they must be lowered to their original resting position before the person using the equipment can release the equipment and stop exercising. Injury could easily result if the weights fell back to their resting position accompanied by the concomitant motion of the bar or the handle attached to the weights. If the person exercising happened to lose his grip, or was unable to hold the weights due to exhaustion or imbalance, serious injuries could and have resulted. Finally, while being raised or lowered, weights of exercise equipment employing weights offer resistance only in the direction opposite to that of gravity. This resistance can be redirected by pulleys and gears, but still remains unidirectional. In almost every exercise performed, the muscle or muscles being trained by resistance in one direction are balanced by a corresponding muscle or muscles that could be trained by resistance in the opposite direction. With weight-based systems, a different exercise, and often a different mechanism, are necessary to train these opposing muscles.

Exercise mechanisms which employ springs, torsion bars, and the like are able to overcome the inertia problem of weight-based mechanisms and can partially overcome the unidirectional force restriction by both expanding and compressing the springs. However, the serious problem of safety remains. An additional problem is the fixed, non-linear resistance which is characteristic of springs and is usually unacceptable to most users of exercise equipment.

The third type of resistive mechanism commonly employed in existing exercise equipment is that of a hydraulic mechanism. This mechanism is able to overcome the inertial problem of weights and the safety problem of both weights and springs. With the appropriate selection or configuration of hydraulic mechanisms, the unidirectional problem can also be overcome. However, previous applications of the hydraulic principle have demonstrated a serious deficiency that has limited their popularity in resistive training. This deficiency is that of a fixed (although perhaps preselected) flow rate though the hydraulic system. With a fixed flow rate, it is a well-established fact that resistance is a function of the velocity of the piston, and in fact, varies quite rapidly with changes in velocity. It becomes difficult for person exercising to select a given resistance to train with since he or she is usually constrained to moving either slower or faster than he would like in order to maintain this resistance. Additionally, at any given moment, the user is unsure of just what the performing force or velocity actually is. For these reasons, hydraulic mechanisms have found only limited acceptance among serious users of exercise equipment.

Feedback Control of Exercise:

The Computerized Exercise Machine possesses several unique advances over other resistive exercise mechanisms, both fixed and feedback-controlled. The most significant of these advances is the introduction of a stored-program computer to the feedback loop. The computer, and its associated collection of unique programs, allows the feedback-controlled resistance to vary not only with the measured parameters of force and displacement, but additionally, to modify that feedback loop while the exercise is in progress. This modification can, therefore, reflect changes in the pattern of exercise over time. The unique program selection can effect such changes in order to achieve a sequential or patterned progression of resistance for optimum training effect. The advantage of this capability over previous systems is that the user can select the overall pattern of exercise and the machine assumes responsibility for changing the precise force level, speed of movement, and temporal sequence to achieve that pattern.

Consider the following typical examples of exercises which can be performed on this machine which would be impossible on any other exercise machine. A user wishes to select a resistance (weight, in classical terms) starting at 1/2 the body weight, and to have that resistance increase by 10 percent in each successive repetition, until the user reaches a "sticking point" and cannot continue. With a classical weight machine, he would have to initially select weights equal to half his body weight. Then the user would have to stop between each repetition to change weights, with the probability that he would not be able to select the desired unit of increase since weights are normally available in 5,10,25, or 50 pound units only. In addition, the training effect of the exercise is considerably affected because, while stopping to change weights, the muscles "recover". If, with the Isokinetic or other devices, there were a force readout (which is not included on any of the currently available equipment), the user would have to watch that readout and match the force pulled with the desired force as it appeared on the readout. (This is analogous to trying to keep the high performance race "car" on the "road" in the video arcade games.) This would require more control and concentration than most persons are capable of especially with the onset of exercise-induced fatigue, With the Computerized Exercise Machine, the person's weight would automatically be determined by having him support himself briefly on the exercise bar. Then the computer would select the pattern of increasing force, starting at precisely half the body weight, and increasing the resistance by just 10 percent after each repetition until it detected that the user could no longer move the bar. At this point, it would report the final force level, the number of repetitious, and, if desired, the progress the user had made since the last exercise session.

A second example is that of a user desiring to exercise with a constant force or a predetermined force pattern (i.e. non-linear force through the range of motion). In addition, at the point in the range of motion where his speed is the lowest (the weakest point), the user may want the bar to "lock" for three seconds so that strength could be enhanced through isometric rather than isotonic exercise. After the three second isometric contraction, the motion would be allowed to continue through the next cycle until this sticking point would again be encountered. Experts in various professions believe that such an exercise is a vast improvement over conventional resistive training for developing strength at a person's weakest points. Yet it would be impossible for this exercise to be performed on any other exercise machine known to exist. Not only can the proposed exercise system perform this pattern of exercise, but during and after the exercise it can display the level of strength at the "sticking point" and how this compares both to previous strength levels and to the strength over the entire range of motion. In addition, the programs are then able to adjust ensuing exercise sessions to select the proper range of forces to continue to build strength based on the progress to date. All of this is accomplished without the user having to remember or reenter any data.

As can be seen from the previously cited review of resistive exercise methods, it would seem that the future will rely increasingly on computerized exercise modalities for training and rehabilitation. Current research revealed significantly greater progress in muscular strength for the subjects who trained on the Computerized Exercise Machine. In addition, more efficient and less time-consuming workouts as well as fewer injuries and higher motivation are possible which can produce improved results. The Computerized Exercise Machine is programmed for several training modes. One mode is diagnostic for determining the individual's range of movement as well as the force and speed exerted through that range of movement. On a color CRT, the user can see the force and the velocity curves or print a copy of the display. A second training mode controls a predetermined resistance which can be set in several ways - linear, exponential, user defined and an "ideal" curve. A third mode allows setting "sticking points", or isometric contractions, at any points through the range of movement. The fourth training mode can set a "fatigue level" to which the user exercises until reaching that level. The fifth mode is a power and endurance training which controls the amount of work performed. Another exercise mode is variable velocity training. In this type, the velocity can be predetermined in many possible fashions which also allows the user to exercise in an isokinetic mode. The amount of resistance can be set as a function of the forces exerted by the user for each repetition. The computer "senses" the changes of forces throughout the range of movement and makes the appropriate adjustments in order to accommodate the user. The Computerized Exercise Machine has many other features which are fully programmable and allow tremendous flexibility for the user.

Some of the capabilities of the Computerized Exercise Machine were studied in several research projects performed at the Coto Research Center at Coto de Caza, California. One study was designed to compare the Computerized Exercise Machine to other existing equipment. The study examined the effect of similar training regimens, using several types of training equipment, on the development of muscular strength. The results of the study demonstrated superiority of the Computerized Exercise Machine over the other types of equipment. The study concluded that the Computerized Exercise Machine was more effective in developing muscular strength. It seems that the Computerized Exercise Machine allows adaptation to the maximum effort of the muscular contraction. In addition the interactive feature of the machine permitted maximum motivation for the user and there was a significant carry over effect to other exercise modalities and other independent athletic skills from training on the Computerized Exercise Machine.

Another study was designed to examine the effect of resistive training on limb velocity. The subjects were tested on the maximum speed they could lift a 32 pound load, and in addition, how fast they could lift loads of 40 and 70 percent of their maximum. Again, the results revealed a significant rate of improvement of the Computerized Exercise Machine users over the other training modalities.

A study was designed to determine the aerobic adaptation to work and fatigue training modes on the computerized Exercise Machine and to compare those effects to the aerobic adaptation of running/jogging. The running group trained three times per week for 40 to 50 minutes of jogging and punning. The Computerized Exercise Machine groups were trained in power/work mode or in a fatigue mode. The results of the Study revealed that, for the same amount of time devoted for exercise, the Computerized Exercise Machine users improved their aerobic capacity by almost 20 percent while the runners improved only 12 percent. The Computerized Exercise Machine users also significantly improved in strength/power and local muscular endurance.

From these results, it can be concluded that the Computerized Exercise Machine is more effective than the other modalities tested for several reasons. The subjects could constantly interact with the machine and receive immediate feedback about their effort. While exercising, the subjects were motivated by the interactive results which reported the average and maximum force produced as well as the velocity associated with the movement. During each session, a comparison to previous sessions was displayed on the CRT, a feature that constantly motivated the subjects to work harder. This motivation contributed to the stimulation for the Computerized Exercise groups to work at their maximum effort. Unlike other modalities, the subjects were not restricted to the range where biomechanically the limb would be at a disadvantage and would have to stop exercising. On the Computerized Exercise Machine, at this point, the intelligence of the machine reduced the resistance and allowed the subject to complete the set at his maximum effort. The Computerized Exercise Machine opens a new dimension in the area of training, rehabilitation, and research.

NEUROMUSCULAR INTEGRATION

In order to understand the computational abilities of the brain, it is necessary to understand something of the basic structure and function of the neuronal substrata. Early descriptions of brain models considered the brain as a randomly connected network of binary neurons. In fact, the brain is highly structured and far from random connections with the neurons functioning as both analog and digital computing devices. The neurons in the brain are arranged in quite regular patterns and are grouped in functional divisions. Precise and regular mappings exist from the sensory organs to the sensory processing regions of the cortex, as well as from the motor centers to the muscles of various parts of the body. Somehow the neurons from one area know how to locate and establish contact with neurons in other quite distant areas.

The unit of the brain structure is the neuron. It is a living entity, that is, a cell like all the other cells in the body. The neuron, however, is specialized for information processing. Each neuron is shaped by its surroundings, by the composition of the chemical bath in which it swims, by the hormones it detects, by the electrical and chemical fields and gradients it experiences during its growth and maturing, and by the nature and timing of the electrical impulses and chemical transmitters produced in its vicinity as a result of activity of other neurons.

The neuron can be compared, in simplified terms, to a "gate" in a digital computer or to an operational amplifier in an analog device. Any movement executed by the body must start with the neuron. Neurons have four basic parts: a cell body, a set of dendrites, an axon, and a set of terminal buttons. Neuronal information is transmitted to the action site through the axon. However, the axon does not transmit the information as a DC or AC current but in pulses with certain frequencies. All the pulses which are transmitted have approximately the same height and the same duration. In digital computers electronics, these would be considered as binary bits and are analogous to "1"s and "0"s. A pulse is transmitted on the axon whenever the analog voltage in the cell body exceeds a certain threshold voltage value. Using electronic terms, this is an "action potential" which initially generates a pulse. After the pulse occurs, the voltage in the cell body of the nerve returns to the initial base line value. In electronics terms, the nerve acts like a Schmitt trigger.

The cell body interacts with the axon from the preceding neuron at the synapse. The synapse can transmit in only one direction and, therefore, acts like a diode. The synapse is an electrical gate, or valve, whose resistance to the flow of current is controlled by the receipt of transmitter chemicals from the axon buttons of other neurons.

Communication of information across synapses is one-way and flows from the terminal buttons of one neuron to the dendrites or cell body of another neuron. The presence of the transmitter causes an electrical current to flow in the synapse of the receiving neuron. This current may be either positive or negative, depending on the type of transmitter chemical released. As a general rule, a particular neuron releases only one type of transmitter chemical. Thus, neurons can be classified as either excitatory, causing positive current to flow in receiving neurons, or inhibitory causing negative currents to flow. There is a synaptic receptor for every axon button. Thus, there are two types of synaptic receptor sites: excitatory and inhibitory. A single receiving neuron may have both excitatory and inhibitory inputs. Communication of information across synapses is one-way, flowing from the terminal buttons of one neuron to the dendrites or cell body of another neuron.

It is interesting to note that the voltage in the cell body is an analog signal and represents an algebraic sum of the inputs. This means that many small low voltage signals, which by themselves would not have an effect, may sum algebraically to produce a quantity sufficiently large to activate the nerve. When all the input signals on the cell body exceed the threshold, a pulse is initiated down the axon and, it is said, that the neuron has fired. In other words, the neuron has digital inputs which are converted into analog values. These values are processed algebraically in an analog fashion. The arithmetic result is then reconverted into a digital form for transmission. The neuron can behave in different ways depending on the level and frequencies of the incoming signals. For example, activation may require several equally weighted inputs in order to reach the firing threshold. This type of response is analogous to an "AND" gate. A different type of response is that any of several inputs can drive the cell past the firing threshold; this is analogous to an "OR" gate. A third possibility is that some signals may be subtracted from the sum. This allows both inhibitory and excitatory inputs providing the neuron with characteristics of both "AND" and "OR" gates. Since the individual cell can have thousands of inputs, one can appreciate the nearly infinite possibilities. Thus, the cell must integrate, differentiate, and process other functions through feedback and analog operations.

Interaction of inputs from different axons is called "spatial summation" and interaction of sequential pulses on the same axon is referred to as "temporal summation". In other words, the signals from the neurons can be evaluated by the brain as "what", "where", and "how much". Once the neuron has computed its result, this information is transmitted to its destination which could be another neuron, a muscle, or a gland. Transmission is not a simple problem because the signal voltage is small, less than a tenth of a volt, and the distance may be quite far. The action potential allows the signal voltage of the neuron to be transmitted over long distances by encoding it as string of pulses. This means that the choice of a particular axon specifies "what" and "where". The amount of frequency indicates "how much". This system enables the nervous system to select which muscle to use and how much resistance to create. If a person wants to flex his or her elbow with a certain load held in the hand, the brain must direct the signal through the axons to the proper muscles activate the correct number of fibrils. If the elbow is flexed first, then the summation of signals activates enough sarcomeres to allow the proper muscles to flex the elbow. Once the elbow is extended if the person wants to lower the weight, the summation signal in the brain must calculate the level of contraction necessary to execute the task including computations needed for the gravitational effects which are an integral part of the movement. The net moment around the elbow must consider also the required stabilization between the extensors and flexors and the geometrical orientation of the limbs active in this movement. This ability of the nervous system allows large numerical quantities to be processed with what might be called a temporal byte or the integration, over a brief time period, of a single input line. Thus, the brain structure receiving the information can determine the type and location of the stimulation with a spatial byte, which is a place code allowing determination of the set of active lines, and the intensity of the stimulation with a temporal byte or frequency code.

All muscular activities utilize a basic unit on contraction which consists of spatial and temporal dimensions. Independent sets of information can be encoded in these two dimensions and they can then interact in the receiving structure in a way determined by physical and chemical properties of the cell's membrane. The spatial aspect of the code is essentially digital information and the temporal aspect of the code is essentially analog information, although it is encoded in the frequency of digital pulses.

A simple explanation of these physiological parameters would be impossible. Even mathematical treatments of this sequence represented in various models incur great difficulties. The number of degrees of freedom exceeds the number of simultaneous equations required to quantify all the possibilities. However, logical and experimental results may provide logical conclusions although inconclusive and possibly erroneous. (Remember the statement at the beginning of this article by Leonardo Da Vinci!)

A very important property of the neuron is that many inhibitory inputs are received and processed as well. The total of these inhibitory signals causes the voltage across the neuronal membrane to move away from the firing threshold. This action cancels the combined action of all the positive inputs. It is also possible to have a negative synapse which negates only a specific input. This type of signal called presynaptic inhibition.

In addition, the speed of transmission along the axon plays an important role in controlling and processing of the motor nervous system. The speed of the transmission of pulses down the axon can vary over a wide range although it is always the same in any given axon. This means that high speed axons can move data quickly, but low speed axons may be employed as delay lines. Because axons can have branches coming off at any point, delay lines may be introduced. A greater amount of depolarization at the neuron will cause a higher frequency. A lesser amount will cause a lower frequency. Thus, analog voltage in the cell body can be converted into a series of pulses at a particular frequency.

Signal encoding by action potentials unfortunately introduces noise into the information channel. This is because the action potential is a discreet event as is the pulse spacing between action potentials. The encoding of a continuous voltage as a string of pulses forms a noise signal. The brain overcomes this noise by redundancy. This information repetition utilizes many neurons transmitting the same message, each encoded slightly differently, so that the average of a large number of neurons produces the accuracy needed for precise control. This redundancy also provides improved reliability which is important in a structure in which approximately ten thousand neurons die every day due to disease, injury, or old age.

It is beyond the scope of this article to provide an indepth discussion of the complexity of the nervous system in creating muscular contraction. However, in general, the basic architecture of the system is hierarchical. Each of the major functions of the system is partially organized at each level of the system instead of having particular levels devoted to specific functions.

The most obvious partitions of the central nervous system divide it into three levels. At the lowest level is the spinal cord, above that is the brain stem, and finally at the top is the forebrain.

At the lowest levels, there are a multitude of relatively simple processing elements doing similar jobs. At the higher levels, there are a few very complex and powerful processing elements defining system tasks and priorities and organizing the activities of the lower levels to achieve the goals.

On the input side, the lowest levels gather raw data, which is then progressively abstracted, sorted, and refined at each stage according to general guidelines which may be either hard-wired or determined at higher levels. The highest levels then receive abstract symbolic information about the general state of the environment rather than discreet bits of information. Therefore, in order to flex the elbow joint, the higher center recognize the flex and extend movement rather then how many sarcomeres are involved in each of the movements. The output functions begin at the highest levels which determine general goals and strategies and transmit these to the lower levels. The lower levels, in turn, send information about desired actions and timing to the lowest levels for execution.

One of the most important signal from the lower centers is the proprioceptive sensor mechanisms in the muscle spindle organ, shown in Figures 22, 22a, and 22b. The output of the spindle sensor travels to the spinal cord where it enters through the dorsal roots and terminates with excitatory synapses on the dendrites of the alpha motor neurons as shown in Figure 23. When the gamma neuron fires at a rate g1, it shortens the ends of the spindle to a length l(g1). If the muscle bundle attached to the spindle is stretched by more than an amount L(g1), the spindle will fire, sending a signal to the motor neuron that controls the muscle bundle commanding it to resist further stretching.

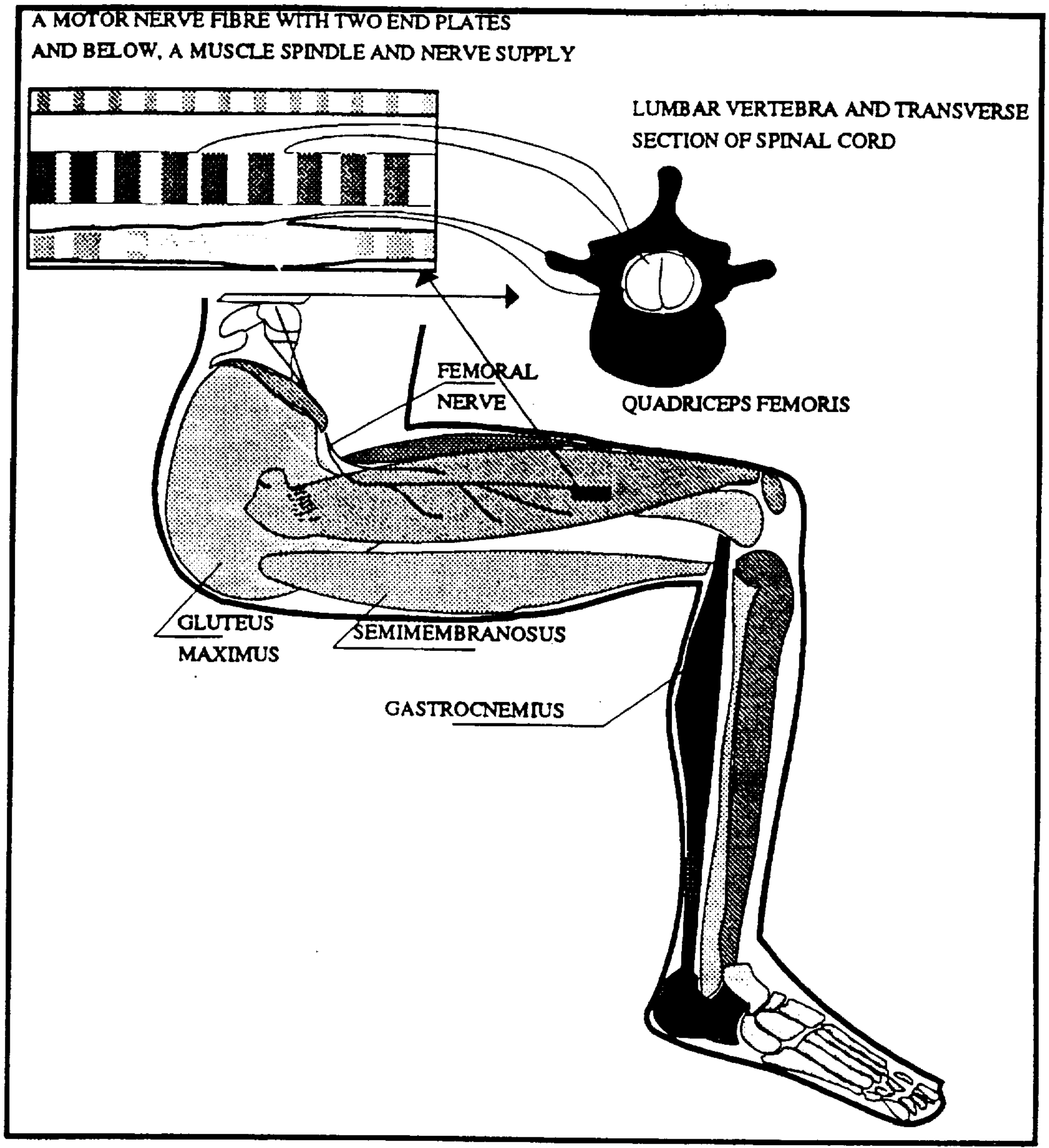


Figure 22

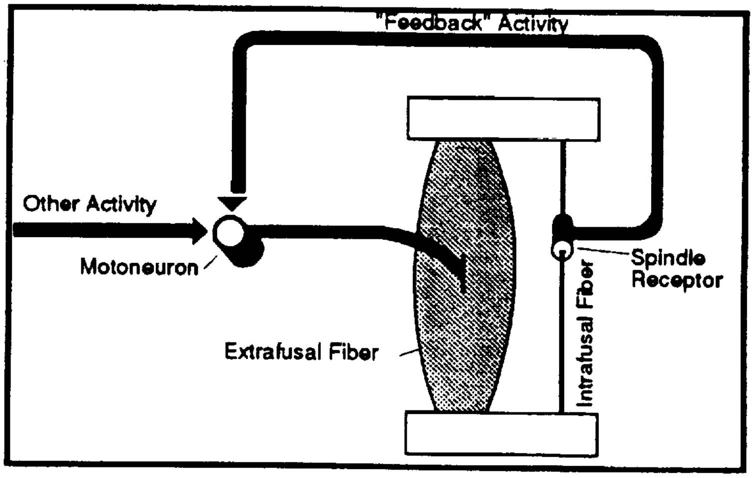
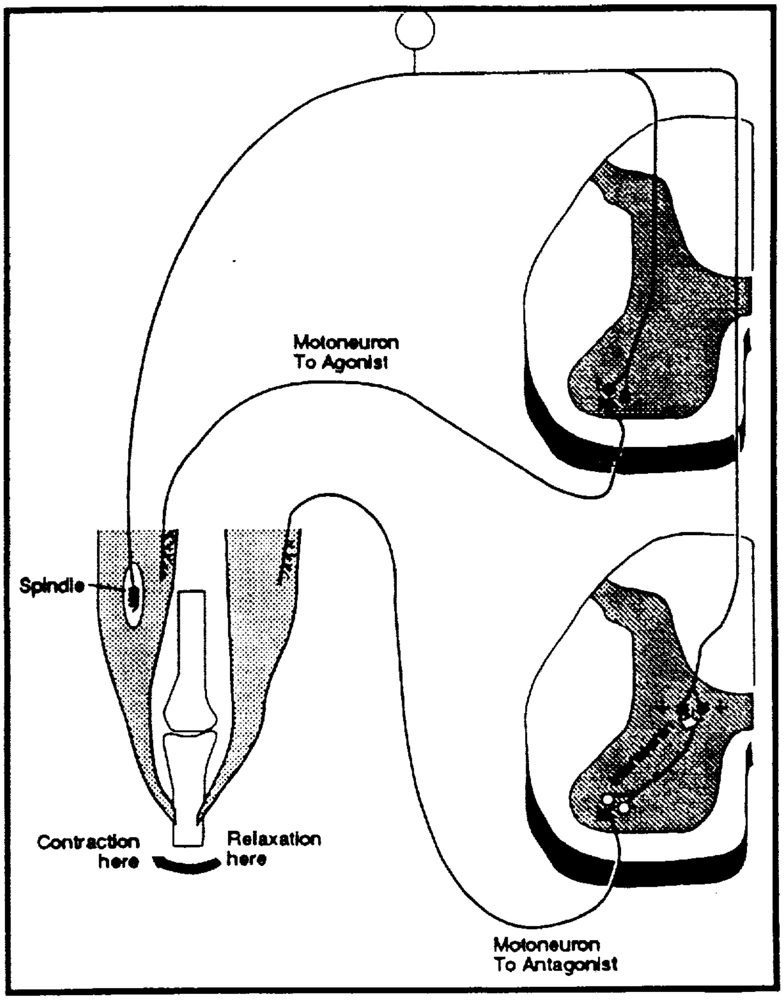


