Experiment demonstrating skeletal muscle biomechanics.

S E DiCarlo, E Sipe, J P Layshock and S Varyani

You might find this additional info useful...

Updated information and services including high resolution figures, can be found at:
/content/275/6/S59.citation

Additional material and information about *Advances in Physiology Education* can be found at:
http://www.the-aps.org/publications/advan

This information is current as of June 3, 2014.

EXPERIMENT DEMONSTRATING SKELETAL MUSCLE BIOMECHANICS

Stephen E. DiCarlo, Eilynn Sipe, J. Paul Layshock, and Sandhia Varyani

Department of Physiology, Wayne State University, School of Medicine, Detroit, Michigan 48201

Many students have limited opportunities to develop scientific expertise. This is caused, in part, by the scarcity of scientific educational materials and the expense of supplies and equipment. To address these concerns, we developed an inexpensive laboratory experience that introduces students to the scientific process. Our objective was to create an interactive experiment that requires minimal equipment. To this end, we created an exercise that examines muscle biomechanics. The students conduct a hands-on experiment as researchers and as subjects by investigating the physiological concepts of muscle biomechanics using only supplies that can be found at any school. Questions are interspersed throughout the text to highlight key principles and challenge student thinking on the important concepts. This exercise not only provides an opportunity for students to interact and discuss the important physiological principles but also provides a window through which students may see a future in science.

AM. J. PHYSIOL. 275 (ADV. PHYSIOL. EDUC. 20): S59–S71, 1998.

Key words: science education; muscle contraction; dry laboratory; sliding filament theory

Educators have recently recognized the developing deficiencies in science and mathematics education in our students. These deficiencies threaten the development of competitive scientific expertise. Without the proper training of the future work force, the effect on the economy, society, and our standard of living will be detrimental. Therefore, it is in the best interest of our nation to raise the level of education of all its citizens in an effort to meet the demands of a changing society. One limiting factor is the availability of appropriate science educational materials.

Circumstances exist in many schools that limit the availability of educational material in the field of physiology, such as insufficient funding and equipment and lack of instructor experience. These circumstances inspired us to create a laboratory experience in physiology designed to introduce students to muscle biomechanics. This exercise presents a means by which instructors and students can work together toward understanding basic physiological concepts and can enhance science and mathematics expertise. The students are given a text of information on muscle biomechanics and a laboratory experiment that incorporates the material into an educational experience. The laboratory requires active participation by the students that will aid in reinforcing the material. The only equipment required for this experience are weights, which may be borrowed from the athletic facility at the school.

To begin, the instructor must select volunteers who will act as subjects. We recommend choosing students who vary in strength to allow for a comparison of data at the conclusion of the exercise. Each subject is assigned to a group of students who play the role of

researchers in completing the exercise. Students in the groups must work together for accurate data collection, completion of tables and graphs, and to help the subject when adding and removing weights. Questions are interspersed throughout the text and exercise to provide a source for further understanding and analysis of the basic physiological concepts.

Our goal in creating this exercise was to promote the understanding of muscle biomechanics through an enjoyable and interactive laboratory experience. We also hope to create a sense of inspiration for future scientific studies.

LABORATORY EXERCISE

The following exercise involves five experimental protocols. The students are challenged to obtain data from human subjects and to analyze and interpret these data by creating graphs and performing calculations to complete tables. The laboratory protocols are modifications of an experiment from a recently published laboratory manual (1).

Objectives

The objectives of this exercise are *1*) to observe the moment of force of the biceps muscle through a range of elbow flexion and *2*) to calculate the moment of force needed to hold a weight through a joint's range of motion.

Materials Needed

This exercise requires a variable-weight one-arm curling bar and a set of free weights (it is essential to have a weight set that can be increased in small increments).

Background and Key Terms Related to This Exercise

Questions are integrated throughout the text as a source of discussion and understanding of key points. Questions with arrows (→) review material presented in the previous passage; questions with asterisks (**) are used to provoke thought on upcoming passages.

Skeletal muscle is a very organized tissue. The entire muscle is composed of individual muscle fibers, which are made up of smaller units called myofibrils. Actin and myosin filaments, the components responsible for muscle contraction, make up the myofibrils. Each myofibril is made up of ~1,500 myosin filaments and 3,000 actin filaments. The organization of actin and myosin filaments forms a banded pattern that can be seen under a microscope. Figure 1 represents a myofibril section of a skeletal muscle. The darker bands represent the area of the myofibril that contains actin and myosin side by side. Light bands represent the area of the myofibril that contains only actin. Actin and myosin are polymerized proteins; their interaction produces muscle contraction.

