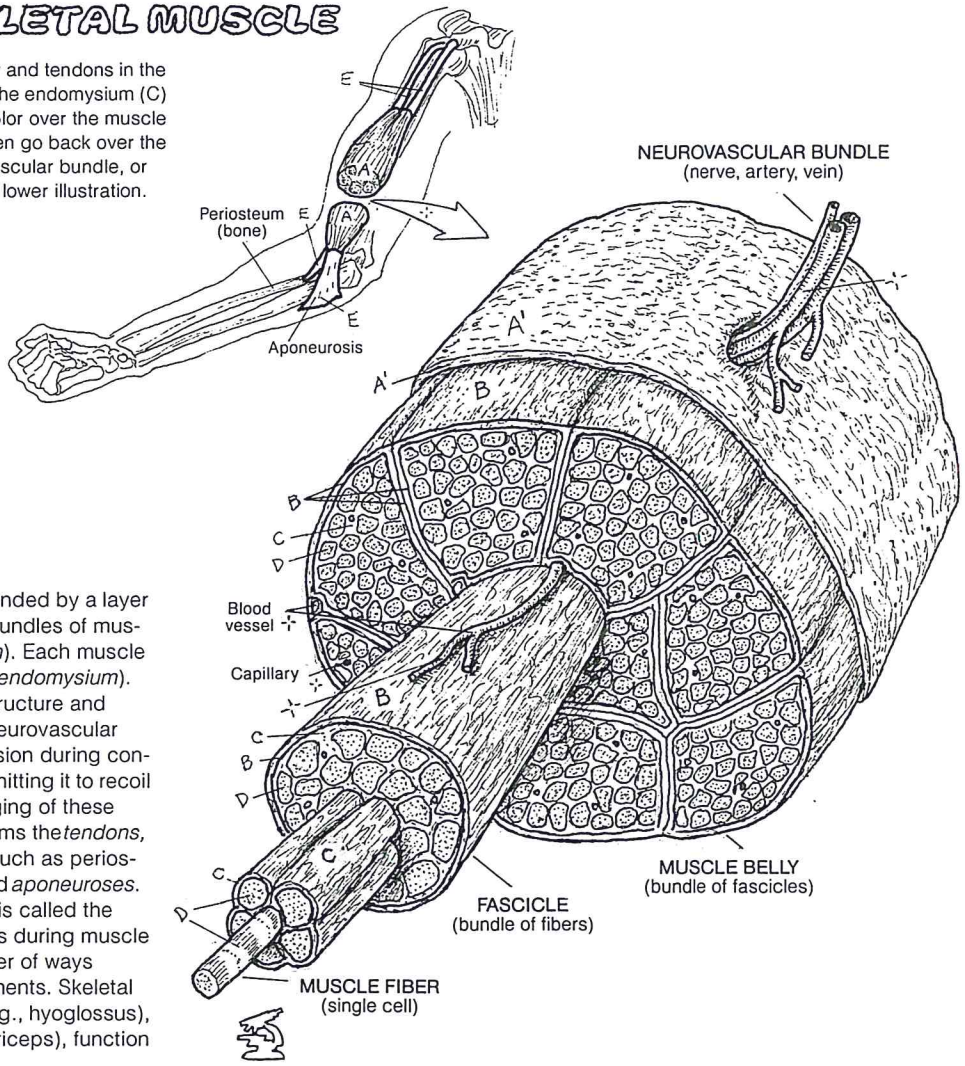
INTRODUCTION TO SKELETAL MUSCLE

CN: Use light colors for A–E. (1) Begin with the muscle belly and tendons in the upper illustration. (2) When coloring the narrow borders of the endomysium (C) in the enlarged section, it is recommended that you also color over the muscle fiber ends (D) with the very light endomysium color, and then go back over the fiber ends with a darker color (D). Do not color the neurovascular bundle, or the cut ends of blood vessels and capillaries. (3) Color the lower illustration.