Figure 22a



Fgure 22b

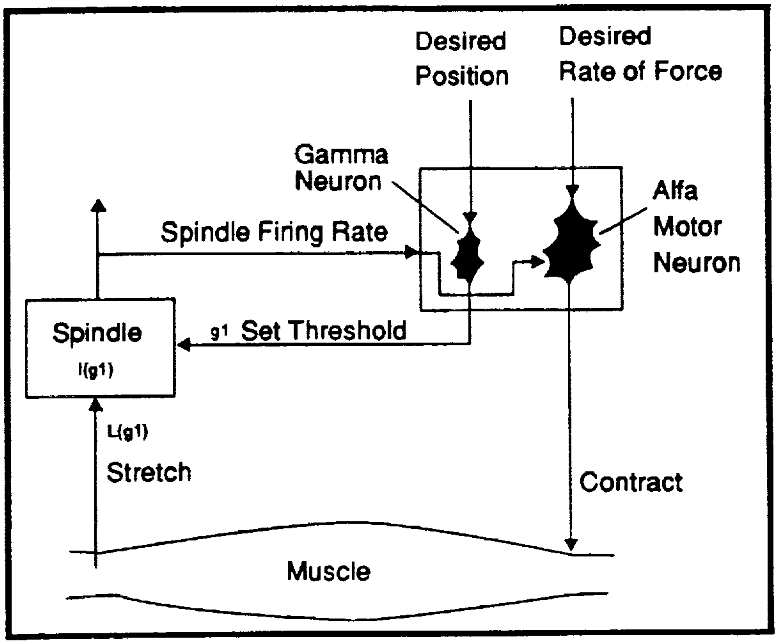


Figure 23

Thus, the gamma neuron can determine the point at which the stretch resists further movement. The result is that the limb moves to a position set by the firing rate on the gamma motor neuron. The gamma neuron, muscle spindle, and motor neuron thus comprise a position servo. A specific firing rate on the gamma neuron tends to produce a particular length of a muscle and, hence, a unique angular position of the joint. Figures 24 and 24a shows a schematic diagram of the computing modules involved in the gamma position servo. The position command enters the motor output module and generates a particular firing rate on a gamma neuron. The gamma neuron sends its indication of what the spindle length should be to the sensory spindle where it becomes an expected position. The spindle compares the actual position with the expected, emits an error signal which is sent to the motor output module as an excitatory feedback signal. The motor output module, whose output is the alpha motor neuron, then uses this feedback together with input from other motor centers to compute its output signal which it encodes as a firing rate to the muscles.

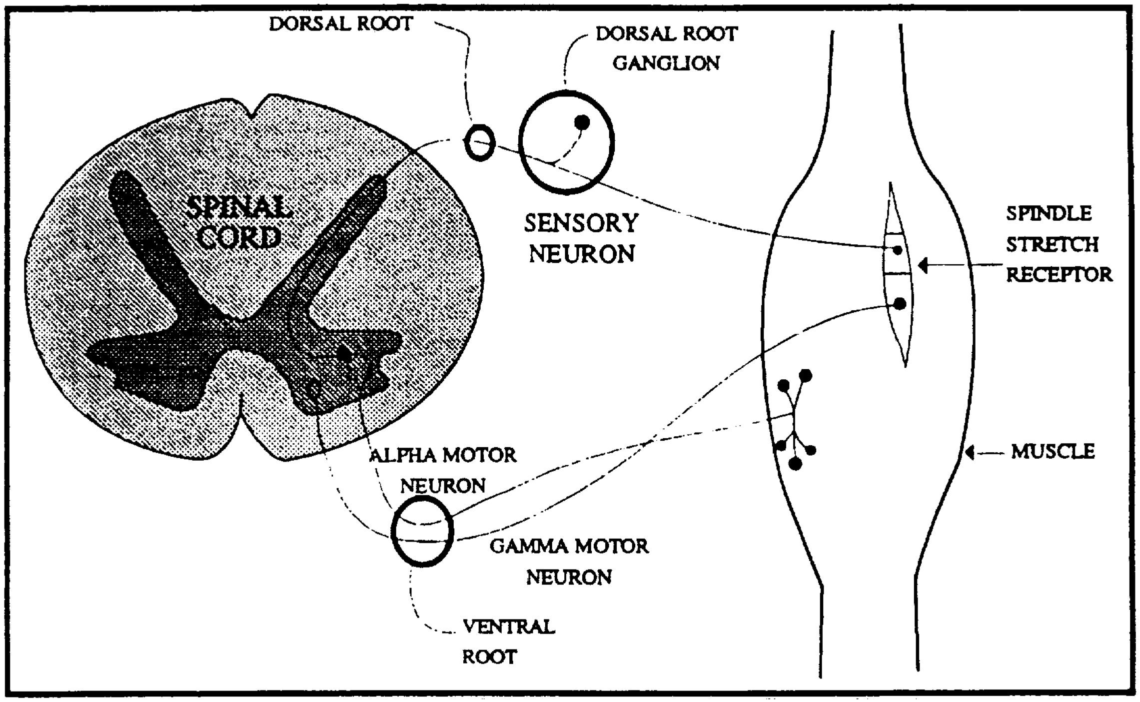


Figure 24

Some of the other motor center inputs come from commands to and feedback from other limbs. The rest of the other inputs come from higher motor centers such as the pyramidal fibers from the motor cortex; extrapyramidal fibers come from the red nucleus, the substantia nigra, subthalamic nucleus, and the vestibular nucleus. All of these synapse directly on the motor neurons. These various inputs essentially command the motor neurons to fire at a particular rate which produce a specific force or rate of contraction of the muscles. This is represented in Figures 25 and 25a.

In addition to the spindles that measure the amount of stretch in the muscles, there are the Golgi tendon organs that measure the tension in the tendons. Axon fibers from the Golgi tendon organs enter the dorsal roots and make excitatory synapses on interneurons. These interneurons then make inhibitory synapses on the motor neurons. The overall effect is to limit the force exerted by the muscle preventing excessive stress from tearing the muscles or tendons. When tension in the tendon organs approaches the danger level, they fire vigorously causing an immediate relaxation of the muscle. Thus, signals from the tendon organs provide the motor output module with the information necessary for controlling the force level in the tendons.

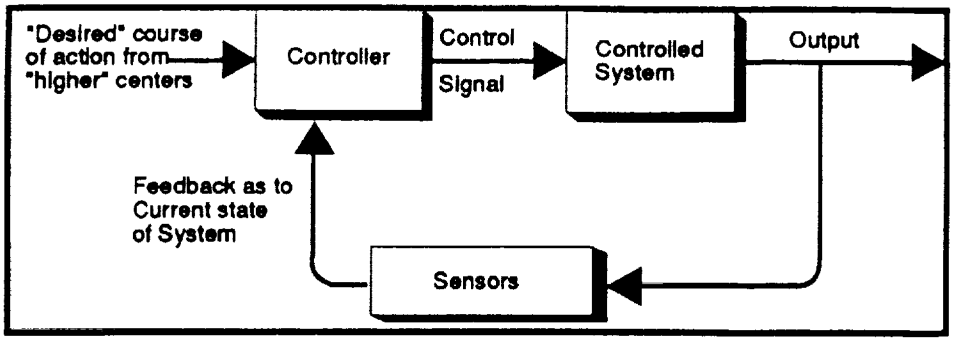


Figure 24a

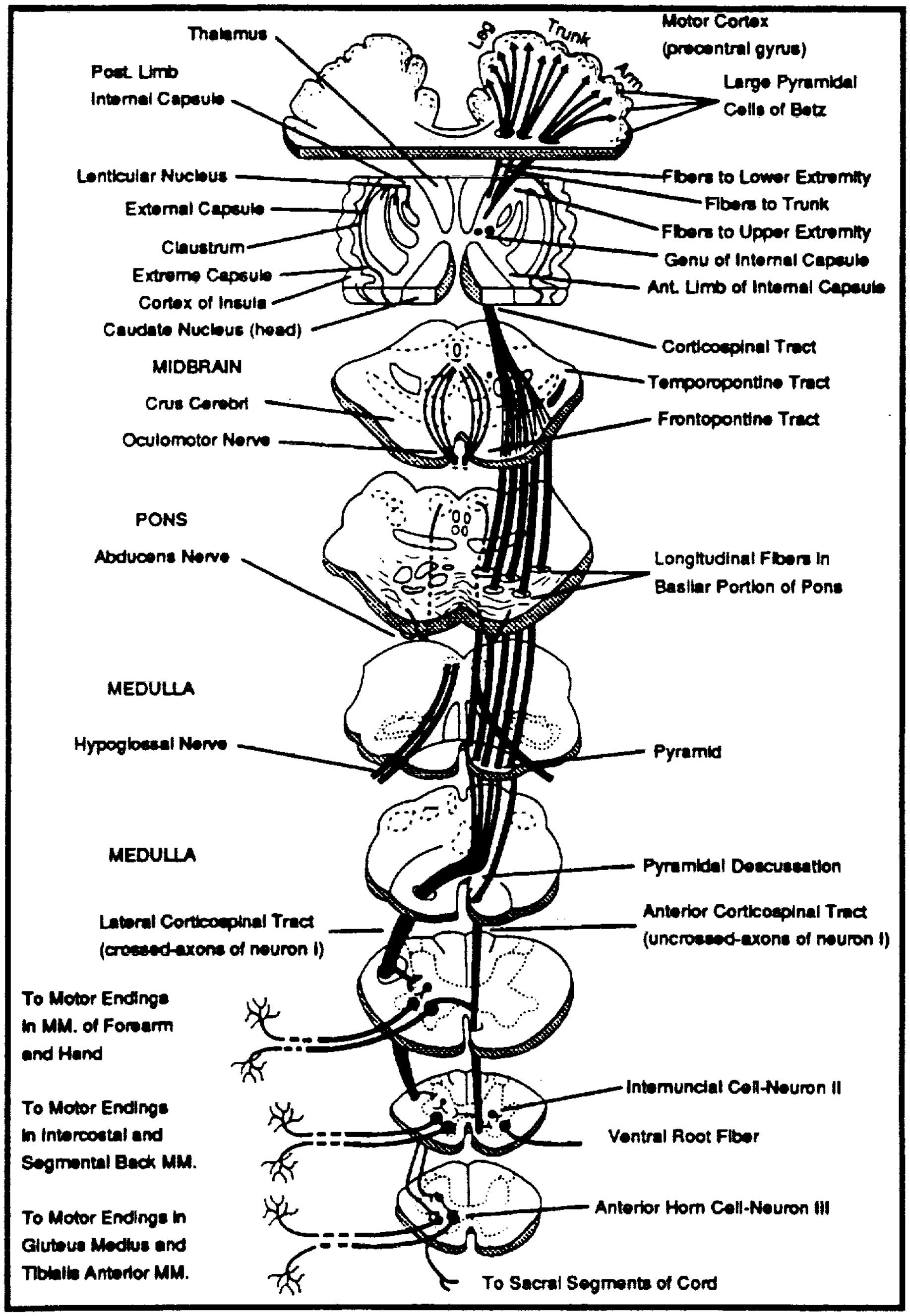


Figure 25

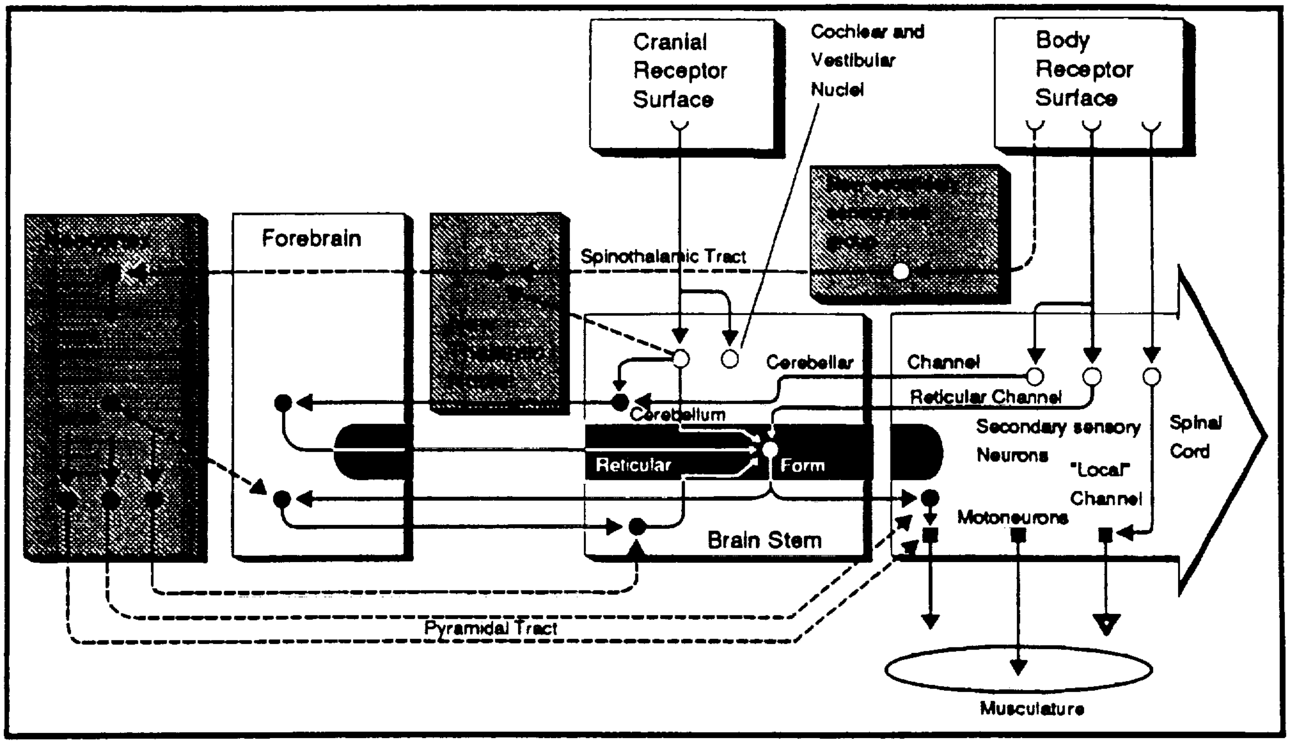


Figure 25a

It is thought local sensory input and commands from higher in the motor system that the gain in the inhibitory portion of the tendon organ loop is modulated. If the inhibitory signal is equal to the difference between the commanded and the observed tension, the motor neuron will increase its firing rate whenever the tension falls below the commanded value. Correspondingly, the motor neuron will reduce its firing rate when the tension rises above the commanded value. The result is that the force in the muscle is servoed to the commanded value.

There are also sensing organs in the joints which measure the position and rate of motion of the joints in addition to the muscle spindles and the Golgi tendon organs. For every sensory input there are specific nerves for each of the different sensations or signals. This nervous system feature has been called the "law of specific nerve energies" or "place encoding." For example, the brain must know the amount of tension on a particular muscle and the position of the joint at that particular angle. If the motor signal is to reduce the angle or flex the joint, the motor system in the brain must know if this task has been accomplished. If the joint center indicates that the limb is moving in the direction opposite to what was required, adjustments must be made. (Attention to such adjustments will be discussed relative to a series of experiments later in this article.)

As a general rule, the intensity of sensory input is encoded by the rate of firing such that each percent increase of stimulus intensity tends to cause an increase in the firing rate by a fixed amount. This leads to a logarithmic or power law relationship between stimulus intensity and firing rate. This is called the Weber-Fechner Law after the two investigators who first carefully measured the effect as shown in Figure 26.

Thus, at each level of nervous system control, there are a number of relatively independent processing elements performing their own jobs in parallel and exchanging information with levels above, below, and laterally. Therefore, any large scale or voluntary task is not processed in a single brain center. Rather, different aspects of the task will be handled by different portions of the functional subsystems within the physical system. For example, consider the case of

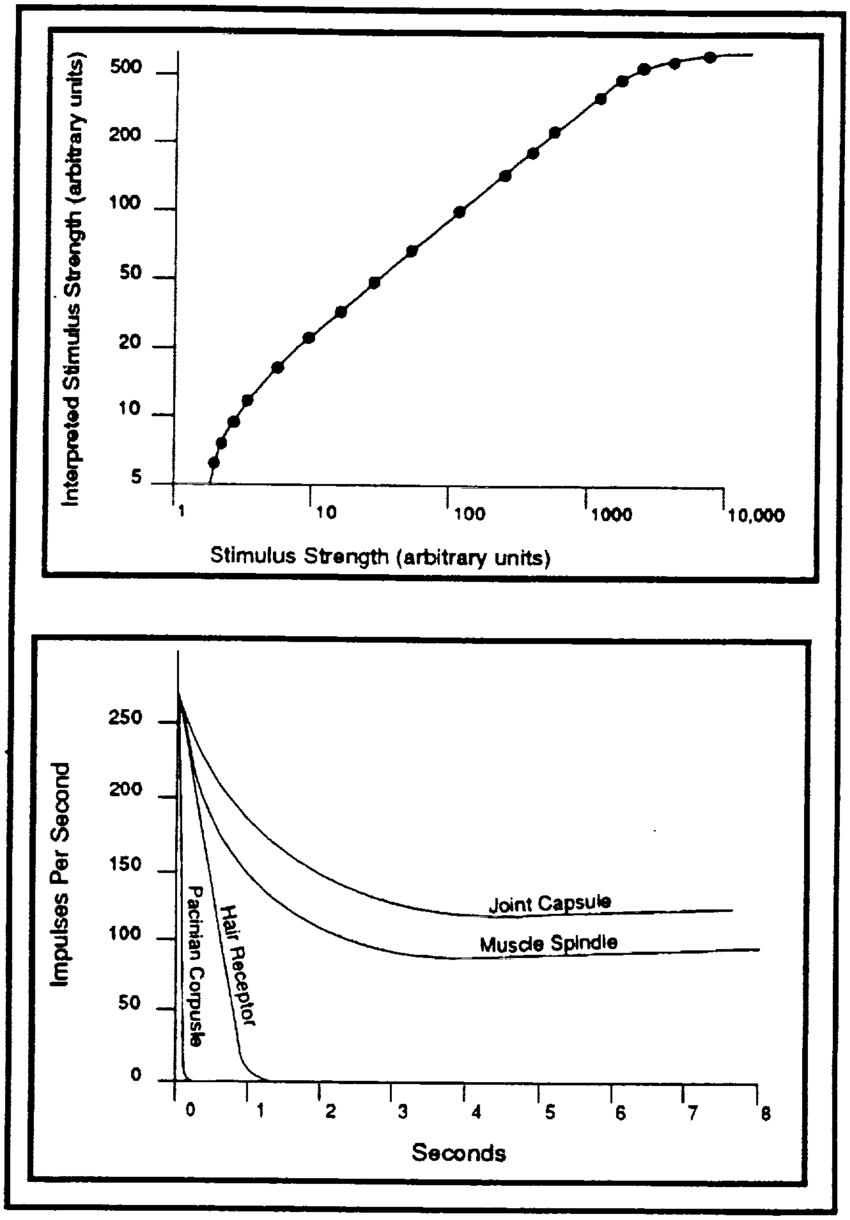


Figure 26

lifting a load by flexing the elbow. There will be continuous computing of forces based on limb positions or velocities requested by higher levels. The brain provides such a processor for each fiber of each muscle and it instructive to examine their approaches to the problem solution involved.