There are two main determinants of muscle strength. The first is the length-tension relationship that is based on the interaction of the microscopic actin and myosin fibers. The biomechanics of the musculoskeletal system is the second component. The length-tension curve of a muscle fiber demonstrates that each muscle fiber has an optimal length generating maximal force. However, this length does not correspond to the most advantageous position according to the biomechanics of our muscles, bones, and joints. The following experiment will examine how these two factors affect our movements and strength.
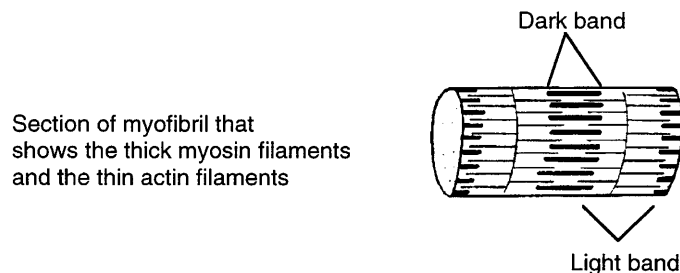
Dark band

Section of myofibril that shows the thick myosin filaments and the thin actin filaments

Light band

FIG. 1.
A myofibril section of skeletal muscle. Dark bands contain actin and myosin filaments side by side. Light bands contain only actin filaments.
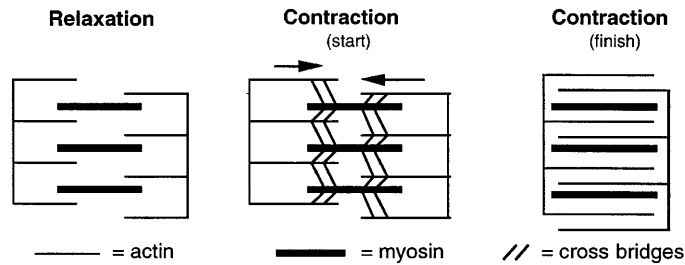
FIG. 2.
Sliding filament theory of muscle contraction in which actin filaments slide over myosin filaments.

Muscle contraction is explained by the sliding filament theory. Cross bridges originating on the myosin filament attach to the actin. The cross bridges pull the actin filaments across the myosin in a step called the power stroke. The actin filaments slide over myosin, thereby shortening the muscle fiber and producing a muscle contraction (Fig. 2). During the contraction, myosin filaments remain stationary.

→ *1) Describe muscle contraction.*

** *2) When is maximum force generated?*

Maximum force is generated when the maximum number of cross bridges between actin and myosin are formed. The cross-bridge formation corresponds with the length-tension curve of a single muscle fiber in Fig. 3, where L_{max} represents the length at which the greatest tension is produced. This graph represents the muscle fiber only in vitro (out of the body). The muscle within the body is limited by surrounding
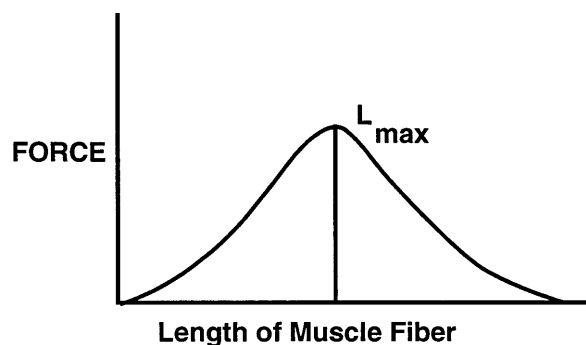
bone and connective tissue from stretching beyond L_{max}. Therefore, only the ascending part of the length-tension curve describes the force-generating characteristics in the muscle fiber in vivo (within the body; Refs. 2–6). Later in this experiment, you will have the opportunity to generate a length-tension curve on a classmate.

Weight lifters utilize the length-tension relationship. Their muscles increase in size because of the existence of greater numbers of myofibrils. Because myofibrils consist of actin and myosin, the muscles of the weight lifter have more contractile proteins to interact with each other. More cross bridges form during muscle contraction, and therefore more force is generated in the muscle.

Physiologically, a muscle can only shorten to ~50% of its resting length. We confront this limitation when we make a simple fist. If we flex the wrist before we try to make a fist, our grip strength is reduced. The flexor digitorum superficialis muscle involved in flexion of the wrist is also involved in flexion of the fingers. Once the flexor digitorum superficialis contracts during wrist flexion, a fist cannot be formed in that hand because the muscle cannot shorten to the degree required to flex the fingers and form a fist. This concept is referred to as active insufficiency. The instructor and students are challenged to make a fist with slight wrist hyperextension versus wrist flexion to illustrate this concept.

By trying to make a fist with the wrist extended and again with the wrist flexed, the students demonstrated the concept of active insufficiency. The students observed that active insufficiency occurs when a muscle shortens to a length at which it can no longer

FIG. 3.
Length-tension curve of a muscle fiber. L_{max} represents optimal length of fiber for producing maximal tension. Greatest number of cross bridges are formed between actin and myosin filaments at L_{max}.

create tension. Active insufficiency occurs only in muscles that cross more than one joint. Because the finger flexors cross the wrist joint and also the joints of the fingers, when the flexor muscles contract to flex the wrist, the flexor muscle shortens partially. It is difficult to make a fist while your wrist is flexed because the flexor muscles required to form a fist are already shortened to flex the wrist; therefore, only minimal shortening of the flexors can occur to make the fist. However, if the wrist is extended, you can make a powerful fist. In summary, the flexor muscles have two main functions, flexing the wrist and flexing the fingers (making a fist). Because the contraction has limited range, both actions cannot be performed simultaneously with maximum force.