SKELETAL MUSCLE

- BELLY (A)
  - FASCIA:
    - EPIMYSIUM (A')
    - PERIMYSIUM (B)
    - ENDOMYSIUM (C)
  - MUSCLE FIBER (CELL) (D)
- TENDON (E)

A named skeletal muscle (e.g., biceps brachii), surrounded by a layer of deep fascia (*epimysium*), consists of fascicles or bundles of muscle fibers enveloped in thin fibrous tissue (*perimysium*). Each muscle fiber is surrounded by a thin sheath of fibrous tissue (*endomysium*). Each of these fibrous layers is important to muscle structure and function, providing support for nerves and vessels (neurovascular bundles), ensuring uniform distribution of muscle tension during contraction, and maintaining the elasticity of muscle, permitting it to recoil to its resting length following stretching. It is the merging of these fibrous layers at the ends of the muscle fibers that forms the *tendons,* which integrate the muscle to its attachment site(s), such as periosteum or another tendon. Broad, flat tendons are called *aponeuroses.* The mass of the fasciae-enveloped contractile fibers is called the *belly* of the muscle. It is the muscle belly that shortens during muscle contraction. The belly may be shaped one of a number of ways depending on its tendinous arrangement and attachments. Skeletal muscles are named in relation to their attachments (e.g., hyoglossus), shape (e.g., trapezius), number of heads (e.g., quadriceps), function (e.g., adductor magnus), or position (e.g., brachialis).

MECHANICS OF MOVEMENT

- FULCRUM (F) (JOINT) (F')
- EFFORT (A) (MUSCLE) (A)
- RESISTANCE (G) (WEIGHT) (G')

Skeletal muscles employ simple machines, such as levers, to increase the efficiency of their contractile work about a joint. Mechanically, the degree of *muscular effort* required to overcome resistance to movement at a *joint* (*fulcrum*) depends upon the force of that resistance (*weight*); the relative distances from the anatomical fulcrum to the anatomical sites of *muscular effort*; and the anatomical sites of *resistance* (joints). The position of the joint relative to the site of muscle pull and the site of imposed load determines the class of the lever system in use.

1ST CLASS LEVER

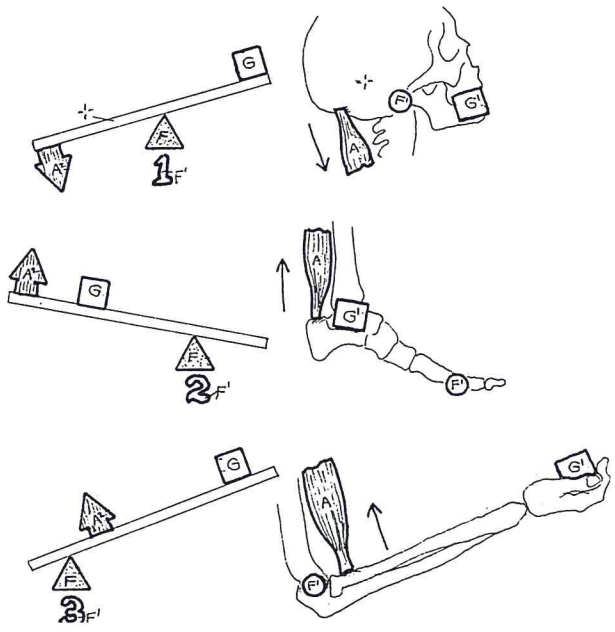
In a 1st class lever, the joint lies between the muscle and the load. This is the most efficient class of lever. By flexing the neck and posturing the head forward and downward, the load (G^1) is appreciably increased (due to gravity), and the muscular effort (A) to hold that posture may induce muscle pain and stiffness/tightness (overuse).

2ND CLASS LEVER

In a 2nd class lever, the load lies between the joint and the pulling muscle. This lever system operates in lifting a wheelbarrow (the wheel is the fulcrum) as well as lifting a 75 kg (165 lb) body onto the metatarsal heads at the metatarsophalangeal joints. This is a relatively easy task for the strong calf (triceps surae) muscles; but try standing on the heads of your middle phalanges (increasing the distance F^1–G^1)!