Voluntary limb movements such as this example of elbow flexion necessitates adjustments to be performed quickly and control of the system is made by anticipation of events. This is one of the major principles of the neuromuscular system, the principle of organization. The theory of the principle of organization is that the higher level structures control the lower, not by turning them on when needed, but rather by inhibiting their actions except as desired. Consider running as an example. In running, the muscles involved in plantar and dorsal flexion of the foot which will quickly come into contact with the ground, are fully activated before the impact. In this way, there is force anticipation to absorb the impact. Another example can be found in long jumping. In the analysis we performed on the world's best long jumpers, the results showed that the man who jumped farther than 8 meters did not use the foot flexors and extensors as driving forces but as blocking forces. This technique enabled the utilization of inertial forces which are much greater than the muscle could generate even though limb muscle contraction was evident prior to takeoff.

The lowest level of the central nervous system is the spinal cord and it is the major route for input and output for the brain. Most of the sensory input from the body and most of the output to the muscles passes through this structure.

The higher centers, including the medulla, the mesencephalon, the thalamus, the hypothalamus, and others, will not be discussed. However, their complexity of regulation and control is an integral part in muscular output. It is interesting to note, however, that the actual physiological mechanisms which are controlled directly by the brain are of only two types: the muscles and the glands. These are the only effector organs to which the brain is connected and, thus, you

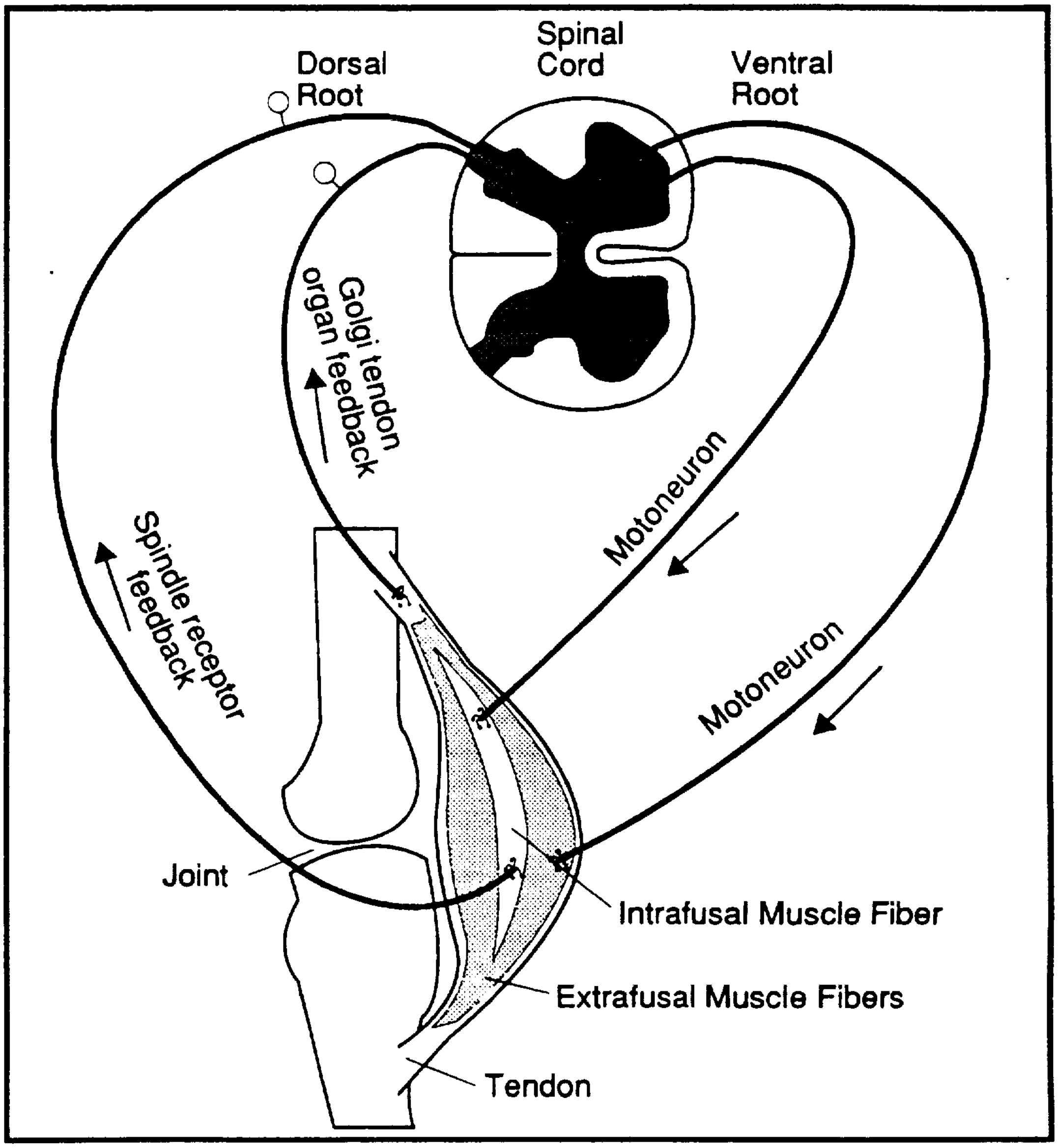


Figure 27

may only contract a muscle and release glandular secretions. The remaining range of physical behavior is only a combination of these two.

Figure 27 provides simplified illustration of the interaction between the high level and the low level controllers. This system governs the servomechanism of muscular contraction.

When it comes to muscular control, there are two fundamental techniques which the brain uses to control muscular contractions. The first mechanism is to equip each level of decision making with subprocessors which accept the commands from higher levels as well as accounting for the inputs from local feedback and environmental information sensors. In this fashion, a descending "pyramid" of processors is defined which can accept very general directives and execute them in the presence of varying loads, stresses, and other perturbations. This kind of input and output control is used for multimodal processes, such as maintaining balance while walking on uneven terrain. However, this type of control is inappropriate for executing deliberate, volitional, higher level goals such as instructing the arm to flex with load held in the hand.

The second technique which the brain utilizes to control muscular contractions applies to the operation of higher level systems which generate output strategies in relation to behavioral goals. These are the categories of output tasks which use informational input rather than the type of generated behavior. The operation of the motor command chain depends upon certain sensory inputs which provide feedback and status information for moment-to-moment operations. The basic required and supplied information relates to the joint angle, muscle loading, and muscle extension or stretch. Various organols at the lower levels of control translate these quantities into neural impulses which are processed by the higher levels of control for the next sequence of instructions by neural transmission.

The functional aspect of muscle control is the motor unit. All skeletal muscle fibers are innervated by the neuron. There are thousands of direct and indirect neural connections to the cell body of the motor neuron, but once an impulse is generated this motor neuron determines the final neural output through which movement is controlled.

All motor neurons transmit impulses from the spinal cord to the muscle fibers they innervate. When the impulse arrives at this point, all of the muscle fibers of the specific motor unit contract. However, motor units differ with regard to speed, force, and endurance. Figure 28 illustrates these differences.

Different populations of motor units account for the speed with which the muscle can react to a stimulus. There are both fast twitch and slow twitch muscle fibers. When considering force production and force-yielding capacity, the force yielding capacity of a motor unit depends on the number of muscle fiber per motor unit, the fiber size, and the type of myofibrils in the particular motor unit.

In different movements, no one type of motor unit is used exclusively. Normally, the requirements for a particular movement will preferentially select slow and fast twitch units in different proportions depending on the movement and the skill desired.

In most cases, muscles work in opposing pairs, that is, one muscle group opens or extends a joint and the other group closes or flexes it. Figure 28 illustrates this kind of arrangement. Local control of this system resides in the spinal cord and it is called the lower motor neuron system. This organization controls the individual fibers of each muscle through input to the motor units that control a varying number of muscular fibers. The organization of the lower motor neuron pool accepts and reconciles commands from a multitude of other systems all of which desire control of the muscle in question.

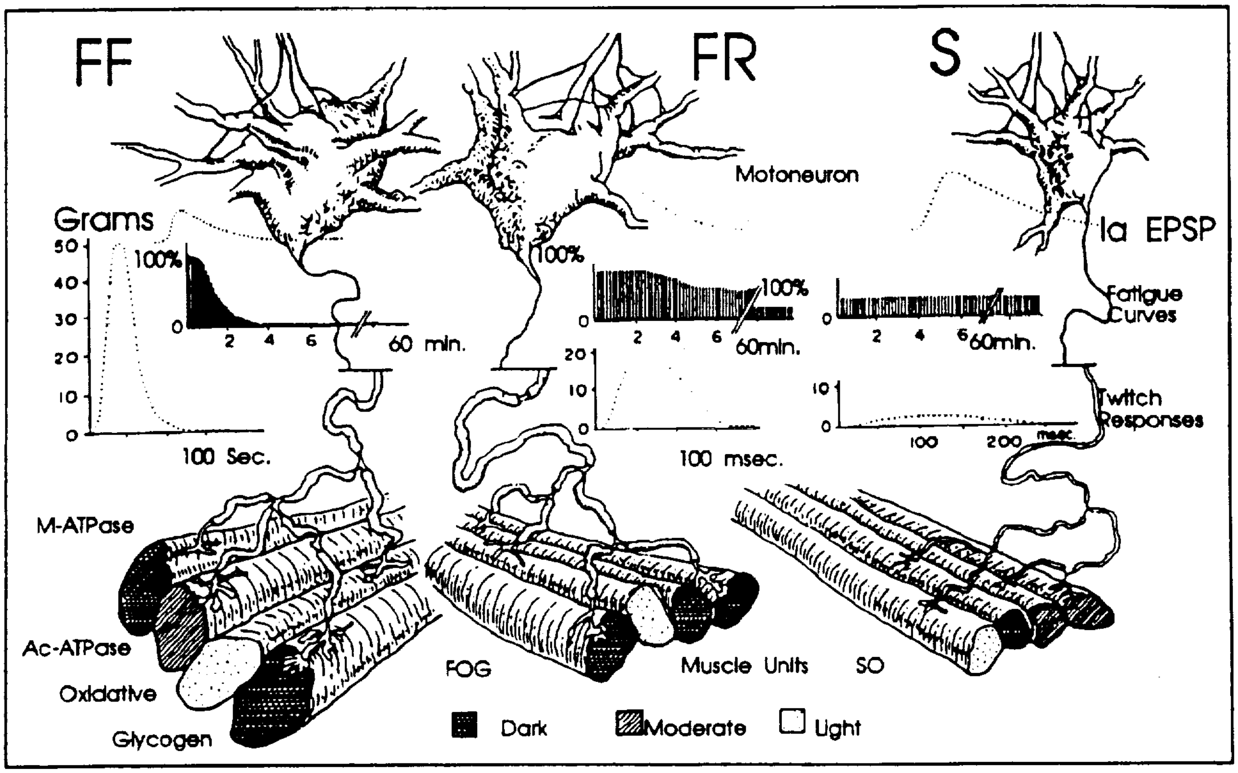


Figure 28

The degree of contraction of the muscle is proportional to the output pulse frequency of the lower motor neuron system. The higher the frequency, the stronger the contraction. In the situation presented in Figure 28, it is apparent that both the extensors and flexors cannot be affected by the lower motor neuron to the same level of intensity simultaneously. There must be a programmable mechanism so that the flexors do not work in opposition to the extensors. Therefore, one group of muscles must be relaxed while the other is active. In addition to the local control system, previously mentioned, there are higher centers of reflex action so the motor system can enact corrective action via other muscles and limbs for the redistribution of weight, to counteract shifts in the center of gravity, etc.

Higher level inputs to the Lower Motor Neuron system may request a variety of actions, such as holding a particular position, moving to a specified position, or moving with a particular velocity. These requests are integrated into the lower motor neuron system according to the following structure. The Lower Motor Neuron system (LMN) attached to the extensor muscle has two functions. One function is to deal with high level instructions while the muscle tension compensates for an external load. The second function is to process information from the muscle itself via the muscle spindle that sends information via the gamma motor neuron. Because the S fiber is mechanically attached to the rest of the muscle, it is passively stretched or relaxed as a result of the neuronal inputs or external forces which extend or contract the main muscle. However, the S fiber's bias, or ambient contractility, is set by its own "private line" input signals from neuron G. The neural component of these stretch receptors is attached to the S fiber, and when this is stretched, the neuron fires at a rate proportional to the degree of stretch.

From a motor integration view, the whole hierarchical motor output system uses a temporal frequency coded as well as analog information derived from the stretch receptors to specify the degree or quantity of an action. In addition, the set of all of the descending input lines to the numerous LMN systems constitutes a spatial byte, or place code, which is essentially digital in character and in which the specified lines select the set of LMN systems which are addressed. This arrangement allows determination of the nature of the movement to be performed, but not its speed, force, or direction.

Figure 29 illustrates some attempts to explain the effect of the higher center on the lower motor neuron pools. Arbib (18) tried to relate the higher center to the control of flexors and extensors system around a particular joint as shown in Figure 29.

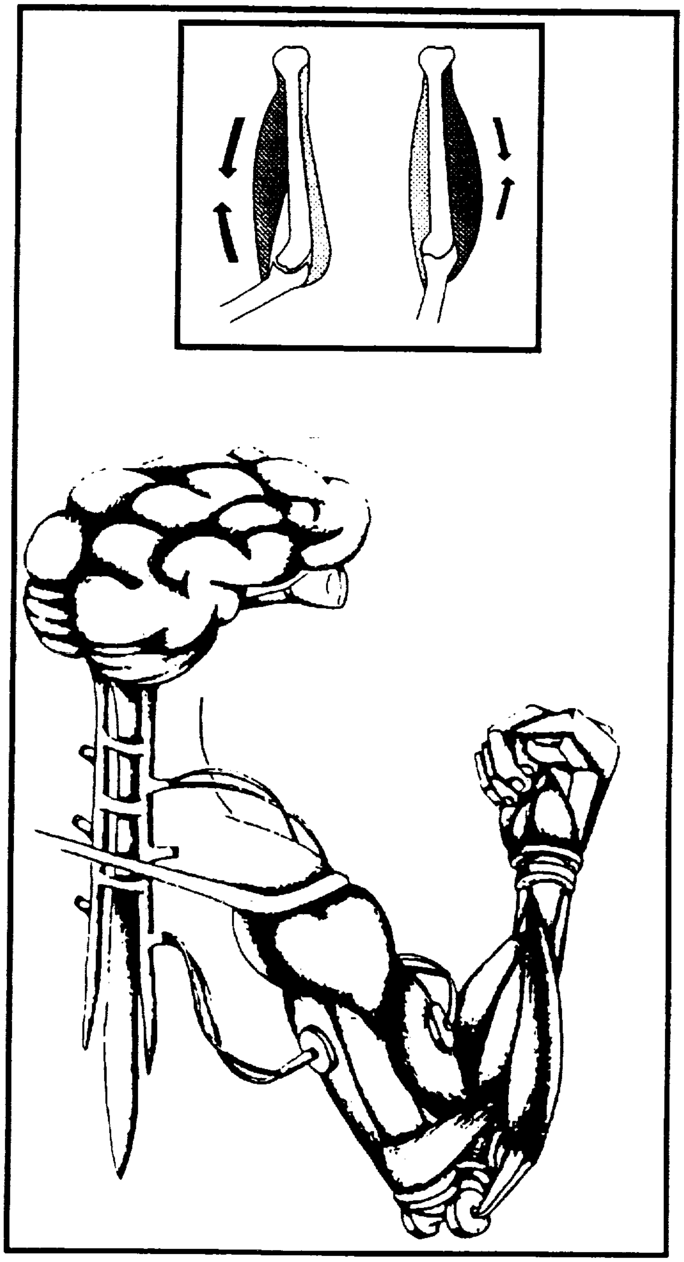


Figure 29

Experiments with rapid movement illustrated a high level of control for a pair of muscles. Studies of isotonic movements, which more correctly should be referred to as "ballistic" or "variable resistance" movements, have shown that muscle activation occupied only a small portion of the movement. In addition, the duration of the activation in an isotonic movement does not seem to be related to the extent of the motion. There is an initial burst of acceleration as the agonist contracts and the antagonist muscle relaxes, an intervening quiet period, followed by a final burst of deceleration as the antagonist contracts. Bizzi (73), experimenting with eye movements, revealed a system in which the initial movement was triggered by an agonist burst and antagonist silence. This activity continued until the end of the movement triggered a return of both muscles to the resting activation level appropriate to the new position.

Braitenberg and Onesto proposed a network for converting space into time by providing that the position of an input would determine the time of the output. This "open loop" system revealed a preset signal in the nervous system which resulted in specific position adjustments. However, the question remained as to how the brain "knows" the joint angle in a cognitive sense. Experiments revealed that the brain processed the angle as a quality and encoded it in terms of which neurons fired. Specific receptors fire at higher frequencies at particular angles. Thus, for each joint angle, there were "assigned" receptors responsible for each specific angle. When the higher center transmitted a command to flex the elbow, for example, feedback information returned from the joint receptors as ascending signals to the higher center for processing and adjusting to the continuous tuning signals to the flexors to contract.

The extent of the kinesthetic receptors' tuning curves suggests that fine discriminations of angle must be made. This is accomplished by establishing "angle detectors" throughout the process of selective inhibitory and excitatory convergence to produce a pattern of activity in a population of inputs which corresponds to the desired action. Activity by any single angle would activate several broadly tuned receptors to varying degrees and not activate others at all. The relative activities could define the angle as finely as desired simply by pulling more of the broadly tuned detectors.

When a body segment is given a signal to move, the agonists muscles are fired to start the contraction. At the same time, the antagonists muscles also receive also a signal of lesser magnitude. Because the activity by the antagonists is smaller, they were believed to be relaxed or inactive. However, it has been found by many investigators that the antagonist functions as a joint stabilizer and, therefore, movement is a product of the net moment around a particular joint. A "burst" of agonist EMG stimulates the required muscular activity to accelerate the segment and this burst of EMG activity is followed by a silent period. The antagonistic activity has reported. This classic illustration of EMG patterning in a ballistic movement utilizing agonist and antagonist muscles is shown in Figure 31.

It is apparent that the brain defines its perceptual qualities so that the nature of the quality is encoded in active cells and the rate of their firing determines the "goodness of fit" between the stimulus and the desired action. The encoding process at the receptors achieves higher intensities with increased firing rates.

A situation to address concerns the rate of firing when the resultant movement is opposite to feedback signal loop such as in a maximal eccentric contraction. For example, the contractile direction may be flexion but the external load exceeds the muscular force in that direction. In this situation, the different joint receptor outputs do not match the required or the anticipated signal. The neural and muscular mechanisms and the various effects have not as yet been investigated.

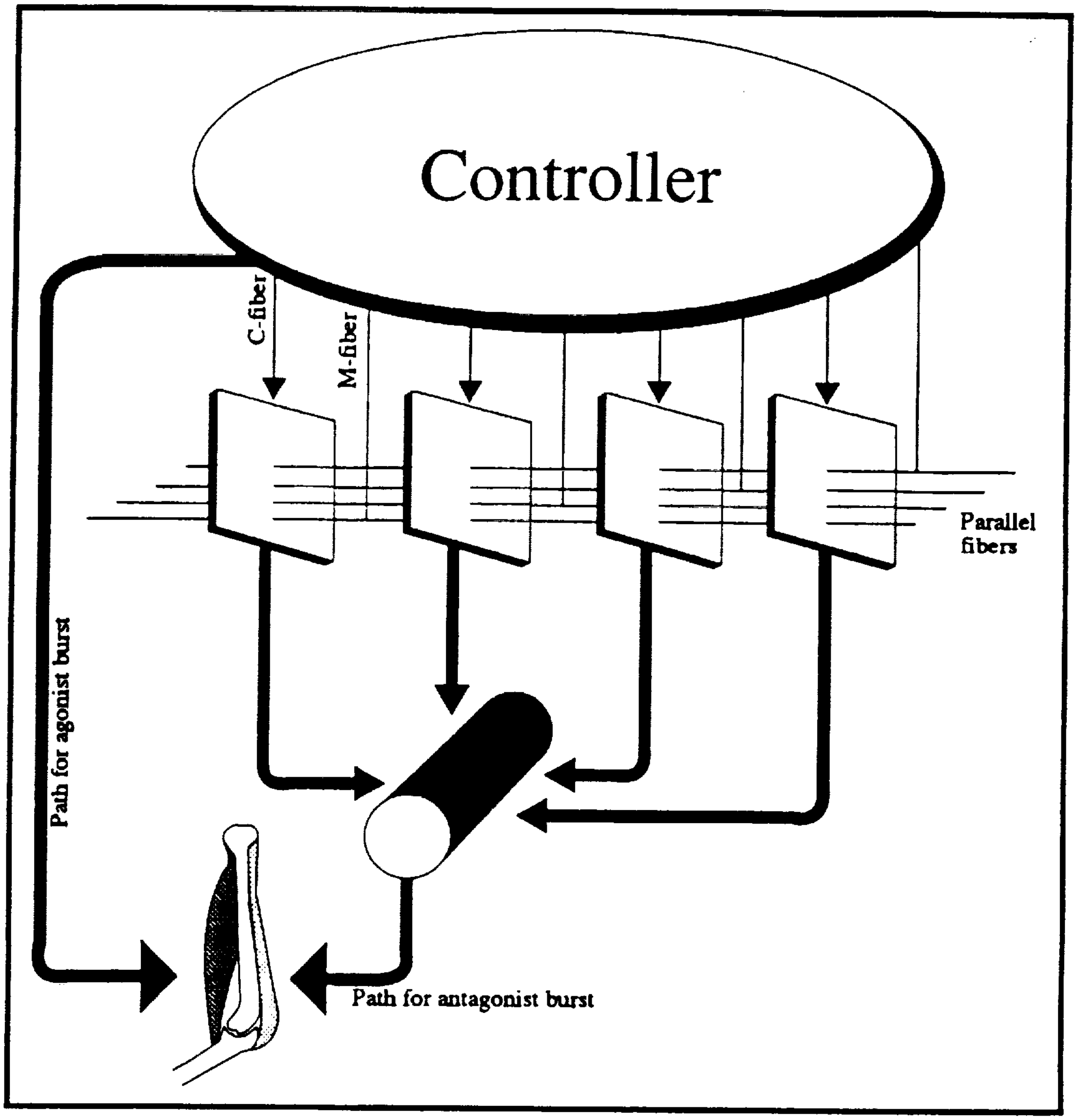

Controller
C-fiber
M-fiber
Parallel fibers
Path for agonist burst
Path for antagonist burst

Figure 30

Types of Muscular Contractions:

When muscles contract, the limbs may appear to move in different ways. One type of motion is a static contraction, known as an isometric type of contraction. Another type of contraction is a shortening or dynamic contraction which is called an isotonic contraction. Dynamic contractions are accompanied by muscle shortening and by limb movement.