Passive insufficiency occurs when the muscle fiber can no longer lengthen. As in active insufficiency, this limitation also occurs in muscles that cross more than one joint. The difference is that the insufficient muscle is not the muscle that is contracting. In the following example, the main contracting muscle is the anterior tibialis (in the front of the lower leg) and the calf muscle is the insufficient muscle. The calf muscle (gastrocnemius) crosses the knee joint and the ankle joint. When the lower leg is extended (knee straight), the foot can be pulled upward (dorsiflexed) only a small amount. The calf muscle is stretched fully when the leg is extended. It acts as a limiting factor in preventing the foot from pulling upward because the calf muscle can stretch no further. In contrast, when the knee is flexed, the calf muscle is slack and the foot can dorsiflex a greater amount. To demonstrate this concept, sit on the floor with knees extended and dorsiflex the ankle; notice that the gastrocnemius is fully stretched, limiting further dorsiflexion. Now flex the knee a little and dorsiflex the ankle again. The range of dorsiflexion should be greater because the gastrocnemius is slack (not fully stretched) and does not limit the action of dorsiflexion. You can use a string to represent the gastrocnemius; place the string on the surface of the gastrocnemius during knee extension and pull it taut. When the knee is flexed, the string should be slack.

→*3) Explain the difference between active insufficiency and passive insufficiency.*

**4) Discuss synergy.*

Most muscles have a primary and a secondary action. This concept can be illustrated by the following example. Have you ever noticed that as you turn a screw with a screwdriver, the harder you struggle the more often the screwdriver pops out of the groove on the screw (if you are right handed)? This occurs because the biceps muscle serves two functions; it primarily flexes the arm and secondarily supinates the arm (turns the arm from palm side down to palm side facing up). When turning the screwdriver with force, you are mainly using the supinator function of the muscle. But because you are strongly contracting your biceps, its primary function, elbow flexion, overrides the secondary function, and the screwdriver pops out of the screw. This is common in muscles with secondary functions. When a muscle is used forcefully in its secondary motion, the primary motion will often take over just as in the screwdriver example.

Synergy occurs when two or more muscles work together to produce a movement that is not possible when the individual muscles act alone. Specifically, synergy occurs when muscles have actions that they share and also actions that are opposite (antagonistic). In a synergistic situation, the antagonistic actions ''cancel'' each other out and only the action that is shared occurs. The action of extending your wrist is the result of synergistic muscles. The muscles involved are the extensor carpi radialis and the extensor carpi ulnaris. The extensor carpi radialis extends the wrist and radially deviates it. Radial deviation is movement of the wrist outward. Similarly, the extensor carpi ulnaris muscle extends the wrist and deviates the wrist in the ulnar direction (turning the wrist inward). When working together, these two muscles extend the wrist. That is, radial deviation and ulnar deviation cancel out and only extension occurs.

Biomechanics is the study of the human body in terms of forces, levers, and friction, using principles of Newtonian physics to analyze human motion. A simple way to explain biomechanics as it relates to the biceps muscle is with the following moment of force equation

$$M \times MA = R \times RA$$

where M is the moment of force or torque required to move the weight, MA (movement arm) is the perpendicular distance from the line of action of muscle force
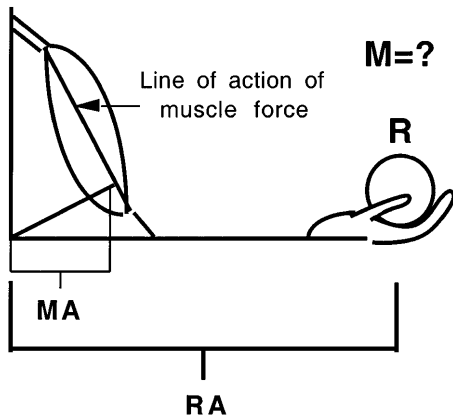
FIG. 4.

Components of moment of force equation, M × MA = R × RA, where M is moment of force or torque required to move weight, MA is perpendicular distance from line of action of muscle force to axis of rotation (joint), R is weight to be lifted, and RA is perpendicular distance from joint to weight (R). MA, RA, and R are easily obtained; therefore, moment of force (M) required to lift or move load through range of motion can be calculated.

to the axis of rotation (joint), R (resistance) is the weight to be lifted, and RA (resistance arm) is the perpendicular distance from the joint to the weight. MA, RA, and R are easily obtained; therefore, the M required to lift or move the load through the range of motion can be calculated. It is important to note that force and torque are not equivalent. Torque is a force applied over a lever arm that causes rotation. It is also important to note that the equation above states a condition of equilibrium, i.e., there is no rotation. However, the moment of force shifts the curve to the left, and torque or movement occurs. To illustrate this concept, a sample calculation is performed below. The data used in the example below are from Fig. 4.