3RD CLASS LEVER

In a 3rd class lever, the muscle lies between the joint and the load and has a poor mechanical advantage here. Consider the difference in muscular effort required to carry a 45 kg (100 lb) bag of cement in your hands with flexed elbows (elbow joint: 3rd class lever) and carrying your 75 kg (165 lb) body on the heads of your metatarsals (2nd class lever at the metatarsophalangeal joints). It is all a matter of leverage.



THE STRUCTURE OF SKELETAL MUSCLE

The beat of the heart, the blink of an eye, the breath of fresh air — these obvious signs of life are all brought about by muscular contraction: How do muscles shorten? Something "inside" must move, but what? Years ago, many physiologists believed that muscles contract because the proteins of which they are made actually shorten, either by folding or by changes in the pitch or diameter of helical molecules. In the 1950s, they were startled to discover that this is not the case at all. True, the contractile machinery is made of protein, but contraction does not occur by protein folding; rather than changing their dimensions, the proteins simply slide past each other and change their relative positions.

An important clue came from early studies of the striped pattern of living skeletal muscle that could be seen under the light microscope. The stripes are localized in long fibrous cylinders called *myofibrils* that run the length of the muscle cell. The muscle cell contracts because the myofibrils contract; they contain the contractile machinery. Each myofibril is punctuated with alternating light and dark bands called *A and I bands*. These bands are "lined up" so that an A band on one myofibril is closest to an A band on its neighbor. When you look at the whole cell, you see stripes instead of a checkerboard. When a muscle contracts, the I band shortens, but the A band does not change size. The mystery of contraction seemed to reside in the I band. Soon after the electron microscope became available, however, a new picture emerged.

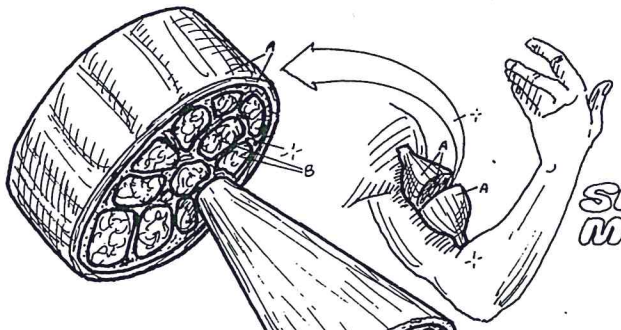
Examination with an electron microscope reveals that each myofibril contains many fibers called *filaments*, which run parallel to the myofibril axis. Some filaments, the thick ones, are confined to the A band; the other, thinner ones seem to arise in the middle of the I band, at the *Z line* (a structure that runs perpendicular to the myofibril through the I band, connecting neighboring myofibrils). The thin filaments run the course of the I band and partway into the A band, where they overlap (interdigitate) with the thick filaments. The next step is to identify the filaments with the contractile machinery.

The chemical identity of the filaments can be determined by using concentrated salt solutions that selectively extract muscle proteins. When the protein called *actin* is extracted, the thin filaments disappear, and when the protein called *myosin* is extracted, the thick filaments disappear. Moreover, when the cell membrane is destroyed and substances other than these two proteins are leeched out, the thick and thin filaments remain intact, and the muscle can still contract (if it is provided with ATP as an energy source). These results imply that the thick and thin filaments are the *contractile machinery* and that the thick filaments are made of myosin, and the thin ones are actin.

Returning to interpret the muscle stripes, we now have a thick A band consisting of a lighter middle region (the *H zone*) with denser regions on each side. The denser edges are where thick myosin and thin actin filaments overlap; the middle (H zone) contains only myosin. The I bands contain only actin. Whenever a muscle or myofibril changes length, either by contracting or stretching, neither myosin nor actin filaments change length, yet they are the contractile machine! It follows that they must slide past each other, increasing their area of overlap during contraction and decreasing it during stretching. During contraction, the I band decreases as more and more of the actin filaments are "buried" in the region of overlap with myosin. The A band cannot change because it represents the length of the myosin filaments, which are invariant. However, if this picture is correct, you might expect the H zone to decrease upon contraction and lengthen on stretching. It does.