Dynamic contractions can exhibit two types of motion. One activity is a concentric contraction in which the joint angle between the two bones becomes smaller as the muscular tension is developed. The other action is an eccentric contractions in which, as the muscles contract, the joint angle between the bones increases.

These two types of dynamic contractions exhibit various characteristics and produce a level of confusion. It was thought that a person could generate more force with an eccentric contraction then with a concentric one. Many studies have focused on this point, however, to date, there has been only confusion and disagreement with the results. To adequately investigate this phenomenon, the following areas must receive consideration:

1. Physiological
2. Neuromuscular
3. Biomechanical
4. Skill and Technique

The physiological characteristics of muscular contraction have been previously discussed. The interactions among the remaining factors, the biomechanics, neuromuscular control, and the level of preprogrammed skill and technique are essential if one is to determine the source of the causes and the discrepancies in force measurements.

Komi (307), a notable researcher in the area of muscular function, concluded his research findings with the following statement: "It would be an overstatement to conclude that the available scientific information guarantees full understanding of the factors involved in production of force and speed by human skeletal muscle." Such sentiment was probably aroused by the fact that, in skilled activities, the muscle does not behave in a manner that is logically explained. For example, Komi observed that the greatest EMG activity occurred before the force requirement. The level of force was greater in the eccentric phase as compared to the concentric phase. The concentric contractions appeared to be less efficient with minimal energy production as compared to the eccentric contraction.

It appear to the author of this manuscript that some of the findings resulted from not amalgamating the total complex of requirements needed to generate force. For example, sufficient time must be allowed for the flow of calcium ions to interact with the cross bridges. Time is also necessary for neuromuscular integration and for the entire system to generate the required potentiations. All the biochemical processes require some activation time. Thus, muscular contractile activation must start before an impact occurs such as in running or walking. These actions must be preprogrammed to allow a sophisticated timing mechanism to initiate a chain reaction of events.

The level of performance is dependent on the integrative programming of the nervous system, the status of the biochemical state of the skeletal muscle, and the biomechanics of the muscles, joints, levers, and external physics affecting the body.

When a limb moves, a sophisticated chain of events occurs before, during, and after the movement is completed. The fineness of control depends upon the number of motor nerve units per muscle fiber (207). The more neurons, the finer the ability to maneuver, as in the case of the muscles that operate the eye. When there are fewer motor nerve units involved, the action becomes less fine or precise. The individual muscle fibers that make up a muscle contract and relax in an elaborate synchronization. Consider the operations required of the human eye and arm. Eye muscles must operate with great speed and precision in quickly orienting the eyeball close or distant focusing as well as tracking. At the same time, the eye muscle does not have to contend with such external demands as lifting weight. The fine control needed in eye movement calls for a high innervation ratio (the ratio of the number of neurons with axons terminating on the outer membrane of muscle cells to the number of cells in the muscle). For eye muscle, the innervation ratio is about one to three, which means that the axon terminals of a single motor neuron release their chemical transmitter to no more than three individual muscle cells.

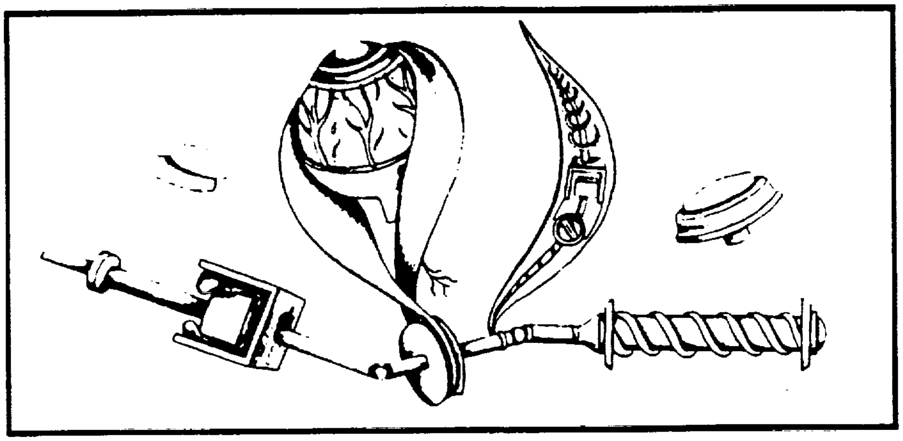


Figure 31

In contrast to this high innervation ratio, the axon terminals of a single motor neuron that innervates a limb muscle, such as the biceps of the arm, may deliver a chemical transmitter to hundreds of muscle fibers. The muscle may, therefore, have a low ratio of one to many hundreds. As a result, the output of the motor unit in limb muscle is correspondingly coarse.

One of the most elementary movements for humans is walking (113,139, 245). It seems as if all mammals and other land animals are born with the ability to walk and run. In experiments with babies between four and six weeks of age, it was found that these infants start to walk when supported, raised to a standing position, and placed on a treadmill. It seems that a baby at this early age possesses and can utilize the built-in walking mechanism with which it was endowed by its genes. The nerve cells controlling the mechanism come from the spinal cord.

Consider one of the most common activities in modern civilization, handwriting, and the execution of one's own signature. Whenever John Smith signs his name, it always looks the same (or enough to be so recognizable) and different from what any other person can write, even if trying to sign the name of John Smith. Even if Mr. Smith uses chalk and signs his name on a blackboard, the signature appears the same though he used different muscles than those employed when writing on paper. The individuality remains.

In this complex handwriting movement, there is a preprogrammed control mechanism. Optimum performance depends on the control efficiency. It does not matter how strong the muscles are or the efficiency of the metabolism. The control of these processes is the most important factor. Most people believe the brain is primarily used for thinking, yet research shows it to be first and foremost a control system. Although, very complex, the task of handwriting incorporates all of the required components: neurological, biomechanical, and biochemical. To begin a handwriting analysis, it should be remembered that there are many ways to move the joints in order to accomplish the task. However, for any given function there seems to be a best way to code the information and receive the quickest response from the system. Therefore, the way in which we activate the muscles and the bones in order to perform any volitional task will greatly affect the amount of computation that is required to assure smooth operation of joints and easy interaction of the organism with the world.

BIOMECHANICS

Biomechanics is an integration of the two disciplines of biology, "bio", and physics, "mechanics". It recognizes that all bodies on earth, animate and inanimate, are affected in the same way by gravity and provides a better understanding of performance. In other words, a bridge, a car, a baseball player, or a horse must all adhere to the laws of mechanics. The additional factors which must be included to more accurately assess motion for the biological entities include such things as bone capacity, neuromuscular coordination, and physiological attributes. From the understanding of each component will come greater appreciation of the integrated result that is called biomechanics.

Da Vinci (118) once observed that while drops of rain are in fact independent of one another, they appear to the human eye as "continuous threads descending" from the clouds, and that therein lies the truth of how the eye "preserves the impression of moving things which it sees." Therein also lies the visual distortion that allows us to see motion pictures. Because of the properties of the human eye and the visual system, a series of separate images on film becomes a smoothly flowing image when projected onto a screen at a certain speed - a movie. Movement of the human body is, also, a series of separate, individual actions. They begin with minute electrochemical processes infinitely swifter and more complicated than any set of film images traveling at 24 frames, or 1.5 feet, per second. Our muscles are thin strands of fibers which, when inactive, have all the strength of jelly. But they contract or relax because of these electrochemical reactions. The result is movement of the body with a fluidity that defies even the sharpest eyes to distinguish the separate actions. For instance, the simplest of human movements, such as crooking a finger or raising an eyebrow, involves a complex of neuromuscular happenings that cannot be duplicated by artificial means. In fact, the best robot still moves in jerks and stops when compared to the subtle, flowing pace of a human (207).

Man fathoms the nature of things by tracking their motion. All motion follows mechanical principles. Like machines he makes, man is a set of levers whose movements copy the geometry of classical mechanics. These levers are powered by muscles, whose actions can be as simple as their characters are complex. Each of the more than six hundred muscles is abundantly supplied with nerves which link the muscles to the brain and spinal cord and which often follow labyrinthian circuits, humming with signals, to control the ebb and flow of muscular energy. Many muscles must work harmoniously together in order to perform even the simplest task (115).

It is biomechanics that seeks to understand how these neuromuscular events occur and to analyze a series which the naked eye only dimly sees and the mind often fails to comprehend. Biomechanics is a science that depends upon the known facts of biology, physics and, to a lesser extent, chemistry. It can be called the study of the structure and function of biological systems by the methods of mechanics. To reap the rich rewards of the more satisfying, fulfilling life which this science can offer, a through understanding of both the "bio" and the "mechanics" of biomechanics must be gained.

The "bio" part of Biomechanics has been covered at length in the beginning portions of this paper. Therefore, attention will be directed at the second half of the word, the "mechanics".

THE MECHANICS

The second half of the science of biomechanics concerns itself with the physical laws that can be applied to the human body, the "mechanical" consideration. Unlike the "bio" portion, which is affected by biological structure, anatomy, physiology, genetics, nutrition, activities and environment, the mechanics portion is governed by mechanical laws which are universal tenets throughout the Earth.

The Italian scientist, Galileo Galilei (1564-1642), found experimentally that different balls of different weights roll down an inclined plane at the same rate (43) If the plane were tipped more sharply, the balls would roll more rapidly, but all the balls would increase their rate of movement similarly; in the end, all would cover the same distance in the same time. This means that freely falling bodies fall through equal distances in equal times, regardless of their weight. In other words, a heavy body will not fall more rapidly than a light body. The importance of the falling masses experiment lies in understanding acceleration.

Galileo determined that the distance traversed by a body rolling down an inclined plane grows greater and greater in successive equal time intervals. This means that the rate of speed is changing. Acceleration is precisely the change in rate of speed or, in more correct terms, velocity. In the falling masses example, each second the velocity of the mass increased by the same amount for this particular time interval. Such a change in velocity with time is called acceleration. On Earth, the acceleration of free falling bodies is a constant of 32 feet per second per second.

It was absolutely necessary to understand acceleration in order for the English scientist, Sir Isaac Newton (1642-1727), to formulate the laws of motion (409). As stated by the Newtonian law, acceleration produced by a particular force acting on a body is directly proportional to the magnitude of the force and inversely proportional to the mass of the body. In other words, the greater the acceleration, the greater the force and, if the mass is greater for the same force, the acceleration will be reduced. From a practical point of view, the greater the mass or the weight of an object, the greater the force necessary to accelerate the object. Also, to produce a greater acceleration with a given mass, a greater force is required.

The importance of discussing acceleration and forces lies in the fact that movement has to start with force. It is impossible to begin movement without applying force, whether it is external force, such as gravity, or an internal force, such as muscular. For example, the force applied to a hockey puck on the ice will create an acceleration and sets the puck moving faster and faster as long as the force is applied. The length of time that force is applied on the puck is important. The muscular forces needed to swing the stick and skate down the ice are also forces requiring consideration.

In measuring external and internal forces acting on the body, the mechanical models can be classified as static or dynamic. The static models are simpler since no forces due to movement occur.

For example, consider a static model with a person standing motionless holding an iron weight in his hand, like in the shot-put event, and assumed that the shot has a 10-kg mass. In this case, the forces acting on the shot is vertical. The gravitational attraction of the earth creates the weight of the mass, and its magnitude is proportional to the mass by the gravitational factor which is the gravitational acceleration in meters per second per second. In other words, the weight of the shot is equal to the mass of the shot times the gravitational acceleration.

Weight equal to
Mass times Gravitational Acceleration

One should bear in mind that forces are vector quantities and, therefore, have a magnitude, a direction, a line of action, and a point of application. In Figure 32, the magnitude of the force is 10 kg times 9.8067 meter per second per second, or 98 Newtons. Newtons represents the force rather than the mass which is represented by the weight of the load which is 10 kg. Since the gravitational acceleration is 9.8067 meter per second per second, then the product of these two numbers yield 98 Newtons. Since it is a static analysis without motion, the direction of the force is vertically down and the line of action is vertical. The point of application of the gravitational force is at the center of the mass.

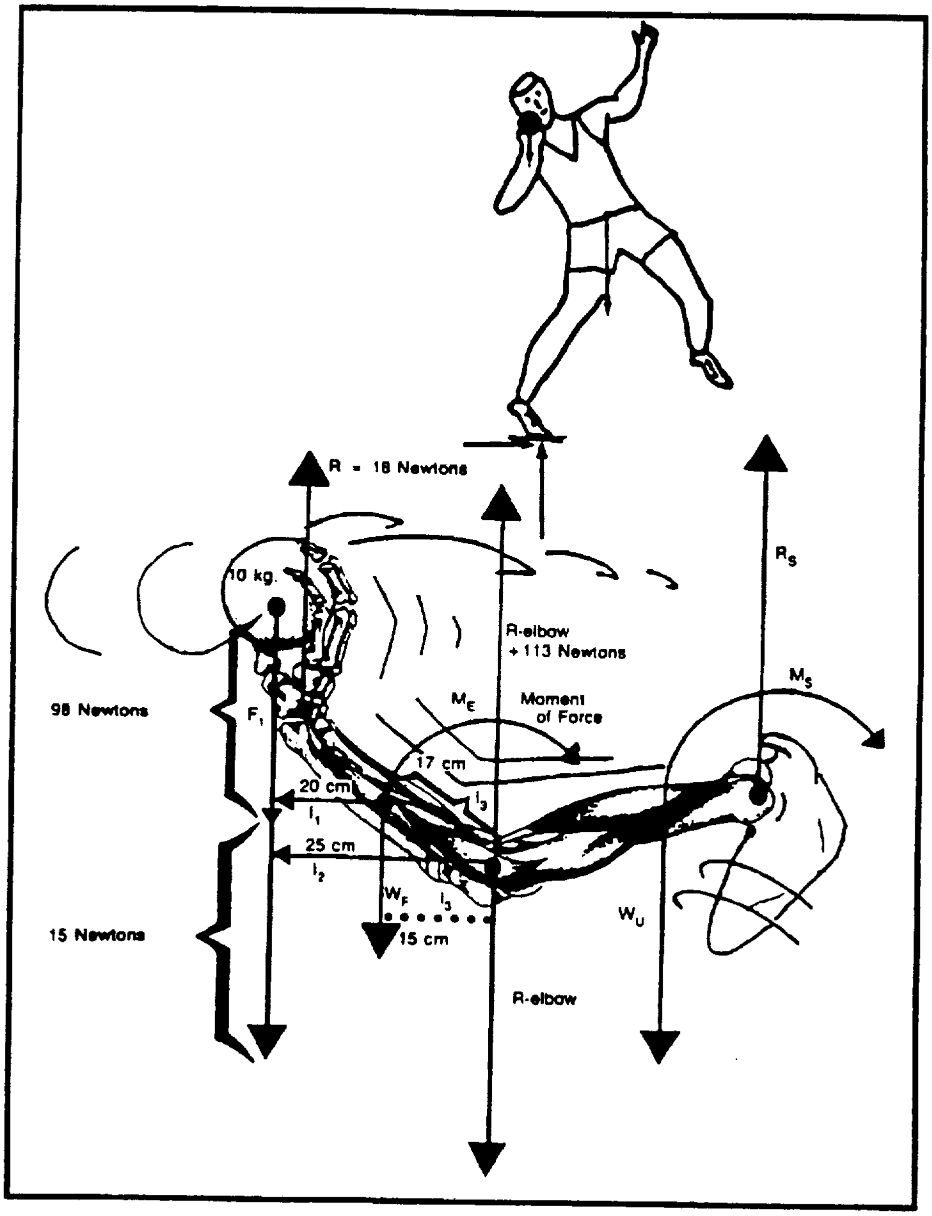


Figure 32

In Figure 32, the load is stationary since the person holding the shotput is motionless. Therefore, the downward force has to be cancelled by an opposite and equal upward force. The force, in this situation, is provided by the hand supporting the mass or shot. The upward force cancels the downward force and the load is said to be in equilibrium. The opposite force is called a reactive force and it is designated in Figure 1a as "R". Since the forces act along the same line of action, no rotation occurs at the wrist, elbow, or shoulder joints.

This example can be described using the Engineering analytic concept which is called a Free-Body-Diagram. In a free body diagram, a graphical representation is given with the magnitude of forces. In this example, the system is in equilibrium so the summation of forces must be equal to zero.

Summation of forces equal to 0

That means:

The force in the down direction is equal to -98 Newtons. The reason for the negative sign is to indicate the downward direction.

The force in the upward direction is equal to positive 98 Newtons since it pushes upward against the gravitational pull. Therefore:

-98 Newtons plus 98 Newtons equal to 0

From this simple equation, it can be determined that the hand has to apply 98 Newton of force in order to keep the shot from falling down.

A more complicated problem is to calculate the static force at the elbow. For this calculation, the length, weight, and the center of mass location of the forearm must be known. Calculations using this information will yield the forces at the elbow joint which resist, or are exerted against, the combined weight forces of the load, the forearm, and the hand. If the forearm and hand segment are assumed to weigh 15 Newtons, then the combined effect at the elbow joint will be:

-98 Newtons -15 Newtons plus the counter force at the elbow equal to zero
(-98N -15N +R elbow = 0)

That means that:

the resultant force R at the elbow is equal to 98N + 15N or 113 Newton in the positive direction or upward to order to cancel the force of the shot, the forearm, and hand which are in the negative or downward direction.

In the above example, the forearm and the hand were considered as one segment for simplicity. A more through analysis would divide this segment into two segments consisting of the hand segment with its center of mass location and the forearm with its center of mass location.

Where, then, does the force at the elbow joint come from to counteract the weight of the shot with the forearm and hand segment. The answer is that this reactive force is generated by the muscles around the elbow joint with some additional force provided by the ligaments and connective tissue around the elbow joint.

In mechanics, one must consider not only the force(s) but also the product of force and time which is called an impulse. For a given mass, a given impulse will result in a particular velocity. The heavier the object, the greater the impulse needed to achieve the same velocity. From that it is obvious that velocity and mass are related to each other and, in fact, the product of mass and velocity is referred to in physics as momentum. This law of momentum is most important in contact sports where different masses collide at different velocities. This law is what allows a smaller football player with greater velocity to block a heavier football player with lesser velocity.

In a hockey game, the puck which possesses a certain mass and is speeding across the ice at a given velocity has momentum equal to its mass times its velocity. If along its travels another hockey puck of the same mass moving at the same speed, but in the opposite direction, collides with it, they will then come to an instant stop. One momentum was canceled by the other. This principle of conservation of momentum is an important component in the game of billiards where solid balls hit others at different velocities.

In running and jumping activities, the forward force applied to the body depends on the force the foot applied to the ground and the amount of time that this force was applied. In other words, the product of the two or the impulse will determine the energy applied to the performance. The combination of greater velocity, magnitude of force, and time of contact with the ground are the essential factors which determine the speed of an athlete along the horizontal or vertical direction.

Consideration of these linear movements, where objects displace all their dimensions at the same rate are important in biomechanical considerations. However, the anatomy of the human body dictates that the parts move primarily in a rotational fashion. A good example for understanding rotational movement is the wheel in which the center remains stationary while the other parts move around it.

Understanding rotational movement necessitates appreciation of torque. A force that gives rise to rotational movement is called a torque. The amount of torque or, as it is also called, moment, depends on the force and its distance from the center of the rotational object. The product of force and distance is equal to torque.

The examples considered thus far have assumed translational motion such as when the forces around the elbow joint react to forces across a line of direction in a particular plane. However, these forces do not stop the segment tendency to rotate around the joint, thus, creating or counteracting a rotational motion. The force on the hand and forearm joint create a moment around the elbow joint forcing it to rotate about its joint. Moments of force are very significant around the body joints since the human structure consists of long bones and, the further the force applied to these long segments, the greater is the moment around the joints of the body.

The Moment of Force around a joint is equal to the product of a force and the perpendicular distance from its line of action to the point of rotation. In Figure 1a, the moment around the elbow joint is equal to the perpendicular distance of the elbow joint center to the line of force which represents the vector of force from the center of the mass at the hand designated as F1 times the combined static force calculated before as 113 Newtons. That means:

Distance from Elbow to Line of force (L2) times 113 Newtons or 25 Centimeters times 113 Newtons equal to 2825 Newton-Centimeters

Moments, like forces, are vectors and, therefore, direction about a point of rotation as well as magnitude must be considered.