For example, if the length of the subject's forearm is 36 cm and the moment arm is 5 cm, we know that RA = 36 cm and MA = 5 cm.

The 110-kg weight that the subject is holding equals the resistance: R = 110 kg. The M required to lift the weight is the unknown. If we insert the values into the equation, we get

$$M \times 5 \text{ cm} = 110 \text{ kg} \times 36 \text{ cm or}$$

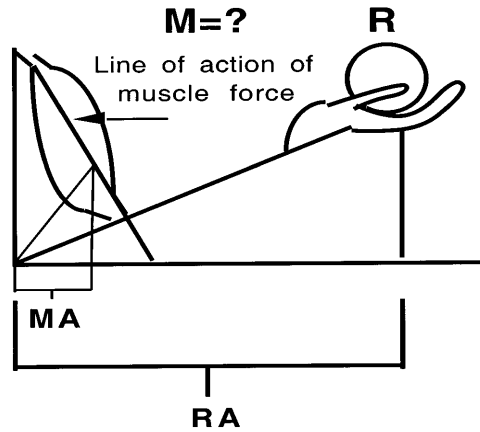$$M = \frac{110 \text{ kg} \times 36 \text{ cm}}{5 \text{ cm}}$$

FIG. 5.

Changes in biomechanical components when arm is flexed to 45°. When subject's forearm is flexed to a 45° angle both MA and RA decrease, whereas R remains the same (subject lifts 110-kg weight again). Insertion remains exactly the same distance from joint, but moment arm changes. Moment arm changes because moment arm is determined by *perpendicular* distance from line of action of muscle force to joint. Length of resistance arm changes also, because resistance arm is perpendicular distance from joint to weight.

Solving for M, we find that 792 kg of torque are necessary to lift the 110-kg weight.

When the subject's forearm is flexed to a 45° angle (Fig. 5) both MA and RA decrease, whereas R remains the same (the subject lifts the 110-kg weight again). The insertion remains exactly the same distance from the joint, but MA changes. MA changes because MA is determined by the *perpendicular* distance from the line of action of muscle force to the joint. RA changes also, because RA is the perpendicular distance from the joint to the weight. The new values are found to be MA = 4.3 cm and RA = 26.7 cm. After inserting these new values into the equation, we find that the new M required is ~683 kg of force. Notice that it takes considerably lower M to lift the same weight when the arm is at a different angle. At the new angle, the arm has a mechanical advantage. Biomechanics are used in variable-resistance machines. These machines provide added resistance as the individual moves the resistance through the midrange of motion so that maximum exertion can be achieved throughout the entire range. In other words, the machine is set to provide more resistance at the angles at which a person is strongest.

**5) Why would it be an advantage to have the muscle insertion farther from its associated joint?

It is easy to see from the moment of force equation that it is an advantage to have a muscle insertion farther from its associated joint. Males typically have muscle insertions that are farther from the point of rotation; this is one of the many reasons why men are typically stronger than women.

Muscle force may be considered a resultant force that can be decomposed into two constituent forces, rotary and joint compressive. The size of each component depends on the angle at which the force is applied. If the force is perpendicular to the segment being moved, the segment moves in a rotating direction. If the force is parallel to the segment being moved, the segment moves in a parallel or compressive direction. The basic idea is that as joint angles increase to the point where the muscle-tendon complex is pulling at 90° to its bony lever, there will be a constant change in the proportion or ratio of compressive to rotary forces. That is, the rotary force progressively increases, thus affording more torque (turning force) about the joint axis, whereas (joint) compressive forces decrease, thus decreasing the joints' inertia and tendency to remain stationary. This explains clinically why subjects or patients have difficulty initiating movements. However, once movement starts, further motion becomes easier. The reverse scenario is therefore also true. As the angle of insertion gets smaller the compressive forces increase whereas the rotary forces decrease. There are two extremes here, one practical and one theoretical. If the muscle-tendon complex is at 90° to the lever then there is only rotary force (i.e., no compression exists). The other case is theoretical. If the tendon's line of pull could become parallel with its lever (it cannot because this would mean that the tendon would have to fall inside the boundary of the neutral axis of the bone), then the force would be all compressive with no rotation.

There are both physiological and mechanical advantages involved in muscle contraction and maximum tension generated. The length-tension concept states that the maximum tension generated by the muscle occurs at its resting length when there is the greatest number of cross bridges between myosin and actin. However, there are optimal angles at which the maximum moment of force or torque can be generated throughout a joint range of motion. The idea of locating the point at which the maximum muscle moment of force can be generated is relevant to exercise training and rehabilitation to increase muscle strength according to the overload principle. Figure 6 presents a concept map of muscle biomechanics for student review.