Because the motive force for contraction is provided by actin and myosin filaments sliding together, there must be some "connecting" elements that allow them to interact. These are the *cross bridges*, taken up in plate 19.

CN: *Use dark colors for G and H.*
1. Begin at the top with skeletal muscle (A) and work your way down the right side of the page to its molecular components. Note that the end surface of each cylindrical example receives the color of its components. In the case of the myofibril (D), only the title and the myofibrils making up the end of the cell (C) receive the color D. The length of the myofibril receives the colors of the various bands of contractile elements.
2. Color the diagrams of the contractile elements on the left side of the page. Note that the first diagram attempts to show how the two kinds of filaments actually make up the bands you previously colored. Note that the thin filaments (E) actually penetrate the A band. This wasn't shown in the drawing of the myofibril on right. Note too, that the lower two diagrams represent a vertical enlargement (in order to show cross bridge activity) of the upper diagram, but not a horizontal enlargement (the Z lines (H) still coincide with the upper diagram).



SKELETAL MUSCLE$_A$

40% BODY WEIGHT$_A$

BUNDLE OF FIBERS$_B$

Whole muscles are made of bundles of cylindrical striated cells called fibers.

CELL (MUSCLE FIBER)$_C$

Cells (muscle fibers) range from 5 to 100μ in diameter but may be several thousand times longer as they extend from one bone to another.

MYOFIBRIL$_D$

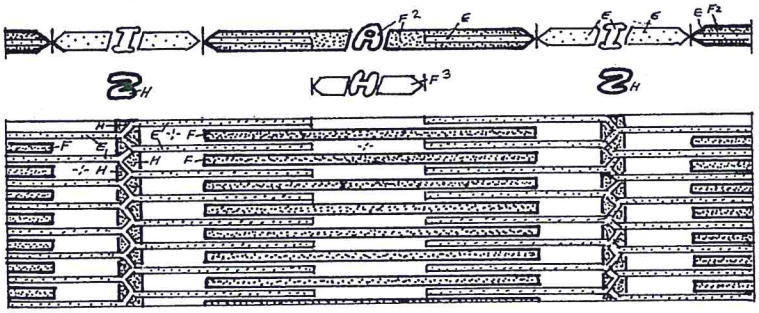
Hundreds of banded cylindrical myofibrils run the length of each cell; they are the contractile elements of the cell.

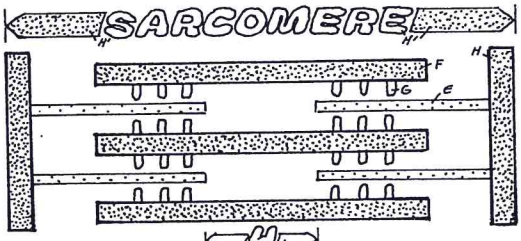
CONTRACTILE ELEMENTS*

A BAND$_{F^2}$
THICK FILAMENT$_F$
CROSS BRIDGE$_G$
I BAND$_{E^2}$
THIN FILAMENT$_E$
H ZONE$_{F^3}$
Z LINE$_H$
SARCOMERE$_{H'}$

Myofibrils are composed of repeating dark A and light I bands which are responsible for the striations (stripes). Electron microscopy shows finer detail as illustrated in the lower two diagrams; each fibril is composed of thick and thin filaments. Thick filaments run the length of the A band; thin filaments run through the I band and peripheral portions, but not the central H zone, of the A band. Thin filaments are anchored in the center of the I band by the Z line. That portion of the myofibril (2.5μ long) between the two Z lines is called a sarcomere. Thick and thin filaments interact through cross bridges which are bud-like extensions of thick filaments. The cross bridges are given a separate color for identification purposes.

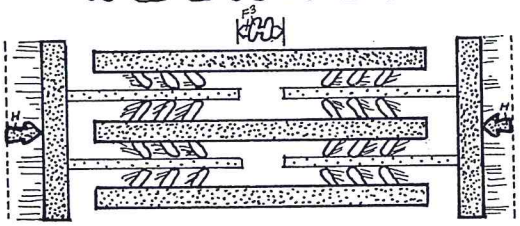
When living muscle contracts, the I band shortens, the H zone shortens, but the length of the A band does not change. Thus, neither thick nor thin filaments change length; they simply slide past each other increasing the area of overlap.