In the previous example, we considered the static equilibrium of forces which are called the first condition of equilibrium. When considering the equations for moments of force, the second condition of equilibrium is assumed which states that the sum of the moments around a joint in static analysis is equal to zero. This means that:

The perpendicular distance from the elbow joint to the center of mass of the forearm (L3) times the weight of the forearm which is the moment due to the forearm and hand segment combine must be added to the moment due to the load at that hand. This moment is equal to the perpendicular distance from the elbow joint to the line of force from the load designated as L2 times the weight of the load. These combine moments must be equal to the counter moment by the elbow flexors muscles designated as Me. In equation form it looks like:

$$\boxed{(L3 \times -Wf) + (L2 \times -WL) + (Me) = 0}$$

From this equation, it is possible to calculate that static moment about the elbow joint as:

$$\boxed{Me = (L3 \times Wf) + (L2 \times WL)}$$

This means that the Moment around the elbow is equal to the combined moments due to the load and the weight of the forearm with the hand. To describe this example numerically, the weight of the shot is assumed to be 10 kg. which is approximately 98 Newtons of downward force. The force due to the weight of the forearm and hand are assumed to be 15 Newtons. The distances of the center of mass of the forearm which is the distance from the elbow joint center is assumed to be 17 centimeters. The perpendicular distances to the lines of force were calculated as follows:

The perpendicular distance from the elbow joint center to the line of force from the center of mass of the forearm is calculated by the product of the cosine of the elbow angle times 17 Centimeters which yield approximately 15 centimeters and the perpendicular distance from the elbow joint center to the line of force of the mass at the hand was calculated from the total forearm and hand length times the cosine of the elbow angle and was found to be approximately 25 centimeters. Using this information, it is possible to calculate the moment around the elbow joint as:

$$\boxed{\begin{array}{l} -(15\text{cm} \times 15\text{N}) + -(25\text{cm} \times 98\text{N}) + Me = 0 \text{ therefore:} \\ Me = 2675 \text{ Newton-Centimeters.} \end{array}}$$

This is the value that the muscles around the elbow joint must exert to keep the arm from rotating due to gravitational force.

The importance of the concepts presented thus far is that there are two types of forces acting on the joint in a static analysis. The translational force affects the tendency to move in the same line of action of the force. The second effect is the moment or the torque that tends to rotate the segments about the supporting joints. To combat the first effect, the joint has to counteract the translational force with tensile forces in ligaments and muscles to hold the joint together as well as the shearing and compressive forces which also act on the joint contact surfaces This is why a business man can develop "tennis elbow" by holding briefcase in his hand since the tensile force at the joint may cause micro tears in the ligaments and connective tissues at the elbow joint.

On the other hand, the rotational moment is a function of the strength of the muscle to move or rotate the joint. When a person plays tennis, the muscles move the racket as a result of muscular contractions. At the same time, ligaments and tendons react to the shearing forces. These shearing forces, which occur during the movement and the impact, can create forces which could result in tissue injury and, therefore, create problems in and around the joint.

Thus far, consideration has been limited to analysis of forces around one segment consisting of the hand and forearm. The problem becomes more complicated when additional segments are considered. It is possible to treat each segment separately and then add the effects of the previous segments to the present segment. In this way, a kinetic chain from one segment to the attached segment is created. The analysis begins at the point of application of the external load and proceeds in sequence, solving the equilibrium equations for each body segment, until reaching the segment that supports the body, which is usually the feet.

To analyze the forces on the upper-arm, all of the external forces and moments operating on the arm must be considered. In this case, the weight of the upper arm and the resultant elbow force and moment caused by the weight of the forearm and hand link must be considered. In this way, it is possible to calculate the static equilibrium equations at the shoulder which result in a reactive force Rs and a moment Ms for the person analyzed.

The principle of momentum that applied to linear movement also applies to rotational movement, and the conservation of angular momentum is one of the key principles in athletic performance. Angular momentum is a function of the mass and the rotational acceleration as well as the square of the distance from the center of rotation. In rotational motion, therefore, the quantity of mass times the square of the distance from the center of rotation is analogous to mass alone in linear motion.

These basic physical concepts are essential to the understanding of human movement and the principles of physical performance. The fact that it is harder to hold a weight further from the center portion of the body is related to torque. The fact that a ballet dancer on her toes and a figure skater on ice can generate high rotational speed is because both performers are affected by the conservation of angular momentum.

The product of a turning body's moment of inertia and its angular velocity is called its angular momentum. According to the law of conservation of angular momentum, a turning body isolated from external forces will have a constant angular momentum; that is to say, the product of moment of inertia and angular velocity about the axis of rotation is constant. If, for example, a man is standing on a revolving turntable without friction, he may increase his resistance to turning threefold by stretching his arms sideways (Figure 33). By the same token, if a man rotating on the same frictionless turntable pulls his hands toward his body, the rotational velocity will increase threefold because the moment of inertia has decreased.

A figure skater makes use of these laws on ice. At first, as rapid a spin as possible is produced with arms extended. The arms are then brought down, and the body spins on the point of one skate with remarkable velocity. The same principle allow throwers, such as discus throwers or shotputters, to generate higher speed across the circle of throwing.

These various laws of motion are critical when applied to the muscles and bones of the body. Muscles and bones constitute a form of basic tool, the lever. To understand the application of motion, therefore, we must first understand the use of the lever.

The combination of muscle and bone forms a lever system which is one of the most basic mechanical systems for performing work. A lever is a machine by which force applied at one point does work at another. Each joint in the human body is the fulcrum of a particular lever.

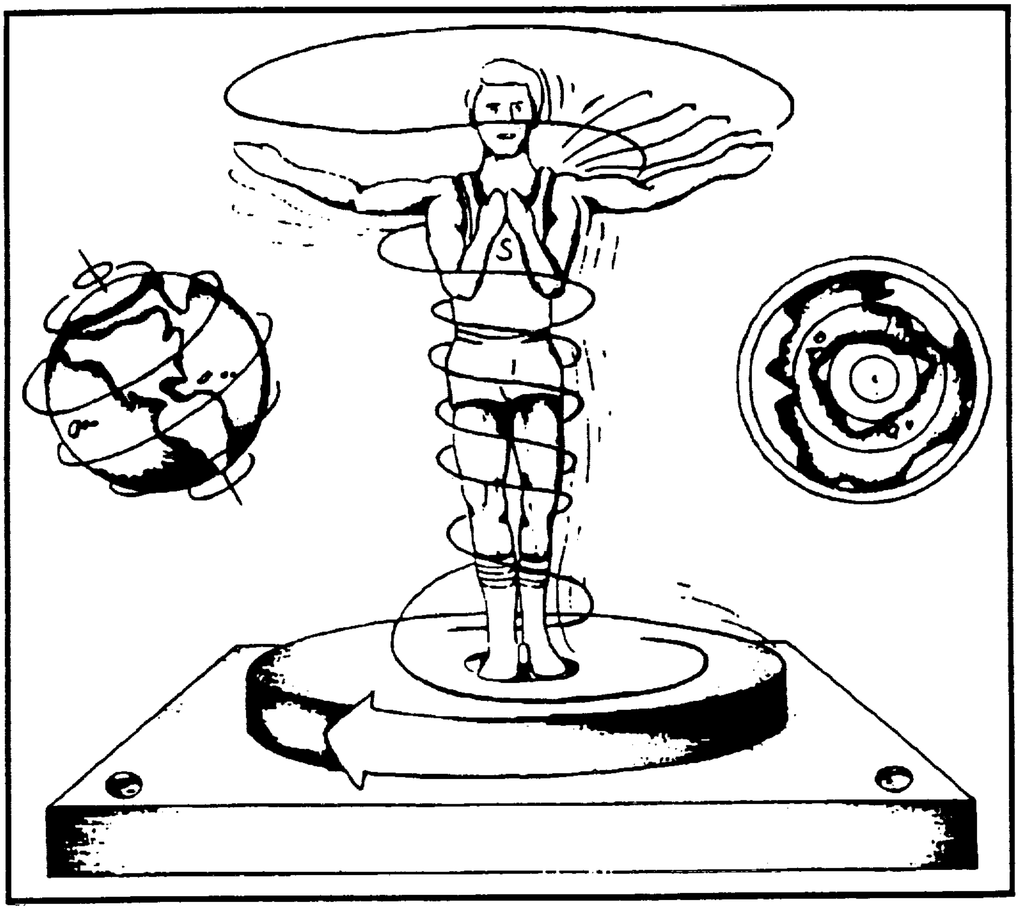


Figure 33

There are different types of lever systems and the human body uses all types. The forces on the different levers are applied by the muscular system. It must be remembered that muscles do all of their work by contraction or shortening. Activity occurs because the muscles contract or pull the various bones, or levers.

Muscles, like many other components of our anatomy, operate in pairs known as "agonists" and "antagonist". Bending the arm at the elbow, for example, requires the biceps to contract while the extensors, the triceps, relax. In order to stop this bending motion, the biceps must stop contracting at the appropriate time and the triceps begin contracting in order to slow and subsequently stop the action. The neural coordination of this system was previously discussed in the "bio" section. It is the bones which constitute the levers employed in the mechanical properties of motion.

Physics has divided levers into three classes (348) In the first of these, the force is applied at one end of the lever and the resistance to be overcome or the work to be done lies at the other end. The fulcrum, or pivotal point, lies between. Two children bouncing up and down on a playground teeter totter exemplify a class one lever.

In the second class, the force is applied at one end but the resistance is located above the pivot or fulcrum. A crow bar underneath a tree stump is an example of class two leverage.

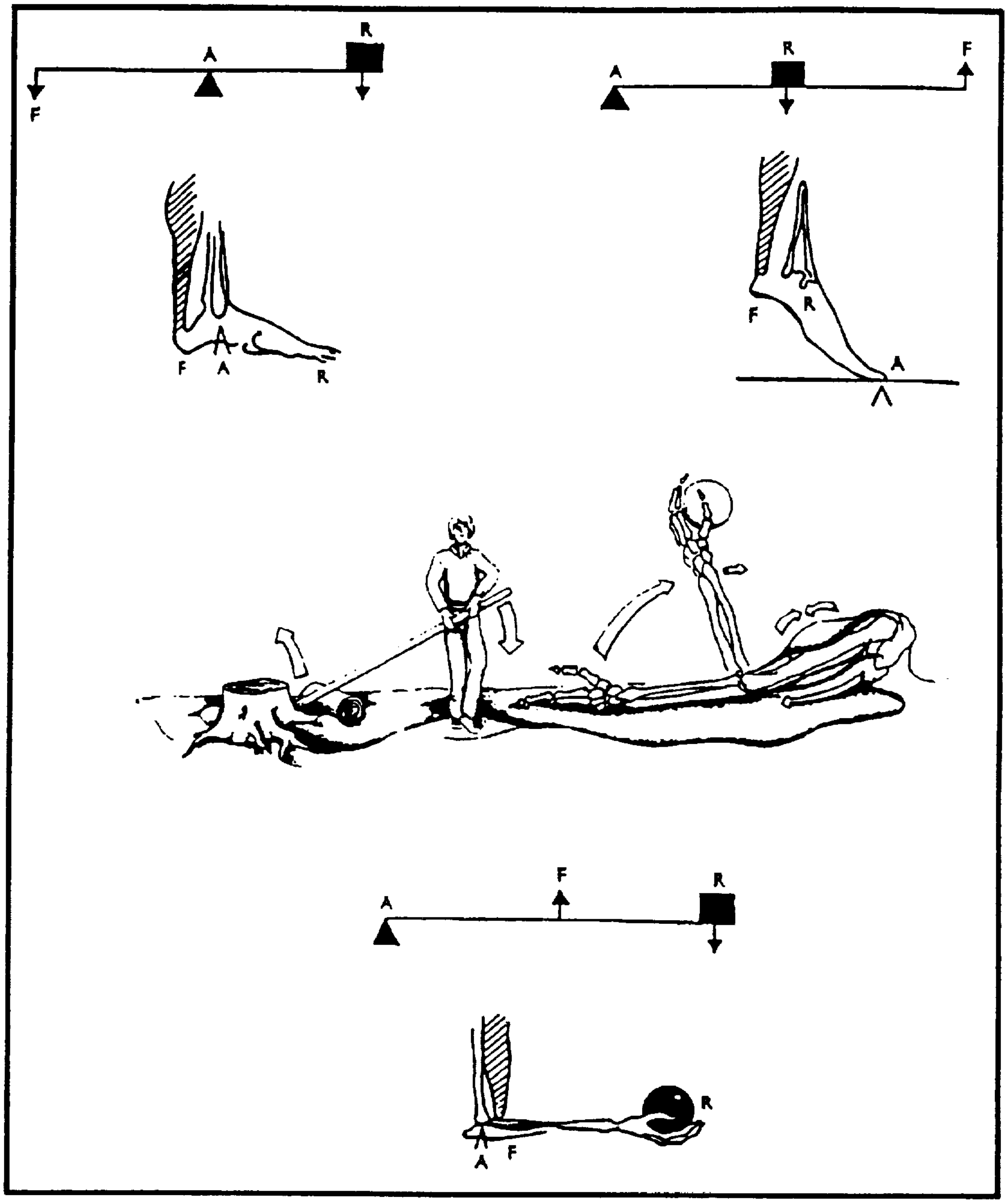


Figure 34

The third type has the force exerted between the pivot point and the resistance, and this is the common lever system within the human body. When you lift a weight with your arm, the pivot is the elbow joint, the force is exerted between your elbow and your hand by your biceps muscle, and the weight in your hand is the resistance (Figure 34).

A lever may either increase the amount of work that can be done with a given input of force or it may cause the work to be done at a faster rate than the application of the force. Archimedes once bragged that he could move the world if given a long enough lever (43). To perform the feat, Archimedes would have used a second class lever with his fulcrum very close to the Earth while he himself would have dangled on his elongated lever somewhere deep in outer space.

The concept to be mastered is that a mechanical advantage is gained with use of a lever, the amount of force is multiplied many times over to produce greater output at the other end. This is true if the fulcrum is situated closer to where the force is to be applied than to where the force is executed. If the reverse is true, and the fulcrum is nearer to the point where the force is executed than to the point of force application (a third class lever), then the result is a mechanical disadvantage.

For humans, the fulcrum usually falls closer to the point where the force is executed or initiated than to where it is applied, or where the work is done. The biceps attaches to the radius bone quite close to the elbow. Therefore, to lift a one pound weight with your hand, your biceps operates at a mechanical disadvantage of approximately seven to one. That is to lift one pound requires a force of seven pounds.

However, the same principle that governs mechanical advantage and disadvantage has its compensations. The hand at the end of the lever of the arm will move seven times faster than the point where the biceps attaches to the radius. It is easily seen that only a slight movement upward of the forearm near the elbow, causes the hand to move several inches during the same time interval. Obviously, the hand traveled considerably faster than the elbow.

For most human joints, the length of the lever does not produce a mechanical advantage. None the less, there is still more potential for production of speed if the human levers are longer. The knees are particularly vulnerable to injury not only because of their limited range, but because, in some instances, the whole body becomes one long lever applying its force at the knees. A situation to illustrate this point is on the ski slopes. If the boot does not release when the shear forces are excessive, the long skis and the body can create an exaggerated and destructive lever ultimately resulting in injury.

While Archimedes required a very long lever to move a very large ball (the Earth), Hannibal needed a shorter lever to throw large balls from his catapult. Individuals concerned with much smaller spheres, such as golf and baseball, can still apply more force to the object or their intentions with a longer lever. Golfers should play with the longest clubs they can comfortably manage, as should batters in baseball.

However, the longer the lever, the less fine the control and the greater the requirement for muscular force. Thus, the putter, the club most concerned with a deft, accurate stroke, is the shortest in the bag. Many good golfers further reduce the potential margin for error by shortening up on the putter and holding it lower on the shaft.

In addition to some of the important components of mechanics, it is also essential to understand the other laws of motion. Newton neatly encapsulated these laws of motion into three principles. The first law states that an object remains at rest until some force acts upon it. If the object is already in motion, it continues at a constant speed unless some outside force is brought to bear. In other words, until the levers of foot and leg are applied to a soccer ball, it remains at rest on the ground. Once having been kicked, however, the ball will continue to roll at a constant rate until it is acted upon by the outside force of friction, from ground or air, or contact from another system of levers in the form of an opposing soccer player.

When two or more forces act upon an object, the subsequent force is known by physicists as the resultant force. If Player A kicks a soccer ball due north simultaneously with Player B's kick of the same ball due west, the ball will travel northwest along a path that will be determined by which athlete delivered the most force. The route taken by the ball and its velocity is the resultant force supplied by Players A and B.

Newton declared that the main task of mechanics was to learn about forces from observed motions. The physics behind movement is related to the law of momentum, which is part of Newton's second law. Momentum is a concept that consists of velocity multiplied by the mass of the moving object. Momentum, in terms of physics, is distinguished from force, which is defined as mass multiplied by acceleration, or the rate of change in velocity. Alteration of momentum, or a change in motion, declared Newton, is governed by the force brought to bear upon the object, which then follows the straight line in which the force acts (Figure 35).

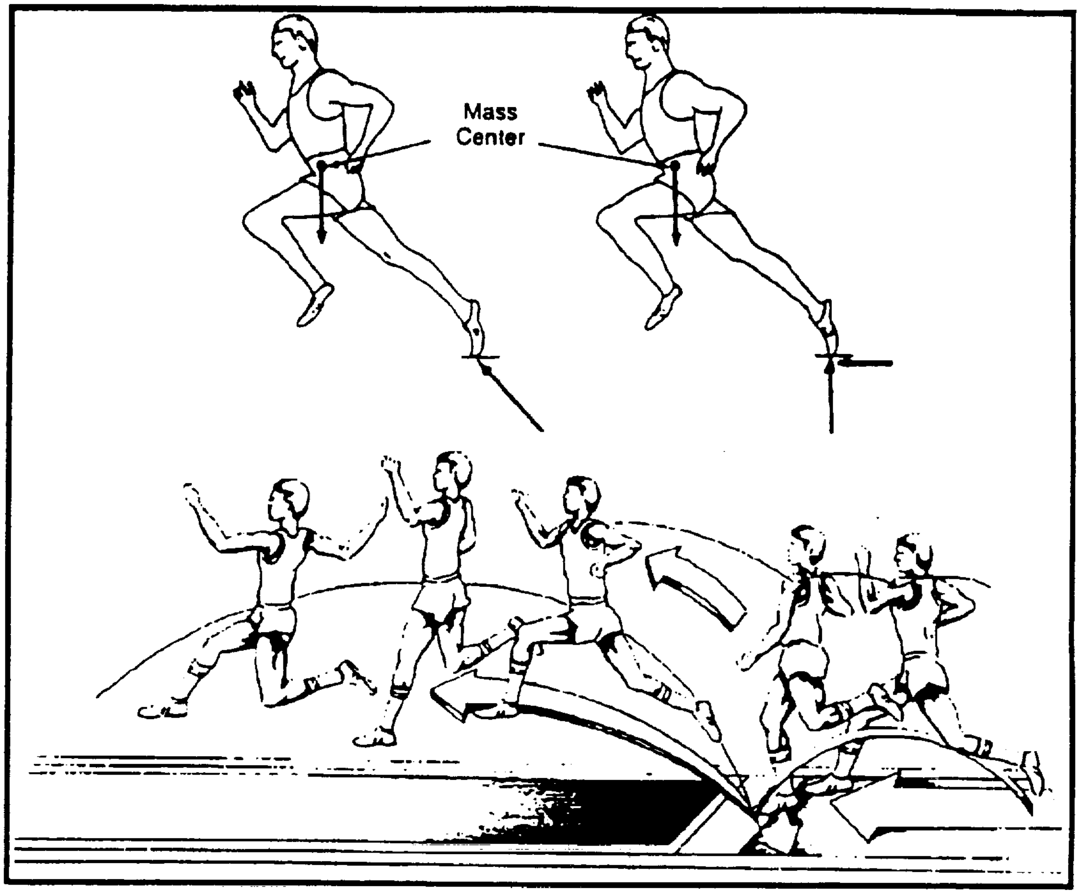


Figure 35

Consider the problem of a man leaping over a small puddle. He runs towards the puddle creating many forces including horizontal ones. As he nears the water, the central nervous system, the movement coordinator, orders the muscles the feet and legs to contract generating a vertical force for the jump. The height depends upon the ability to generate enough force to temporarily exceed gravitional force. If the man weighs 150 pounds and produces only 140 pounds of vertical force, he will have wet feet. Once airborne, he can no longer add any force to the jump. The force of momentum, the velocity at takeoff multiplied by the man's weight, must be enough to overcome the demands of gravity in order to jump over, not in, the puddle. The vertical force combines with the horizontal force for the leap. That is to say, the body does not travel in either a purely vertical direction or continue to move in a direction solely horizontal. Rather the path becomes a combination of horizontal and vertical forces, a direction that physicists call a resultant.

The third law of Newton was that for every force that acted upon an object, the object itself exerted an equal and opposite amount of force. When you kick a ball with your bare foot, the painful sensation in your big toe confirms Sir Isaac's third law. The recoil of a fired rifle is also an example of equal and opposite reactions. A car striking a bridge abutment at 60 miles per hour is demolished while one that nudges the wall at 5 miles per hour remains intact. The wreck is an example of a much greater degree of equal and opposite force.

Another principle affecting your body is derived partly from theories of Einstein. An old bedroom farce joke uses the punch line, "Everybody's got to be someplace," and Albert Einstein said that energy can neither be created nor destroyed. In other words, energy or a visible manifestation of it in the form of force also always must "be someplace."

This means that when one generates a force by swiveling his back, and then suddenly tries to stop the movement of the back, the force developed in the trunk of the body does not simply disappear. It must go someplace. The secret to efficient use of a body for work or sport, for fitness or injury prevention, depends to a great extent on where these forces go or how well they are exploited.