PROCEDURES

Protocol I: Measurement of Maximum Weight That Biceps Muscle Can Hold at Various Joint Angles

Students will measure the maximum weight that can be held at various joint angles. Students will test the concept that changing the joint angle changes the length of the muscle and changes the mechanical advantage of the lever system. Thus the maximum weight that can be held will vary as the joint angle changes.

1) With the aid of a protractor, mark a 60-cm-wide by 30-cm-high poster board with angles of 20, 45, 60, 90, and 120°. Mark the 90° angle exactly in the middle (30 cm from the edge), and mark the remaining angles starting with 20° from the left side of the poster board. Label the respective angles as shown in Fig. 7.

2) Have the subject place his or her right arm (shoulder to elbow) flat on a desk. Now line up the forearm (elbow to hand) with the poster board at an angle of 20°.

3) Estimate the maximum weight that the subject can hold at the specified angle. Place a weight smaller than the estimated maximum in the subject's right hand. The subject should maintain his or her arm at the same starting angle even as weights are being added.

4) Add additional weight in the smallest increments possible until the subject can no longer hold the
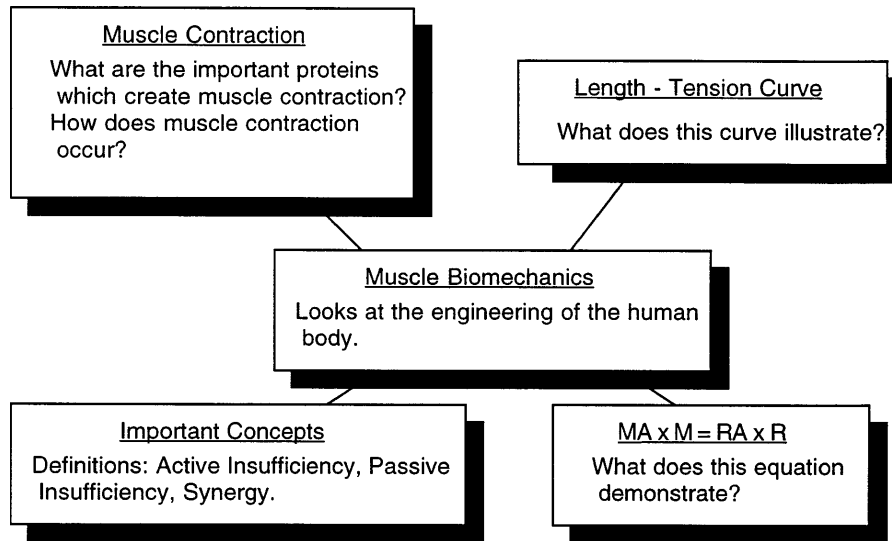
Muscle Contraction

What are the important proteins which create muscle contraction? How does muscle contraction occur?

Length - Tension Curve

What does this curve illustrate?

Muscle Biomechanics

Looks at the engineering of the human body.

Important Concepts

Definitions: Active Insufficiency, Passive Insufficiency, Synergy.

MA x M = RA x R

What does this equation demonstrate?

FIG. 6.
Concept map that organizes basic principles of muscle biomechanics. Students may find concept map useful in reviewing the material presented within text.

weight. Record the maximum weight that the subject can hold at the 20° angle in Table 1. Repeat the procedure for each angle labeled on the poster board. Record results in Table 1.

5) Repeat *steps 1–4* with the left arm at each labeled angle. Record the maximum weight held at each angle in Table 1. Plot the maximum weight at each angle for the right arm and for the left arm in *graph 1* (Fig. 8).

Use a solid line for the right arm and a dashed line to represent the left arm.

Analysis of Protocol I

1) At which angle can the biceps muscle hold the greatest weight?

2) At which angle is the body at a mechanical advantage? Why?
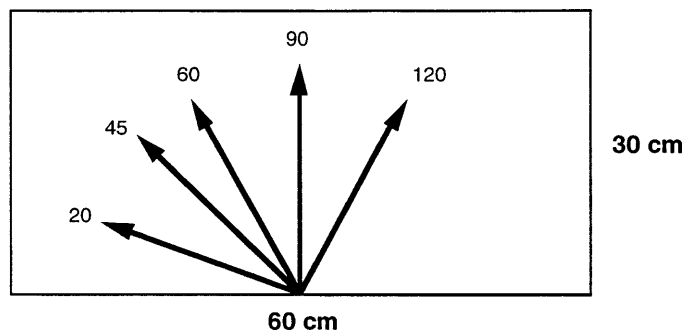
FIG. 7.
Model for poster board to be made in *protocol I*. With the aid of a protractor, mark a 60-cm-wide × 30-cm-high poster board with angles of 20, 45, 60, 90, and 120°. Mark the 90° angle exactly in the middle (30 cm from edge), and mark remaining angles starting with 20° from left side of poster board.