SARCOMERE$_{H'}$

RELAXED$_{H'}$



CONTRACTED$_{H'}$

ACTIN FILAMENT (THIN)$_E$

Thin filaments are highly ordered assemblies of protein molecules called actin.

MYOSIN FILAMENT (THICK)$_F$

Thick filaments are highly ordered assemblies of protein molecules called myosin.

ACTIN MOLECULE$_E$

Actin molecules are pear shaped (approx. 4nm in diameter). In thin filaments they are joined together like two strings of beads intertwined at regular intervals. (Note: Thin filaments also contain other proteins in addition to actin).

MYOSIN MOLECULE$_{F'}$

Myosin molecules have long (160nm) rod-shaped tails with globular heads. The heads form cross bridges between thick and thin filaments.

CROSS BRIDGES & SLIDING FILAMENTS

In relaxed muscle, the *cross bridges* are detached from *actin filaments*. During contraction, they attach and provide the contractile force. How does this come about? *Thick filaments* are ordered assemblies of *myosin* molecules; each molecule contains a long rod-shaped tail, a shorter rod-shaped neck, and two globular heads, which form the cross bridges. Only one head is shown in the drawings. (The signficance of the second head is not known.) There are two flexible *hingelike* regions. The hinge closest to the thick filament, between tail and neck, allows the cross bridges to attach and detach from the actin filament. The hinge next to the globular head allows the head to tilt. This tilt is the *power stroke*; it is responsible for propelling the actin a distance of about 75 nm relative to myosin. Following the power stroke, the bridge detaches and then repeats the cycle farther upstream. The cycles of individual bridges are not synchronized as shown. They are out of phase, some attaching while others are detaching. Thus, at each moment, some of the cross bridges are entering the "power stroke" while others leave. The movement is not jerky, and there is no tendency for the filaments to slip backward.

Gross muscle movements are brought about by a cyclic reaction of the cross bridges: *attachment* (to actin)→*tilting* (producing movement)→*release attachment*→etc. By repeating the cycle many times the small movements add up to the smooth, coordinated, macroscopic motions we all enjoy. But cyclic reactions cannot occur without an energy source (if they could, we would be able to build perpetual motion machines). Further, muscle can do physical work (i.e., lift a weight), and work requires energy. The immediate source of this energy is *ATP*. When we incorporate ATP in our scheme the details of each cycle become more complex as we are able to distinguish more steps. These are shown in the set of diagrams at the bottom of the page. Attachment of ATP to the myosin head groups allows the myosin heads to release the actin. Further, a *"high-energy" phosphate* is transferred from the ATP to the myosin, which becomes "energized," while the original ATP, having lost a phosphate, becomes *ADP*. The energized cross bridge is now ready for action. If the muscle is stimulated, the cross bridge will attach to the actin, tilt, and move the actin along (the *power stroke*). Following the power stroke, the myosin and actin remain attached until the beginning of the next cycle, when ATP once again binds, releases the attachment, and energizes the myosin cross bridge. Note that if ATP has been used up, the myosin heads will remain locked to the actin filaments, and no sliding can take place. The muscle will become rigid, resisting both contraction and stretching. This is the condition known as *rigor mortis*, which is common after death when ATP has degenerated. Also note that ATP splitting is not directly involved in the power stroke. Its energy is used to "prime" the myosin head so that it can attach to the myosin and repeat the cycle.

If ATP is present, why doesn't the muscle continue to contract until all the ATP is used up? The answer involves an additional substance, Ca^{++}, which is required for the attachment phase of the cycle. If sufficient Ca^{++} is present, attachment can occur; at lower levels, it cannot. The action of Ca^{++} as a trigger for contraction and its removal for relaxation are taken up in plate 20.