In the human body, the bones, or levers, move in a rotational manner. These angular movements create linear movement for the total body. The same laws that govern linear motion also govern angular motion. The only difference is that the length of the lever also plays an important part. If the body begins a rotation, it will continue to turn on its axis until the movement is altered by either a change in body position or the application of some other force. Consider the previous example of the ice skater and imagine that this skater begins a spin with the arms abducted or outstretched, building up angular momentum by the maneuver. If this athlete suddenly drops the arms to the side, the velocity of the spin will increase because the momentum that was initially generated is constantly maintained around the axis. The change in the arms' distance from the center of the body transfers this angular momentum to the body itself.

Angular momentum can be redistributed throughout the body. When a long jumper leaves the ground, he or she is propelled forward and angular momentum is developed. Unless that momentum can be redirected, however, the jumper will land flat on his or her face. Such a disaster is prevented by transferring some of the angular momentum to the arms, which explains the wild flailing exhibited by long jumpers.

Angular momentum can be expressed in terms of two other important parameters of rotation: angular velocity and moment of inertia. Angular velocity is represented by the body's rotational speed and direction. For example, if a diver performs a forward double somersault in one second, the magnitude of his average angular velocity is two revolutions per second.

The moment of inertia of a body about an axis is the body's tendency to resist changes in angular velocity about that axis. It is obvious that massive and extended bodies have a larger moment of inertia than do lighter and smaller ones. In fact, the contribution of each particle or segment in a body to the total moment of inertia about an axis is equal to the mass of the segment times the square of its distance from the axis of rotation. For example, a typical diver with this body straight and his arms at his sides has a moment of inertia of 14 kilograms times meters squared about his somersaulting axis, but a moment of inertia of only one kilogram times meters squared about his twisting axis.

Angular momentum is the product between the angular velocity and the moment of inertia about a specific axis. In the case of the diver, that will be the sum of angular velocities around the two axis and the moment of inertia around these axis.

The analogy between angular momentum (moment of inertia times angular velocity) and linear momentum (mass times linear velocity) is not perfect. The reason is that the body can change its body segment lengths while performing angular movement, such as the diver straightening from a tuck position into a straight body. That changes the moment of inertia about his somersaulting axis. In linear momentum, this does not occur.

Any mechanical phenomenon created by the human body must be initiated by the energy produced by the skeletal muscles. This energy allows the movement of a body segment in rotational fashion to create movement. The faster the movement the more powerful is the motion.

There are some limitations to any analogy between power created by muscles and that produced by an engine. An engine will be rated as having a certain amount of horsepower, meaning that it will produce a specific amount of work each second that it is in operation. It will lift or push a number of pounds a certain distance. We can measure sustained human efforts the same way. A woman pedaling a bicycle can be rated for the horsepower she produces in transporting her weight and that of the bike over a certain distance within a certain amount of time. This type of power rating is valid for a rhythmic and sustained amount of force. But it does not serve as a useful description for impulsive actions.

Consider for a moment what happens when one fires a rifle with the barrel pointed straight up into the sky. Most of the power to speed the bullet on its way is produced before the bullet is actually moving. Because of the confines of the rifle barrel, there may be some power added as the explosive charge pushes toward the muzzle behind the bullet. There is no way to accurately compute a value for the amount of horsepower generated. The force is not constant and gravity and friction constantly alter the velocity.

The same is true for an impulsive action by a human, such as in a high jump. It may be said that one jumper will actually generate more force than another jumper, but still not leap as high, because of a failure to coordinate all of the force into as large a single impulse. The key measurement, therefore, is not how much "horsepower" was developed as the athlete sprinted to the launching point and then hurled himself into the air, but only the amount of ultimate ballistic muscle force that was generated for the actual liftoff.

Another factor necessary to understand movement is appreciation of the classification of mechanical energy, which is defined as the capacity to perform work. Kinetic energy is that which the body possesses by virtue of its motion. During the motion of the windup of a pitch, the arms of the baseball pitcher contain kinetic energy. Potential energy consists of that which owes its existence to the position of the body. A diver at the edge of the platform possesses a certain amount of potential energy through the imminent application of gravity.

Sometimes the types of energy can be totally separate aspects of a movement. For example, the instant that a person begins to rise from a trampoline, the kinetic energy begins to diminish while the potential energy increases. At the highest point of the maneuver, the instant of zero velocity when the gymnast is neither ascending nor descending, the kinetic energy is zero and the potential energy is at its maximum. During the descent, the potential energy in effect is transformed to kinetic energy. At the deepest penetration of the trampoline bed, the strain energy reaches its maximum.

These mechanical, physical precepts are useful in the analysis of human movement because they permit examination of the forms of energy, forces, directions, or speeds that comprise an activity. Quantification can also assist in determining the most efficient use of effort, that is, the optimum way to do something.

THE BIOMECHANICS

Quantification of an action, regardless of whether for evaluative purposes or to attempt optimization, can be accomplished through biomechanical analysis. Biomechanical assessments normally begin with the quantification of the kinematic portion. This is usually accomplished by utilizing high speed cinematography or videography which allows careful scrutiny of even the fastest movements of humans or other animals, such as dogs, cats, horses, etc. The films or videos are traced and the resulting data stored in a computer which calculates the results by applying the principles of physics and mechanical engineering. Tables and graphs can then be generated which give a precise profile of what actually occurred during the execution of the movement. The researcher then carefully examines this output in order to understanding the motion and, in the case of an athlete for example, to determine which patterns are most important in distinguishing championship from average performances.

Biomechanics is a science still in its adolescence with many discoveries yet to be made. Hand analysis of high speed films is a slow and tedious process, and it is only recently that the computer has been harnessed to make the process more efficient. Development of this technology in the United States has meant that many complex analyses can be executed in a relatively short time.

In the past, athletic achievement depended mainly on the individual's talent, although skill was often enhanced or ruined by existing facilities, equipment and, undeniably, coaches. Athletes with superior genetic compositions who successfully interacted with the available facilities dominated the list of world records. Continual improvement of equipment and techniques has complemented raw talent.

However, with the advent of new measurement tools and knowledge in the field of sport science, athletic achievement has attained a new dimension. The athletic teams of the United States, which for years had dominated amateur sports, were no longer the leaders. Countries such as those of Eastern Europe and Cuba, which have relatively small populations, have achieved a spectacular level of success in athletic events. Current evidence suggests this trend may continue through the remainder of the 1980s and 1990s. Such domination stems from the application of science to the realm of athletic performance.

Modern coaches can use biomechanical means to optimize the human body in each event. Since the human body obeys the same physical laws as all other earthly objects, the laws of motion govern its performance. In order to throw, run or jump, physical laws must be obeyed. It is impossible to throw the shot 20 meters if the shot velocity and angle of release do not attain certain values. These values do not differ for different athletes, since for each particular shot velocity there is one specific optimal angle.

For the jumper to leap 8 meters, it is necessary to produce certain forces on the ground in order to propel the body with a specific reaction force at a particular angle. This force is unique, and it is impossible to cover the same distance with only a fraction of the force since gravitational pull acts uniformly regardless of the jumper.

The concept to be reemphasized here is that all bodies, athletes, implements or machines, are affected by and must adhere to the laws of motion. The science of biomechanics specifically deals with motion of the body and the resultant forces. A number of scientists have long recognized these facts of force and motion and their relationship to humans. But the kind of equipment that could measure and analyze the motion and forces involved was lacking and, thus, impeded further research.

The field of biomechanics can be divided to Kinematics, which describes the motion of the body and its segments without reference to the forces that cause the motion, and Kinetics, which describes the forces which caused the movement. The kinematic parameters includes linear and angular displacement, velocity, and acceleration. The kinetic parameters include the external and internal forces acting upon the body segments.

In order to measure the kinematic and kinetic parameters, it is necessary to make a few assumptions. If it were possible to disassemble and reassemble the human body like other machines, then it would simplify and make the measurements more accuracy. However, this is obviously impossible. Therefore, some of the measurements are derived from cadaver and additional assumptions are made upon the linkages of the human body. This is not different from any other field involved with living bodies. In the field of physiology, for example, many assumptions are made on the ability of the body to consume oxygen. In the conversion of energy measurements from external measurements to internal measurements, many reasonable assumptions are made. In determining the composition of different muscles and their classification into fast and slow twitch muscles, many assumptions are made concerning the chemical staining methods and the counting methods. Of course all statistical methods, which are the bases for most behavioral research, utilize assumptions about the normality of the populations and the distributions of the data samples.

Therefore, to view the human as a machine made of links is an oversimplification but it is possible to create a humanoid model as a representation of the body made of rigid segments. In this way, it is possible to facilitate quantitative analysis of the movement. The links which represent the body's limbs are a series of interconnected rigid segments which demonstrate independent motion.

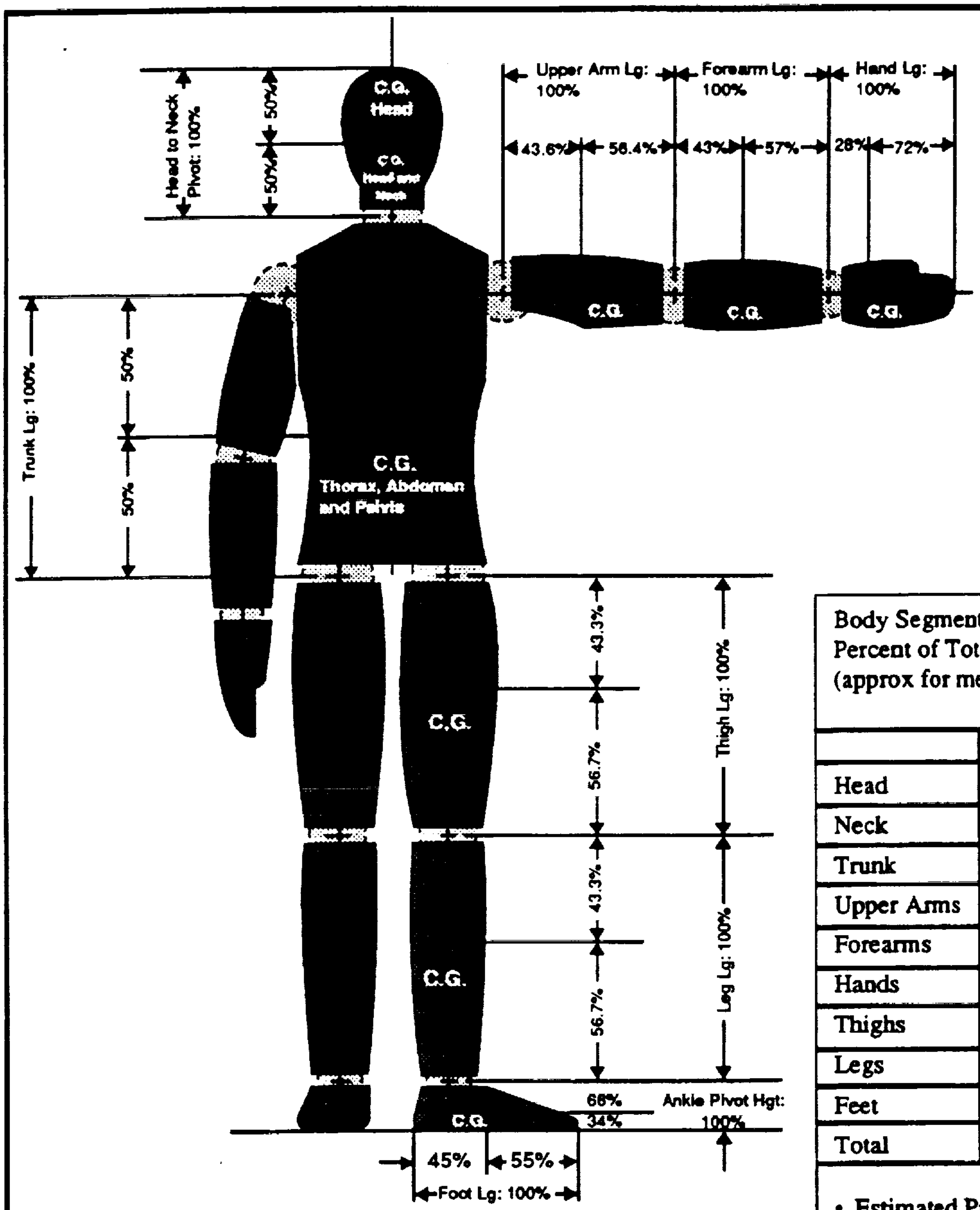
To more accurately facilitate the above mentioned system, it is important to realize that there are different body types. It is clear that body differences in shape occur between ages, sexes, and within individuals. The field which deals with different body shapes is the field of Anthropometry.

Anthropometry is the science that deals with the measure of size, weight, and proportions of the human body (96). Anthropometric data is fundamental to biomechanics because some of the assumptions made in the calculation of movement parameters made based on its data. In performing a biomechanical analysis of any movement, the human body is considered to be a system of mechanical links with each link of known physical size and shape given by anthropometric measurement.

After adapting the anthropometric measurements to the different body segments, the next assumption is that this link system is connected at identifiable joints. Since the body landmarks or the body segments are covered by muscle, fat and skin tissues, it is sometimes difficult to identify joints such as the hips and shoulders. However, with the aid of statistical and numerical methods it is possible to filter some of the errors.

This field of anthropometry has made tremendous contributions by dissecting cadavers and measuring the location of joint centers. Some of the pioneers are Braune and Fischer (81), Dempster (126), and Snyder, Chaffin, and Schulz (419). From the cinematographical data, it is possible also to use tracing methods which connect the intersection of the long axis line of the segments during movement. Some of the landmarks used in the field of biomechanics are illustrated in Figure 36.

In addition to landmarks required for biomechanical tracing, it is important to predict the segment mass and location of the center of the mass. Body-segment mass and volume are related to the density of the segment. From the field of Anthropometry, these measurements were



Body Segment Weights
Percent of Total Body Weight
(approx for medium build)

	M	F
Head	• 7.1	• 5.7
Neck	• 2.5	• 2.0
Trunk	45.8	46.3
Upper Arms	6.6	6.0
Forearms	3.8	3.1
Hands	1.3	1.0
Thighs	21.0	23.0
Legs	9.0	10.5
Feet	2.9	2.4
Total	100%	100%

- Estimated Proportion of Head and Neck

Figure 36

determined by immersing cadaver body segments in water and measuring the volume of the water displaced. From the equation of:

AVERAGE DENSITY IN MASS PER UNIT VOLUME EQUAL TO THE MASS OF THE BODY SEGMENT DEVIATE BY THE VOLUME OF THE WATER DISPLACED.

$$\boxed{(D = M/V)}$$

The values for the different body segments are available in various biomechanical text books.

In addition to the segment weight and its volume, the distribution of the mass within the segment is necessary in order to compute the kinetic information. From this distribution of the mass, it is possible to calculate the location where the gravitational effect on the segment occurs. In other words, where the segment can be considered to be in its gravitational balance so that if one were to hang the segment at this point, it would be in balance regardless of the orientation of the segment in space. This point is known as the mass center or the center of gravity of the segment.

There are a few methods to calculate the segment center of gravity. One method involves the distribution of forces by allowing a person to be suspended between two force platforms and calculating the change in vertical forces by moving various segment to different angles. Another method involves submersion of the segment in water. Regardless of the method used, there exists a sufficient data base from various investigations which have calculated the center of mass for different segments for different populations.

Knowledge of the center of gravity location of each segment and its weight and length allow the calculation of the static force and torque at each body joint for a given posture. However, in athletic performances and in normal human life, we are seldom concerned with static posture. More realistic are the dynamic performances where the forces due to the motion in addition to the forces due to gravity act upon the body.

For these dynamic analysis of the human body, it is necessary to know the inertial property of the segment. This property is referred to as the Moment of Inertia. The formula which describes the moment of inertia considers the following:

MOMENT OF INERTIA OF THE SEGMENT IS EQUAL TO
THE MASS OF THE SEGMENT TIMES THE
SQUARE OF THE PERPENDICULAR DISTANCE FROM A GIVEN AXIS.

$$\boxed{I = M X R X R}$$

There are different methods for calculating the Moment of Inertia of the individual body segments and these methods are described in various Biomechanics text books.

It is important also to calculate the location at the body segment where the moment of INERTIA effect the segment. This point is called the Radius of Gyration.

THE RADIUS OF GYRATION IS EQUAL TO:
THE SQUARE ROOT OF THEMOMENT OF INERTIA DIVIDED BYTHE MASS OF THE SEGMENT

According to Drillis and Contini (134), the radius of gyration is "the distance from the axis of rotation to an assumed point where the concentrated total mass of the body would have the same moment of inertia as it does in its original distributed state". This information is necessary to quantify the dynamics of human motion in conjunction with other parameters.

Another important contributor to biomechanical analysis was the National Aeronautics and Space Agency which have also made detailed measurements of human body composition, the relative mass for segments such as arms, legs and hands, given the overall height and weight of the individual. The specifications may not be exactly accurate for each individual, but they are close enough to humans in general for the purposes of even the most exacting scientists.

It should be remembered that all of these estimated parameters are used in calculating the dynamic forces rather than merely describing movement in qualitative terms. These parameters are available in numerous sources and the normal analysis of human movement does not require the individual calculation of all of these parameters. The information resides in tables and charts which can be accessed at will. The normal analysis of movement relies on this information in the same way that physiologists depend on the tables presenting characteristics of different gasses and their coefficients at various temperatures and pressures.

Without a computer to store information, retrieve it, and perform the myriad computations, such calculations can place the scientist in an impossible position. But before a computer can perform its job, whether it is to guide a robot, print a check or retrieve a space vehicle, it needs a program, that is, a sequence of instructions which tell it how and what to do.

Programming a computer involves hundreds and, at times, thousands of hours of work. But once the instructions have been fed into the computer, it will automatically execute the hundreds of steps without any need to restock the computer with further instructions, and the execution will only take a few seconds. The beauty of a computer is that it can play the great game of "what if?". In sports, one could ask, "What if I hold the shot down here and then whirl in this fashion?" The computer will calculate the distance the shot will travel, applying the amount of force developed in previous analysis. Through use of the computer, then, biomechanics can write equations and construct models which will result in optimal performances.

Another critical element is the camera which can be either a high speed movie or sufficiently fast video system. It provides sequences of the body in motion. Knowing the speed with which film or video tape travels through the camera allows calculation of the velocity and acceleration of body segments using its joints as points of reference. For example, if the shutter speed on the camera is 200 frames per second, one can identify the location of the right knee at the start of a sprint, and then compare the position of the right knee in frame 20 of the film, thereby learning how far the right knee has moved in one tenth of a second. The data can be further utilized to determine velocity, acceleration and, with some additional information, even the forces involved. The forces can be calculated by measuring the length of the leg, for example, from knee to ankle, and by using the NASA specifications, determine the mass of that segment as well as determining the center of gravity. Using these values, quite reasonable estimates of the exact forces and torques around the joint center can be calculated.

Along with analyses based upon films taken during actual events, highly sensitive force plates have been developed for precise impact measurements. These allow controlled laboratory testing of forces, such as when an object like the human foot strikes the plate during a sprint or the vertical component of a monkey leaping from the plate onto a table. The plate is capable of recording three different components of forces: vertical, horizontal, sideways or lateral, as well as the moment or torque.

Any kind of athletic movement or work action which can be photographed with a high speed motion picture or video camera can be fed into the computer. Forces can be plotted for each segment of the body as the accelerations and lengths of the segments are measured. The maximum amount of force that can be generated using a particular approach in an activity can be calculated (19). For instance, it is feasible to calculate how high a jumper might go if he changed from his customary form of the roll to the flop style, assuming he was able to generate the same amount of force for the flop as he did for the roll. Analysis have shown that the flop happens to be a more efficient use of forces for athletes who do not possess extremely powerful legs.

It is important to remember that because of both gross and subtle variations in the neuromuscular system of each human, the biomechanical actions of individuals are as unique as their fingerprints. The shades of difference from one person to another are, in fact, great enough to permit the development of a foolproof method for guaranteeing a signature. A person could file his or her signature in a computer bank. The information in the computer would contain not only the shapes of the letters, but the amount of force the individual applied to every loop, line and curve. With this device, a buyer in a store need only sign the chit on a force plate or use a pen with a force sensitive transducer which transmitted the information directly to the computer. The patterns of force would be compared instantly and, if not the same, the new one would be rejected.

Similarly, detection of variations or errors in human movement has always been one of the most difficult problems facing coaches, trainers and physicians in athletic situations. If the error detection is inaccurate or non-specific, the quality of correction will be poor. Failure to recognize the causes of error stems from an inadequate understanding of the mechanisms of human motion. Impacts in sports, automobile accidents, falls, and other movements involving forces can be accurately quantified through biomechanical applications.

The designer of protective equipment for sports, such as hockey and football, must have an understanding of biomechanics since it is necessary to comprehend before the equipment is designed how the human head reacts to impact forces or how a skier's leg reacts to twisting forces. The forces produced by the human body cause a change in acceleration or speed. The change might involve the entire body, as in sprint starting, skating, or volleyball (in a vertical jump to block). It may also be a body segment or combination of segments, as with a boxer's upper arm and forearm, a golfer's arms, or a soccer player's thighs and lower legs. Through use of biomechanical analysis, it is now possible to scientifically detect errors which are beyond the visual capabilities of the human eye.

When the muscle contracts and there is a change in limb position, work is performed. When time is required to perform the physical work, then units of power measurement are employed, since the rate of work is power. In human performance, striving for excellence on the athletic field or in recreation, it is important to be able to sum the forces exerted on the various joints. This principle is called the summation of joint forces.

For example, in swinging the golf club in the drive, the amount of force exerted by the club on the golf ball depends on how much of the forces totaled by the body actually reach the club. If there is any loss of force due to bad timing, the golf club head will not move at the same velocity. Any violation of the principle of summation of joint forces can result in too small a force being exerted by the golf club.