TABLE 1
Maximum weight held at each angle with right and left arm

Angle, °	Max. Wt Held With Right Arm	Max. Wt Held With Left Arm
20		
45		
60		
90		
120		

3) At which angle is the body at a length-tension advantage? Why?

Protocol II: Calculation of Moment of Force Required to Hold Maximum Weight at Various Angles

Students will calculate the moment of force required to hold a weight at various joint angles. The students will measure and record the change in the moment arm and the change in the resistance arm that occurs as the elbow is flexed. Subsequently, using the moment of force equation, $M \times MA = R \times RA$, students will calculate the M required to hold a weight at various joint angles. MA, at an angle of 0°, is the distance from the elbow to the point of insertion of the biceps muscle (it is estimated that the biceps insertion is ~2.54 cm from the elbow in females and
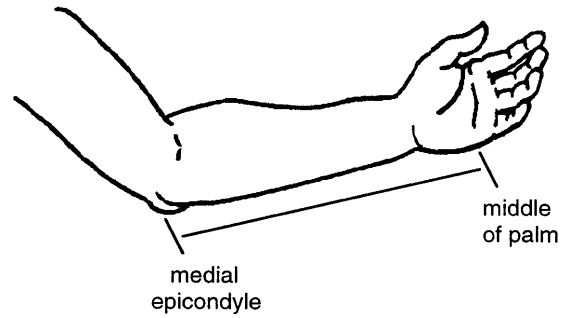
FIG. 9.
Distance to be measured in *protocol II*. Measure length of each subject's right forearm in centimeters. This is length from medial epicondyle, a bony prominence that can be felt on inside of arm at elbow, to middle of palm. Place your thumb and forefinger on bones on each side of your elbow; as you flex your elbow you should feel bones moving. If your body were split into right and left halves, midline would separate right side from left side. Bone on medial side (toward midline of your body) is medial epicondyle.

~5 cm from the elbow in males). RA, at an angle of 0°, is the length of the forearm. At angles other than 0, both MA and RA will change.

1) Measure the length of each subject's right forearm (RA) in centimeters. This is the length from the medial epicondyle, a bony prominence that can be felt on the inside of the arm at the elbow, to the middle of the palm (Fig. 9). Place your thumb and forefinger on the
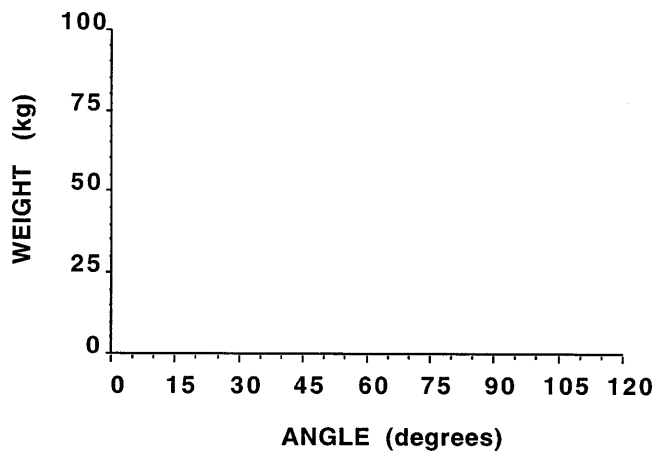
FIG. 8.
Graph 1: plot maximum weight held at each angle for right and left arm. Use a solid line for right arm and a dashed line for left arm.
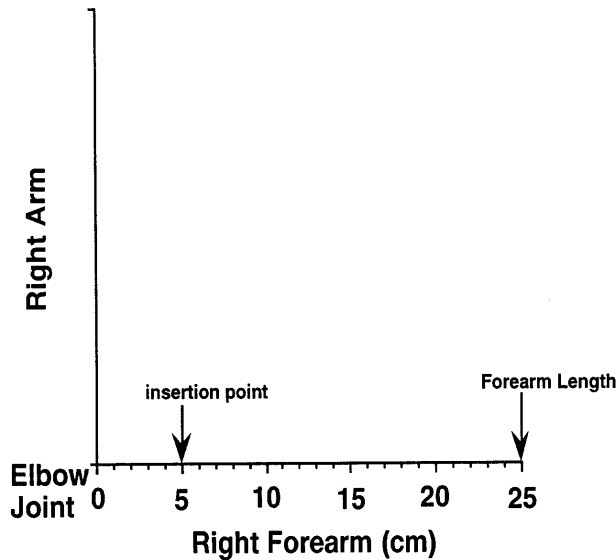
bones on each side of your elbow; as you flex your elbow you should feel the bones moving. If your body were split into right and left halves, the midline would separate the right side from the left side. The bone on the medial side (toward the midline of your body) is the medial epicondyle.