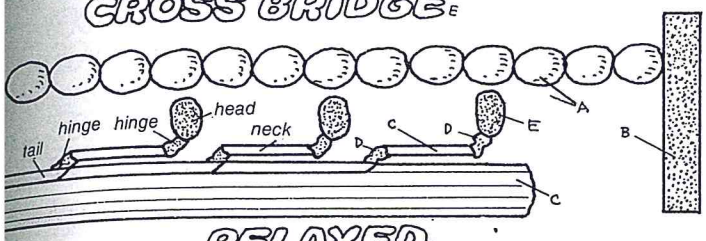
CN: *Use the same colors as on the previous pag for actin (A), Z line (B), myosin (C), and cross bridge (E). Use a bright color for F and I, and a dı color for G.*

1. Begin with the diagram in the upper right corne of the contractile mechanism of a myofibril. Then color the details on the left showing how cross bridges operate to cause contraction.

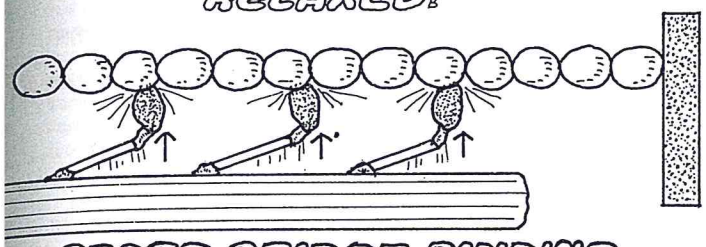
2. Color the diagram explaining the cross bridge orientation of the myosin filament. Color the entire myosin filament (including the bare zone).

3. Color the cycle of energy transfer and contraction after coloring the formula at the top of the panel.

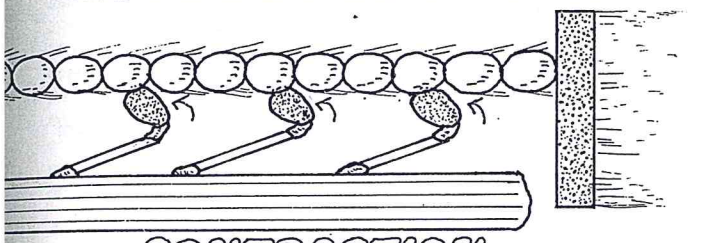
THIN FILAMENT (ACTIN)A
Z LINEB
THICK FILAMENT (MYOSIN)C
FLEXIBLE HINGED
CROSS BRIDGEE