Another important biomechanical principle is that of continuity of joint forces. This is illustrated by the fact that not only must the golfer use all body joints efficiently, but he must also time their use so that the motion begins at the larger segment (such as the thigh), and then continues and is overlapped by motion of the hip and trunk. There must be no pauses in the flow of motion from the legs to the trunk and to the club. It must be continuous. A violation of this principle not only results in too small a force, but also in bad timing and a poor "feel" on the golf club.

Because club speed is determined by the force applied and the length of time of force application, the best combination of force application should be determined — a large force in a short time or a small force for a longer time.

There is an optimal combination for each activity. The size of the force multiplied by its time of application is called "impulse" and it is actually this force/time combination which produces the golf club velocity. Therefore, the impulse in any activity should be determined to result in optimum efficiency. Although compromises in the size of force and duration of application often have to be made in sport to achieve an optimum combination, one such combination to be avoided is a small force applied for a short time.

The size of the force an athlete can produce is determined by his or her ability to comply with the principles of summation and continuity of joint forces. In the absence of measuring devices, assessing whether the force application time is as great as possible presents yet another problem. In general, if each joint has gone through a complete range of motion, one can be assured that the maximum time available has been used.

It was previously pointed out that not only must the range of motion of the joint be complete, but the joint must straighten fast and the combined joint motion be continuous. The concept of the combined effect of force and duration of application in producing speed changes is called the principle of impulse. Violation of this principle causes further errors in performance.

Direction of force application is another important principle. Not only is the direction of the application of force to the golf club vital, but, in addition, from the club head to the golf ball. In an optimal situation, the force is exactly 90 degrees to the club and the club head hits the ball exactly at its center. However, some deviation is at times necessary if the flight of the ball has to be changed in a predetermined pattern. Incorrect direction of force can be disastrous in events such as gymnastics and diving. A good technique implies that the principle of direction of force was followed.

A final principle is the summation of body segment speeds. Especially in any throwing, kicking and striking events, it is important to obtain as high a hand, foot, stick blade, racket head, or club head speed as possible at the instant of impact or release. The speed of last segment in the chain is built by adding the individual speeds of all the preceding segments with appropriate timing. If any of the segments contribute low or negative values, the resultant measured for the last segment will be less than optimum. This principle is similar to summation of joint forces and is closely related to it.

To summarize, any motion to seek optimum should obey the principles of summation of joint forces, continuity of joint forces, impulse, and the direction of joint forces. Through the use of biomechanics, all of these principles can be quantified and optimized so that better and safer results will be obtained.

EXPERIMENTAL STUDIES

To evaluate the behavior of some of the factors previously discussed, the author administered a series of experiments. The experiments were conducted with a small sample as these preliminary studies were intended as pilot projects only. Sophisticated measuring devices were utilized to quantify displacements, velocities, accelerations, forces, and EMG activities in single and multi joint movements. The equipment is described in Appendix A, B, and C.

METHODS

Subjects:

Ten subjects, 8 males and 2 females, ranging in age from 25 to 51 years took part in the study. They were healthy, active, and regularly participate in fitness exercises. Subject training programs generally consist of jogging 3 to 7 miles 3 to 5 times weekly and engaging in resistance exercises 2 to 5 times weekly.

Exercise:

To activate the elbow flexors and extensors concentrically and eccentrically, the subjects stood holding the bar of a computerized exercise device. The position used was the same position in which the Subject had performed the curl exercise with the elbow in full extention initially, then flexed to approximately 135 degrees, and then extended to the start position. The Subject was not restrained and the technique did not differ from the method used during the preceding two years of training on the equipment. Therefore, learning had previously been accounted for and would not contaminate the study.

Equipment:

The computerized exercise devise used in the present study is described in the Appendices. Its validity and reliability have been tested and presented. One of the unique features of these experiments was that a sophisticated programmable servo valve was utilized to control the speed of the mechanical member held by the hand. All the forces were measured with a pressure transducer and processed by the computer in real time. Special calibration procedures were used and described in Appendix A. Positions, velocities, and accelerations were measured and calculated simultaneously. EMG activity at the elbow flexors (biceps motor point) and at the elbow extensors (long head of the triceps) were measured simultaneously with the other parameters. Other parameters which were measured were forces for various muscular contractions, EMG activity during various motions against resistance, and various physiological parameters representing muscular contractions.

Different velocities were set for the concentric and eccentric contractions. Concentric contractions were performed by each subject as he or she tried to move the resistance bar as fast as possible while the bar motion was restricted to a specific velocity. For the eccentric contraction, an external force was applied on the mechanical bar to a level that exceeded the subject's ability to resist it. Since the bar was moving down at a specific velocity, the eccentric phase was restricted to that velocity and, therefore, could not damage the subject's arm. Each subject was encouraged to try as hard as possible to stop the bar from moving down throughout the specific range of motion. The range was set at 125 degrees for the elbow joint and 25 degrees for the axes of rotation of the machine.

Experimental Conditions:

The experimental design consisted of three basic conditions. In Condition One, the subjects performed concentric contractions in both directions, flexion and extension. In Condition Two, the subject flexed his elbow concentrically and extension was done eccentrically with a super-maximal force when the subject could not resist the extension at a specific velocity. In Condition Three, the subject was subjected to a sub-maximal force during the eccentric extension of his elbow. In other words, the subject could resist the force of extension but could allow the elbow to extend.

RESULTS

Condition One - Concentric contractions:

In this phase, the subjects were required to exert concentric contractions for both flexion and extension at various velocities. Figure 37 illustrates the force curve for flexion and extension. The displacement curve illustrates the flexion, passive delay where the subject was pausing between actions, and then the extension phase. In the same Figure, the associated EMG signals for the flexor and extensor muscles can be observed. During the flexion phase, the biceps generated high EMG activity while the triceps produced less EMG activity. However, it is important to note that EMG activity was present in both antagonistic muscles. To determine whether this was due to an artifact or "crosstalk", EMG activity was measured in a resting position with the arm motionless on a table. Figure 37 illustrates the EMG secured in a resting condition. Comparison of the EMG activity during an exercise and during a passive, motionless situation revealed that the EMG activity was significantly higher during exercise than at rest. It should be noted that the EMG electrodes were not removed or displaced at any time.

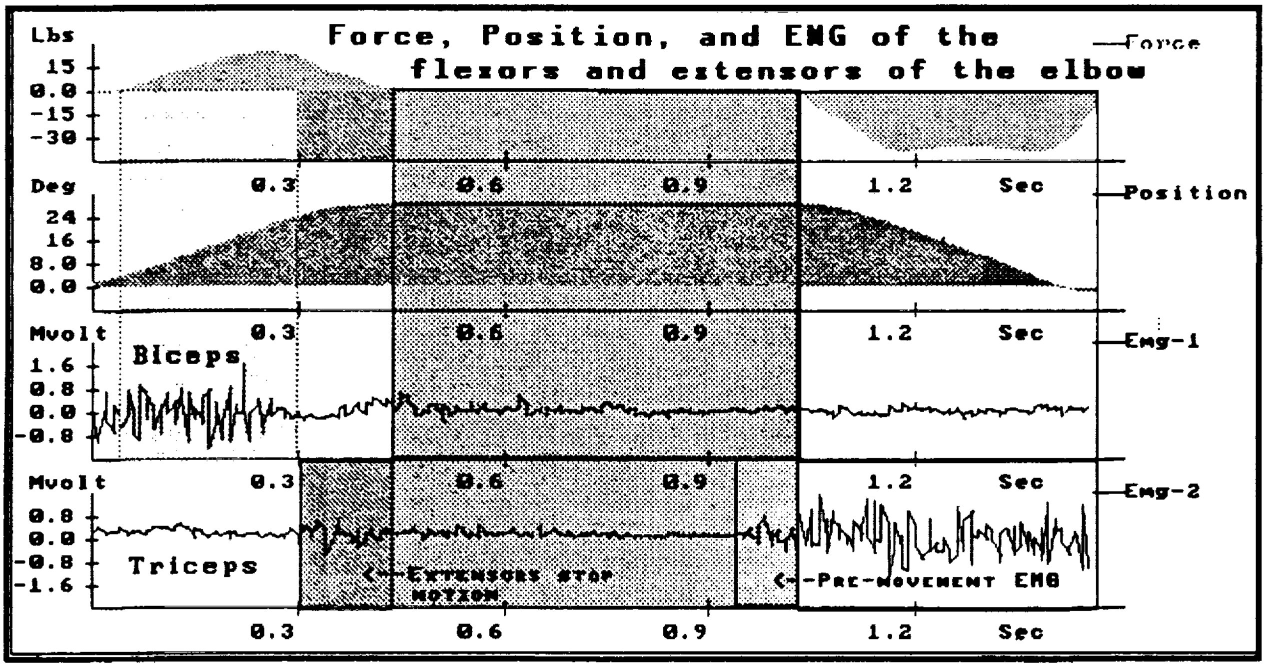


Figure 37

Figure 37 also illustrates that in the tricep's concentric phase, the muscle began firing, as indicated by the elevated EMG activity, despite the fact that the movement had not started. This phenomenon has been well documented by other investigators (70,72, 73) It can also be seen that during the concentric extension, the biceps muscle produced EMG activity as well.

In addition, it was found that during the flexion phase, the triceps showed elevated EMG activity before the end of movement. This phenomenon is well documented (223,305,306, 307,308) and illustrates the anticipatory effort needed to decelerate the segment to a resting position. Therefore, while the biceps fired the most at the beginning of the movement, the EMG activity lessened near the end of the movement. Although the triceps showed significant activity during the beginning of the movement, it demonstrated higher activity near the end of the movement.

Figure 37 illustrates the time relationship between the forces, displacements, and EMG activity. While each subject produced unique results, the general pattern displayed is like that shown in Figure 37 which represents one of a specific subject's trials.

Figure 38 illustrates typical displacement and force curves. The elbow was flexed concentrically and produced a force at maximum flexion of 25 degrees on the bar corresponding to 125 degrees at the elbow joint. Then the force dropped to zero with a delay at that maximum angle. Approximately one second later, the subject extended his elbow utilizing the elbow extensors (triceps) in a concentric phase for the extensors. This type of exercise is called a "double concentric exercise".

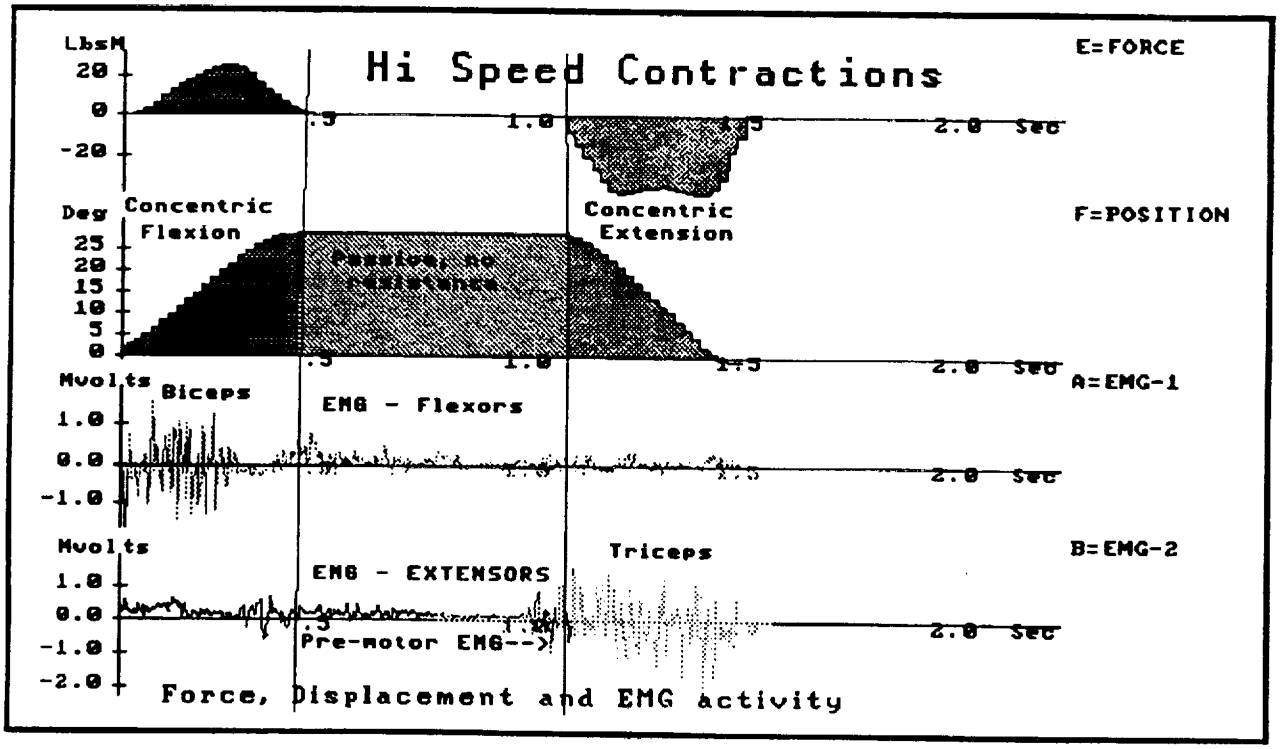


Figure 38

Figure 37 illustrates typical force, displacement and EMG curves obtained simultaneously in the double concentric exercise. It can be observed that the elbow flexors (biceps) became active before any displacement or force was produced. At that point, maximal EMG activity was observed at the flexors. At the same time, some EMG activity was recorded from the extensors indicating co-contraction. Before the end of the movement, more EMG activity was observed at the extensors apparently in anticipation of cessation of movement by the flexors. Also, the flexors reduced the level of firing indicated by a lower EMG activity before the end of the movement. When the muscle was in the delay phase before the extension portion of the exercise, the flexor force dropped to zero and both the extensor and flexor EMG activity decreased significantly. Approximately 50 milliseconds before the extension phase began, the extensor EMG increased significantly indicating potentiation or firing of the motor units of the extensors. This phenomenon has been reported in the literature and is referred to as the electro-mechanical delay. The level increased when the extensor force reached a peak. The flexor EMG activity indicated co-contraction in this phase as well.

In this phase of the study, the subjects were exposed to concentric contractions at various velocities in both flexion and extension directions. It is significant to note that for both concentric activities, the agonist and the antagonist worked in a coordinated pattern. That is, when the biceps was the prime mover, the triceps, as the antagonistic muscle, was active; when the triceps was the prime mover, the biceps, which functioned as the antagonist, was active as well.

Condition Two - Supermaximal Concentric Eccentric Contractions:

In the eccentric phase, a supermaximal external force was applied to the bar which was moved at a specific speed under servo valve control. The subject initially raised the bar (elbow flexion) in a concentric fashion. During the second part of the exercise, elbow extension, the subject tried to resist the downward movement of the bar until the position was returned to the origin.

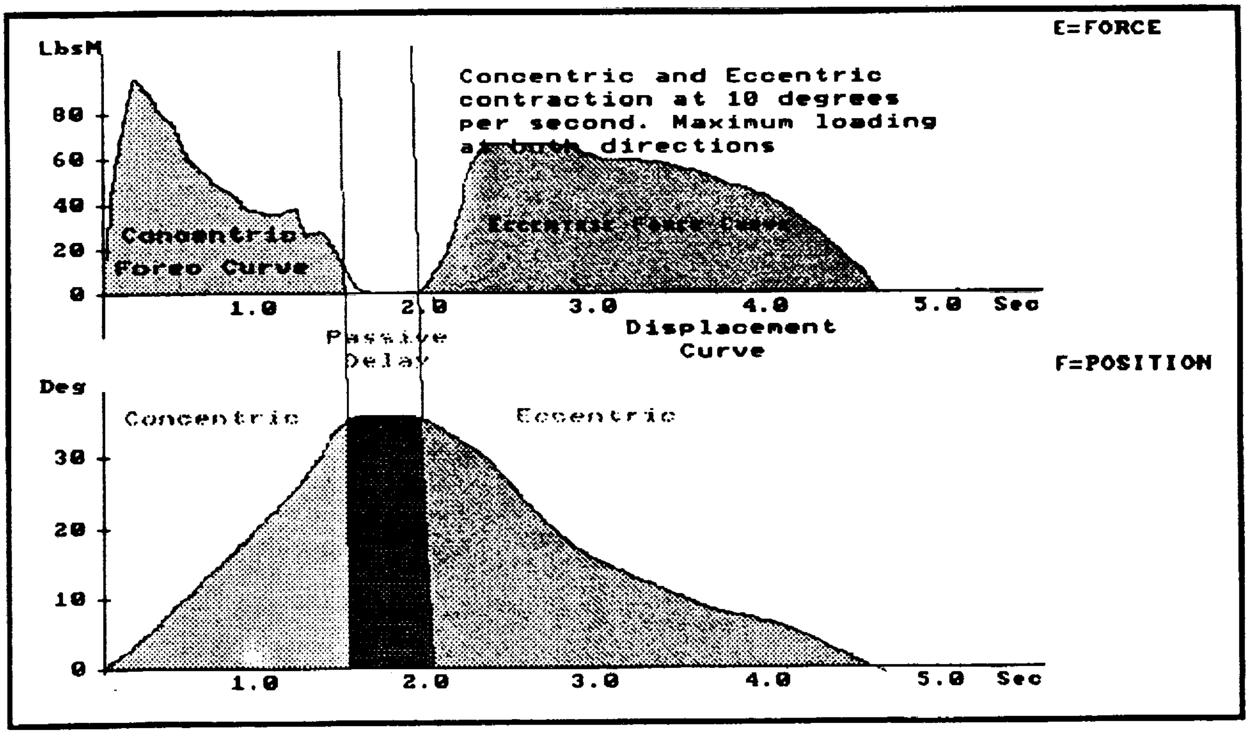


Figure 39

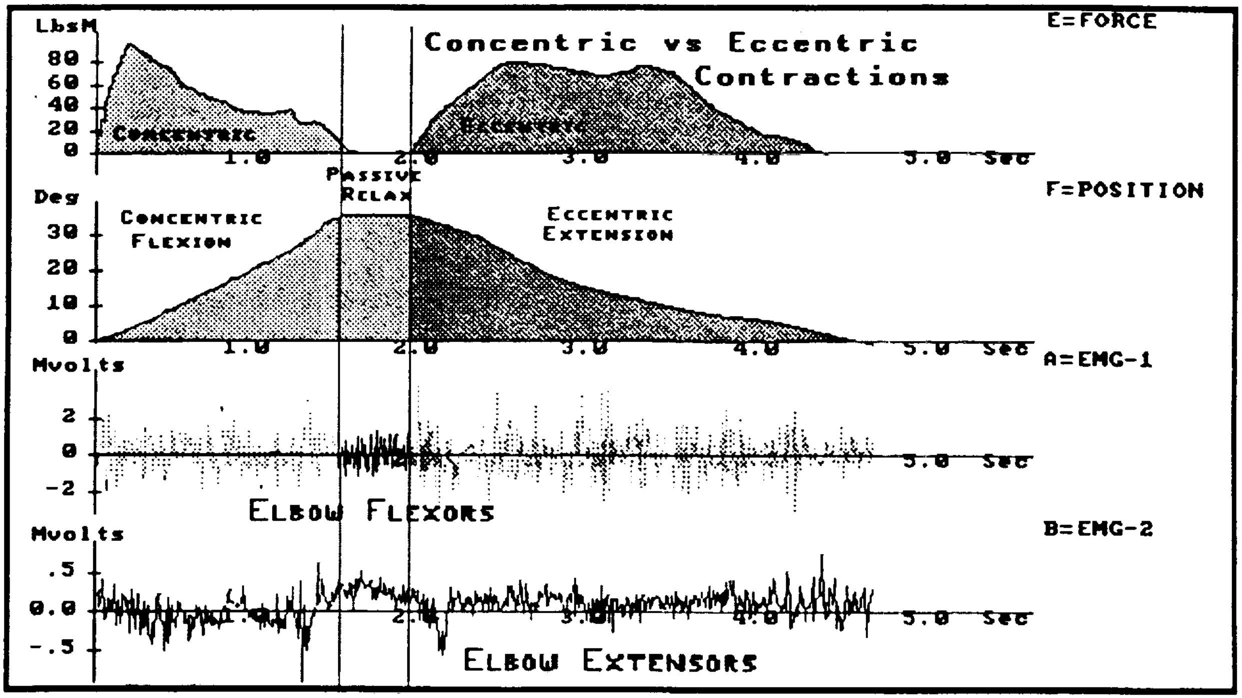


Figure 40

Figure 39 presents a typical force curve throughout the range of movement. Figure 40 shows the force and displacement curves as well as the corresponding EMG curves from the flexors and extensors of the elbow in the concentric and eccentric phases.

When a subject applies muscular force to an external device, a few factors must be considered. The first factor is the pattern of velocity. In this situation, the movement began ate "0" velocity, accelerated to the assigned velocity, and the equipment recorded the velocity of the mechanical bar. This is a very important factor since much of the previous research reported in the literature was conducted with isokinetic type equipment which did not report the instantaneous velocity throughout the range of movement but rather yielded an average quantity. This means that at an assigned velocity of 100 degrees per second beginning from a point of zero velocity, the investigators would be unable to determine the time it took to reach the designated velocity and at what point the segment returned to "0" velocity.

This limitation was overcome in the present experiment by selecting a different measurement device. Examination of Figure 41 illustrates a control curve with the velocity programmed to be 25 degrees per second in the flexion direction and 125 degrees per second in the extension phase. As can be seen, the subject needed approximately 5 degrees before reaching the selected velocity of 25 degrees per second and the subject never attained the 125 degrees per second during the extension phase.

Controlled velocity curves with data throughout the range of motion were recorded in the present set of studies. In addition to the velocity curve data, a second factor which must be considered is the acceleration pattern. In other words, consideration must be given to the amount of acceleration needed to achieve the required speed. When acceleration occurs, there are inertial forces affecting the movement. Even if the subject does not reach the assigned velocity, force is created by the muscle and is related directly to the level of acceleration. In

Figure 41, although the subject did not reached the velocity assigned during the extension phase, a force curve was calculated. It can be seen in the flexion phase that the velocity was reached and, therefore, the force level was measured to approximately 50 pounds. In the downward direction, due to acceleration of the bar, a force of approximately 25 pounds was achieved during the acceleration phase and then dropped to 0 during the deceleration phase.