2) Plot the right forearm length on the *x*-axis of *graph 2*, Fig. 10 (this length represents the RA). The *y*-axis represents the right arm. (Remember that the arm is the region from the shoulder to the elbow, and the forearm is from the elbow to the wrist). Figure 11 illustrates how the forearm length is plotted on the graph.

3) Plot the length from the elbow to the point of insertion of the biceps on the *x*-axis of *graph 2* (this length represents the MA). Again, it is estimated that the biceps insertion is ~2.54 cm from the elbow in females and ~5 cm from the elbow in males. Figure 12 illustrates how the point of insertion of the biceps is plotted on the graph.
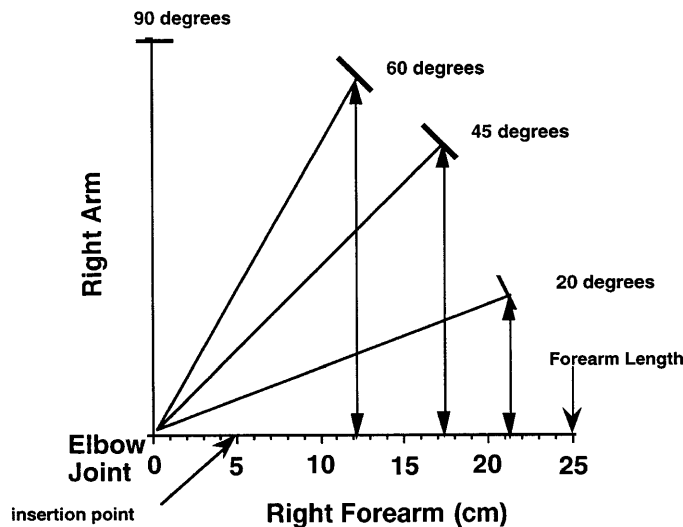
FIG. 10.
Graph 2: students should use *graph 2* to plot forearm length and point of biceps insertion at each joint angle (See Figs. 11 and 12). Using this graph, students will calculate how moment and resistance arm change as joint angle changes. As moment and resistance arm change, moment of force also changes.

FIG. 11.
Example of how forearm length is plotted at each joint angle. Each line is exactly the same length (length of subject's forearm). By drawing a perpendicular line from end of line that represents forearm length to *x*-axis, students can measure how resistance arm changes as joint angle changes. From this example, students can see that resistance arm (perpendicular distance from resistance to joint) changed from 25 cm at 0° to ~21 cm at 20°, to ~17 cm at 45°, and to ~12 cm at 60° of flexion.
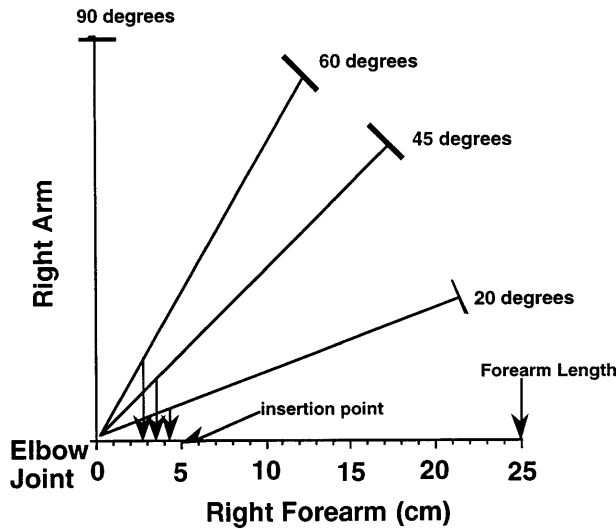
FIG. 12.
Example of how biceps insertion length is plotted at each joint angle. Each line is exactly the same length (2.54 cm for females and 5.0 cm for males). By drawing a perpendicular line from point that represents insertion of biceps muscle to x-axis, students can measure how moment arm changes as joint angle changes. From this example, students can see that moment arm (perpendicular distance from point of insertion to joint) changed from 5 cm at 0°, to ~4.5 cm at 20°, to ~3.5 cm at 45°, and to ~2.5 cm at 60° of flexion.

4) Use a protractor to mark the angles 0, 20, 45, 60, and 90° on *graph 2*. Line up the protractor with the y-axis so that 0° is at the x-axis and 90° is at the y-axis. Use a ruler and draw lines the length of the right forearm from the x-y intercept through each angle. All five lines should be the same length. Figures 11 and 12 illustrate how the lines the length of the forearm are drawn for each angle on the graph.

5) Use a ruler to mark the point of muscle insertion on the line at each angle; the distance from the joint to the insertion remains the same through all of the angles. For example, if the subject is a male, mark the insertion 5.0 cm from the joint (x-y intercept = 0) on the lines for each of the angles. Figure 12 illustrates how the point of insertion of the biceps is plotted at each angle on the graph.