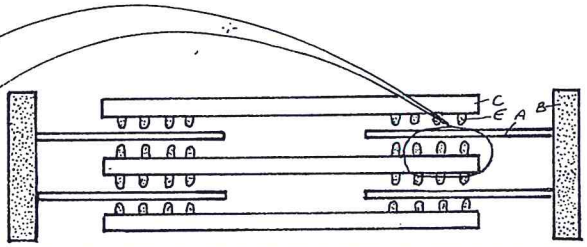
RELAXEDB



CROSS BRIDGE BINDINGE

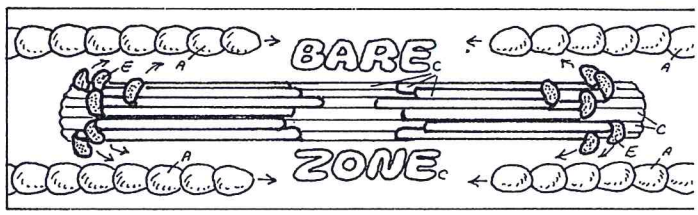


CONTRACTIONB



HOW FILAMENTS SLIDE*

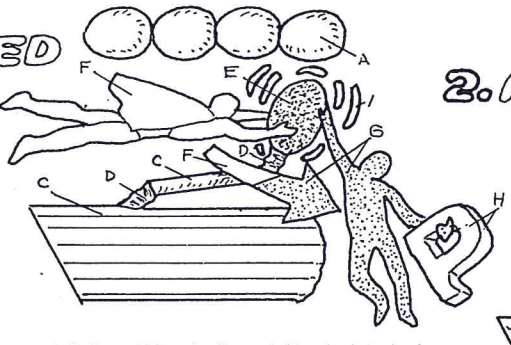
In relaxed muscle the cross bridges are detached from actin filaments. During contraction they attach and provide contractile force. Thick filaments are made of myosin molecules; each molecule contains a long rod-shaped tail, a shorter rod-shaped neck and 2 globular heads which form the cross bridges (only one head is shown). There are two flexible hinge-like regions. The hinge between tail and neck allows the cross bridge to attach and detach from the actin filament. The hinge next to the globular head allows the head to tilt. This tilt is the power stroke. But, how do cross bridges on each side of the H zone "know" which way to tilt? The diagram below shows that the middle of the thick filaments is bare with no cross bridges. Myosin molecules on one side of the bare zone are oriented in one direction, those on the other side in the opposite direction. Since the heads always tilt towards their tails, they always propel actin filaments on each side of the H zone in the proper direction. Actin molecules are also oriented in their chains; actins on each side of the Z line "point" in opposite directions — this helps coordinate contraction.



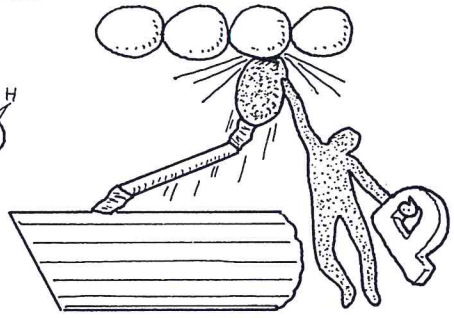
ENERGY FOR CONTRACTION*

ATP → ADP + PHOSPHATE + ENERGY

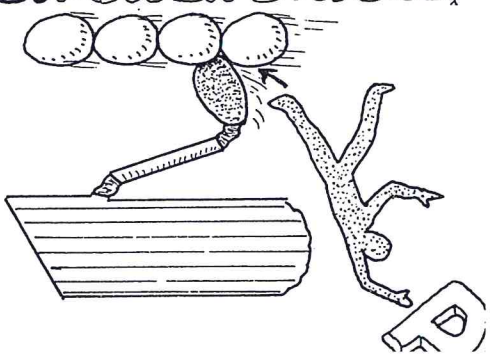
1. RELAXED MUSCLE*



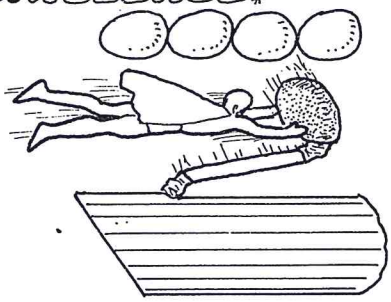
2. ATTACHMENT*



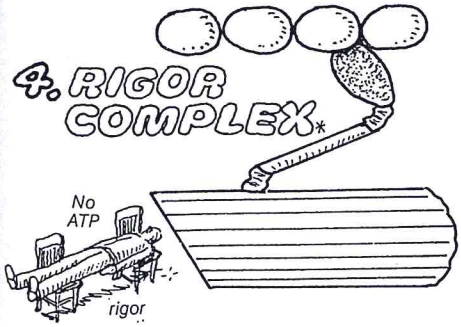
3. POWER STROKE*



5. RELEASE*



4. RIGOR COMPLEX*



1. Relaxed Muscle: *Cross bridge is detached. Although the muscle is relaxed, the cross bridge is in a high energy state which results from the prior binding and splitting of ATP. The products ADP and P_i remain bound to the myosin head which is "cocked" and ready for action.* 2. Attachment: *Contact is made. The cross bridge with bound ADP and P_i attaches to actin.* 3. Power Stroke: *Interaction of actin and myosin promotes: (a) release of energy; the head tilts and propels actin filament, (b) release of ADP and P_i.* 4. Rigor Complex: *The cross bridge is stuck to actin, but only momentarily.* 5. Release: *ATP binds to the myosin head, allowing the head to be released from actin and making the muscle pliable. ATP is then split, energizing the cross bridge and the cycle repeats (Go to 1). If no ATP is available, crossbridges remain stuck to actin and the muscle becomes "stiff." This is the rigidity of rigor mortis which follows death.*