The ability to report displacements, velocities, and accelerations throughout the range of movement is essential for the correlation of test results. For instance, two different subjects exercising under the same condition may yield different force curves results due to the pattern of their movement. Figure 41 shows different force curves resulting from different levels of acceleration with the same assigned condition of 25 degrees per second in the flexion and 125 degrees per second in the extension phases. Obviously, EMG activity will vary significantly depending upon these conditions. Figure 42 illustrates that in a high speed exercise, it takes time to reach the assigned velocity as it cannot be attained instantaneously.

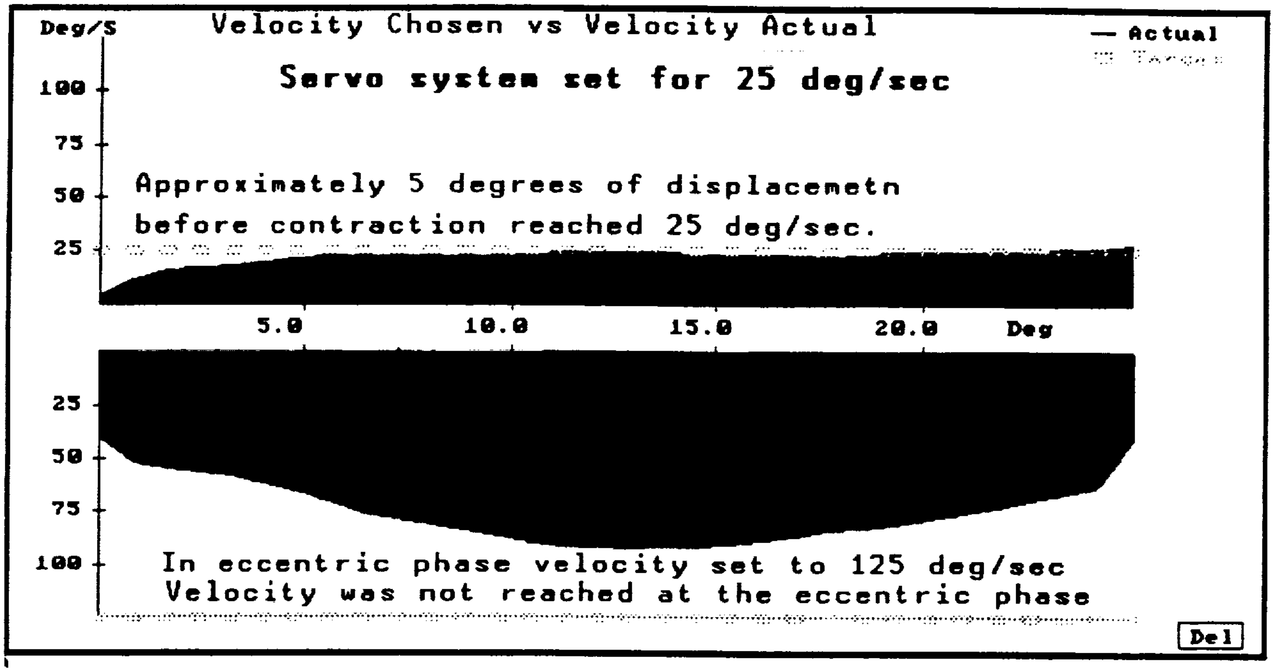
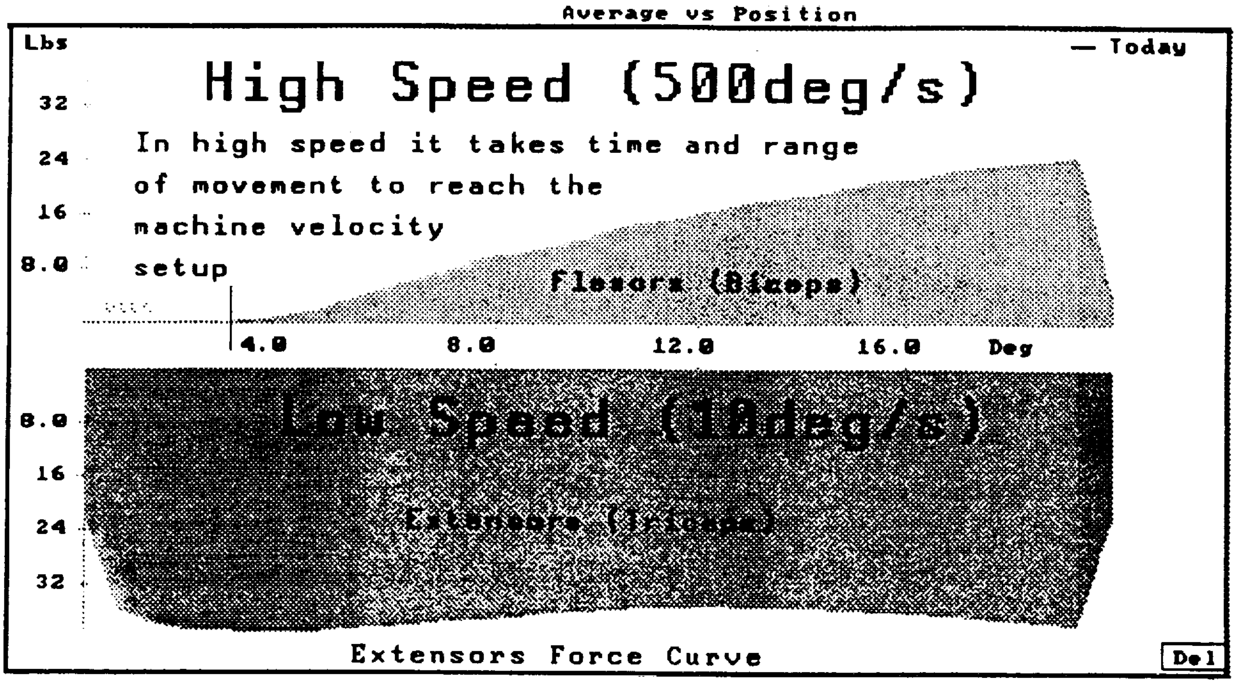


Figure 41

Condition Three - Submaximal Concentric Eccentric Contractions:

In this procedure, the subjects flexed the elbow concentrically to maximum flexion, paused approximately one second at the end of the range, and then the machine applied a submaximal force to extend the subject's arm so that the elbow extended. The subject tried to resist this extension against the active force of the machine. The machine mechanism moved the bar at a given velocity at a very high force, thus, preventing the subject from stopping the bar's movement. Since the velocity was controlled at a given speed, the subject was able to sustain the movement without injury. As in the previous study, the machines mechanism used was providing limited force to prevent injury. In the present study, the force applied was to exceed the ability of the subject to resist it by at least 500 percent. The only safeguard against injury was the fact that the bar moved at manageable velocities.



In high speed it takes time and range of movement to reach the machine velocity setup

Figure 42

Figure 39 illustrates the concentric phase followed by the eccentric phase. The concentric phase by the flexors illustrates the same typical results as previously observed. In the eccentric phase, Figure 40 illustrates the displacement curve as well as the EMG activity of the flexors and the extensors. One can observe that in both the concentric and the eccentric phases, the flexors and extensors demonstrate EMG activity. As expected, the flexors demonstrate higher activity. It is interesting to note that during the passive rest phase, the extensors EMG shifted above the base line. Also, at the onset of extension, the extensors exhibited a sharp negative spike. This may indicate the result of a pre-stretch reflex which augmented the antagonistic muscle, the extensors, at the beginning of the eccentric contraction.

Figure 43 illustrates a typical concentric eccentric combination utilized in this experiment. The force curves, the displacements, and the EMG activities are presented. One of the goals of this experiment was to determine if the firing characteristics of the extensors and/or the flexors change during the concentric and/or eccentric phases. A typical result is presented in Figure 44. A fast Fourier Transformation revealed that the frequency characteristic of the EMG signal did not change for the same muscle group during the concentric and eccentric contractions. However, the amplitude of the EMG signal did vary. Amplitude is referred to as "power" and the power of the EMG activity measured in the current study did change. Higher power signals were observed during the eccentric contractions.

A third factor to consider provides information about the EMG activity and this is known as the "value reset integration". A value reset integration provides insight into the relationships of the EMG activity between the two phases of contractions. A specific level of EMG activity was set in this study as 100 millivolt seconds for the value reset integration. The reason for the selection of this type of integration was to determine if the activity level changed during the time of contraction for the concentric and eccentric phases.

Figure 45 illustrates a typical concentric and eccentric contraction with the associated displacement, raw EMG and value reset integration for the flexor and extensor muscles. As can

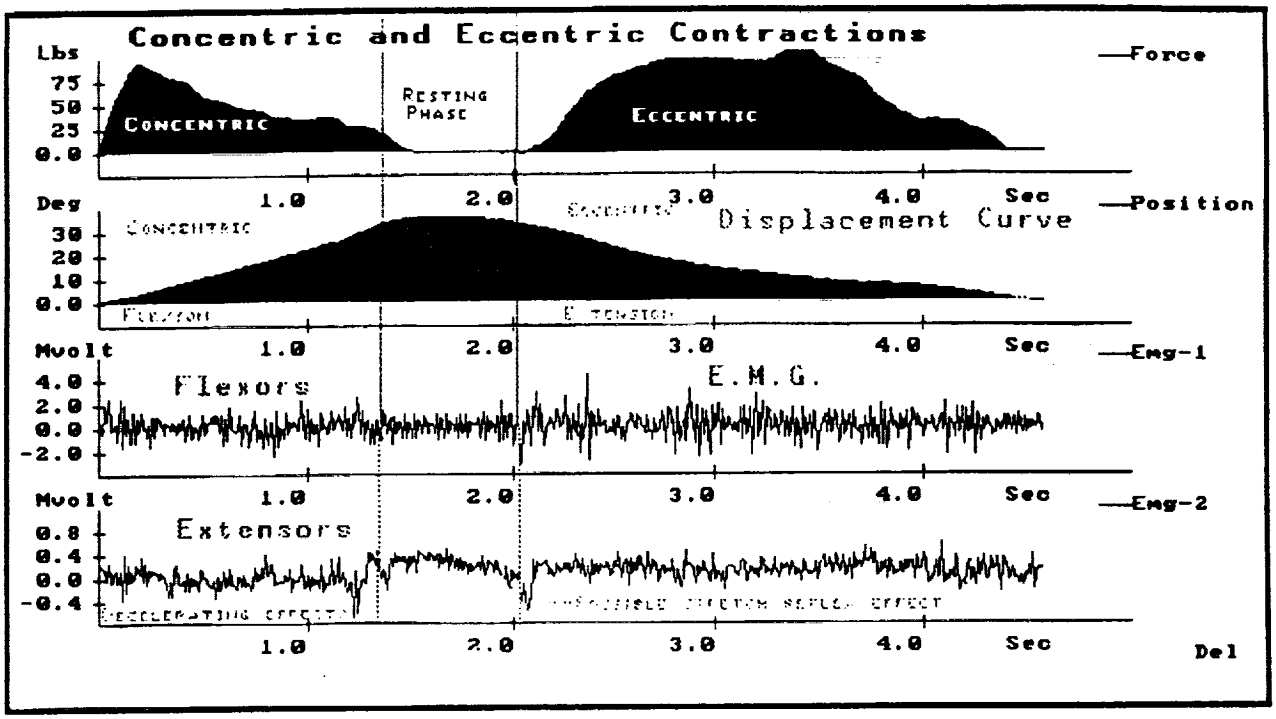


Figure 43

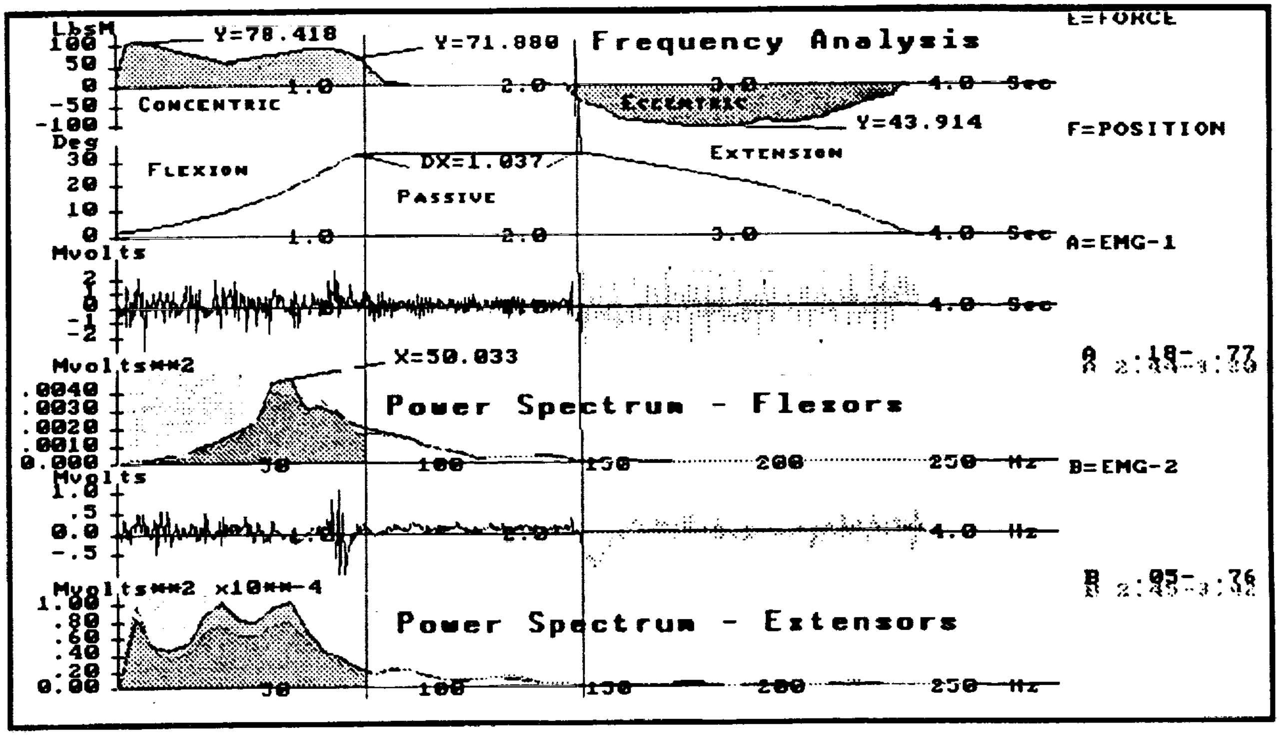


Figure 44

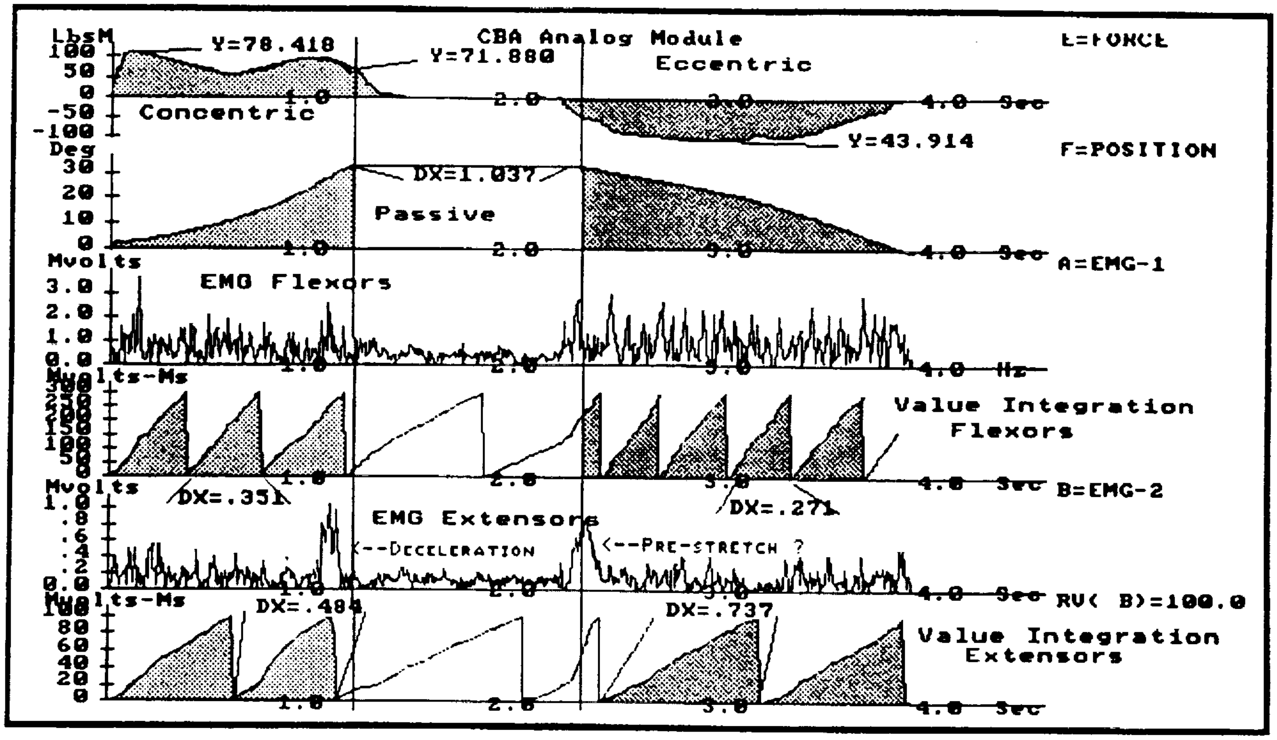


Figure 45

be seen in this Figure and, in general for all cases, the flexors were more active during the concentric phase as indicated by the shorter time required to reach a particular EMG level of activity indicated by the area under the integral curves. In the eccentric phase, the value integration of the flexors muscles shows even more activity as indicated by the smaller time interval to reach the chosen value for the reset integration of the EMG activity. However, the extensors muscles indicated less activity to reach the selected level of EMG activity as revealed by the longer base line. This phenomenon was repeated in most of the super maximal eccentric contraction trials. When measuring the same parameters during sub-maximal eccentric contractions, the extensor activity did not change significantly but the flexors showed less activity.

DISCUSSION

The present studies show that during dynamic contractions, whether concentric or eccentric, there is a control mechanism which simultaneously regulates the amount of EMG firing in the flexors and extensors. The level of activity appears to be regulated by some higher level neural control program. The net effect is responsible for the level of force produced in each movement.

It seems that there are differences between maximal and submaximal eccentric contractions. In the maximal eccentric contraction, where the external force was significantly greater than that generated by the muscle, a regulator mechanism was initiated so that the activity level of the antagonistic reduced, thus, enabling the agonist to perform in a more efficient manner. That is to say, the antagonistic effect was reduced in order to allow better "net" activity by the agonist. By reducing some of the antagonistic muscle activity, the agonist force produced a greater net moment. However, if the individual continues to try to overcome a large externally applied force, the net force may reach a level where internal injury to the tissue occurs. This situation can only occur in an eccentric condition.

When the eccentric contraction was sub-maximal, the antagonistic activity was not effected. In that situation, the elongation of the agonist muscle was achieved by "progressive relaxation" as the number of motor units firing decreased as indicated by the level of EMG and the force associated with this type of contraction.

It appears that eccentric contractions should be classified as two types. In both cases, the agonist is elongated during a dynamic contraction. In the case with a super-maximal external resistance, the regulatory mechanism of the agonist-antagonist relationship "turns off" or reduces some of the antagonistic activity allowing the agonist to exert a greater net moment. In the case of the sub-maximal eccentric contractions, the relationship of force production is changed by simply "turning off" some of the agonist muscle and progressively relaxing the amount of agonistic activity and allowing the limb to extend.

When examinating activities, such as walking and running, it appeared that the body tended to use progressive relaxation to achieve the proper level of shock absorption and gait efficiency. However, in a task involving jumping from a height in excess of 3 feet, it seemed that this mechanism gradually changed to a maximum eccentric contraction. An activity such as high jumping would probably incorporate both types depending on the intensity of contraction and external resistance.

Application to Training:

The literature is filled with contradictory findings concerning the muscular strength level which can be achieved with both methods of training, eg. concentric and eccentric. There seems to be a "carry over" effect regardless of the system of training whether concentric, eccentric, or a combination of the two.

Based on the literature and the experimental findings presented here, this author believes that for efficient and safe training, exercise should be done concentrically. This assures neuromuscular regulation of the desired movement. If one elects to train eccentrically, these exercises should be performed only at super-maximal contraction levels which will produce a higher net moment. Any level lower then the super-maximal will result only in progressive relaxation of the agonist muscle. A complete training regimen should include exercises with the body weight utilized in a way that mobilizes the parallel and serial connective tissues to absorb elastic energy and to maintain a full range of motion for each joint. These types of exercise necessitate eccentric contractions at some level; however, at a maximal resistance level, the risk of injury increases significantly.

Training should always include the natural movements of the human body. The body will not gain maximum benefit with training on mechanical machines which cannot reproduce the number of degrees of freedom the body requires for movement. Therefore, a healthy exercise program should include running, jumping, gymnastics, calisthenics, swimming, and rhythmic activities. These essential programs can be supplemented with exercise machines which, preferable, possess artificial intelligence to evaluate and coordinate the program.

In the particular situation of microgravity, in order to simulate "natural" resistance to the body, only a machine can perform adequately to stimulate the desired responses in an "artificial" environment. An exercise device properly designed should be able to accommodate the limitations of microgravity, since the body can be restrained in its environment and can execute activities providing high resistance externally thereby simulating exercise in 1-G condition.

Needless to say, more research is needed to determine the ideal training conditions for people to achieve the most efficient fitness level for performing specific activities on earth and in microgravity conditions.

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