6) Using the protractor, draw perpendicular lines from the endpoints of the five lines drawn through

TABLE 2
Maximum weight held at each joint angle, moment arm, resistance arm, and moment

Angle, °	Max. Wt Held With Right Arm	Moment Arm	Resistance Arm	Moment of Force
10				
20				
45				
60				
90				
120				

Maximum weight held with right arm (resistance) from Table 1. Moment arm, perpendicular distance from line of action of muscle force to joint; resistance arm, perpendicular distance from joint to weight; moment, force calculated to hold weight.

each angle. The distance on the x-axis from the joint (x-y intercept = 0) to the perpendicular line represents the resistance arm (RA). Figure 11 illustrates how the perpendicular lines are drawn on the graph. Record this measurement for each angle in Table 2.

7) With the aid of a protractor, draw perpendicular lines from the muscle insertion to the x-axis. The line from the insertion point should intersect the x-axis at a right angle. The distance on the x-axis from the joint (x-y intercept = 0) to the perpendicular line represents the moment arm (MA). Figure 12 illustrates how the perpendicular lines are drawn on the graph. Record this measurement for each angle in Table 2.

8) Compute the moment of force (M) the subject requires to hold the weight at each angle. For the resistance (R), use the values entered in the first column of Table 1. Insert the value calculated for the moment of force in Table 2.

Protocol III: Active Insufficiency

1) Have the subject extend his or her wrist and make a powerful fist. Record your observations.

2) Have the subject flex his or her wrist and make a powerful fist. Record your observations.

Observations

_____

_____

_____

Protocol IV: Passive Insufficiency

1) Have the subject extend his or her knee. Hold a string from the side of the knee to the heel. Pull the string tight.

2) Have the subject bend his or her knee a small amount while the string is still in place. Notice what happens to the string. The string represents the events occurring in the calf muscle.

3) With knee extended, have the subject dorsiflex (pull toes back) the foot.

4) Have the subject bend the knee and dorsiflex his or her foot as far as possible. Record observations on subject's range of motion in both positions.

Observations

_____

_____

_____

Protocol V: Designing Your Own Experiment

A) We mentioned above that muscle strength is a function of both the length-tension relationship and the ''biomechanics'' of muscle contraction (i.e., the muscle system functioning as a lever system). The experiments described above result in *both* of the determinants of muscle strength being varied simultaneously with the joint angle. The students are challenged to design an experiment to separate these two determinants. This can be achieved, for example, by maintaining the subject's elbow at 20° with the forearm extending beyond the edge of the table. In this position a maximal weight could be ''hung'' at various points along the forearm. Thus muscle length and joint angle would be held constant while the ''lever system effect'' could be studied in isolation. That is, the resistance arm could be changed while all other variables remain constant. The students could then plot maximal weight lifted as a function of distance, which would be equal to RA.

Can you design a similar experiment to isolate the individual components of muscle strength or torque?

B) The students are challenged to measure the length-tension curve on a classmate. This can be achieved by measuring the subject's grip strength by having him/her squeeze your finger. Your finger should be squeezed with the subject's wrist completely flexed, again when the subject's wrist is in the neutral position, and finally with the subject's wrist hyperextended. By moving the wrist from extreme flexion to extreme extension, the muscles that grip the hand are moving from a shortened to a lengthened position. In the shortened position fewer cross bridges are interacting, and therefore, the grip strength is low. In the lengthened position more cross bridges are interacting, so the grip strength is high.

Plot this relationship on *graph 3* (Fig. 13). Design an experiment to determine the length-tension relationship of another muscle.
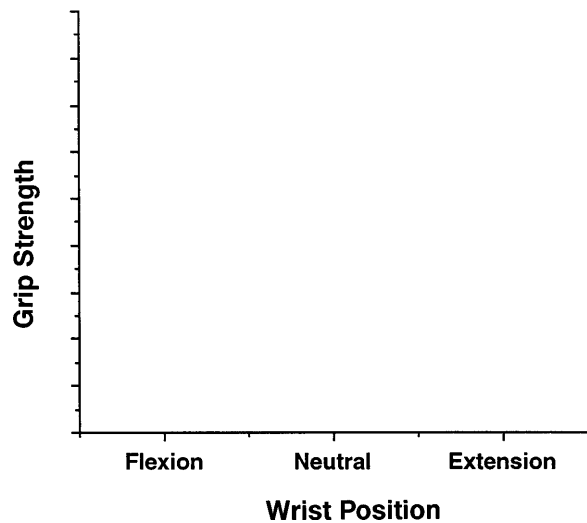

FIG. 13.
Graph 3: length-tension relationship of finger flexors. As wrist moves from flexion to extension, muscles that make a fist are lengthened. As muscle is lengthened, number of cross bridges that interact increases. An increase in number of cross bridges interacting leads to an increase tension development. Students should use this graph for *protocol V*.

Teacher's Copy of the Answers to Text Questions

1) Muscle contraction occurs because of the interaction of proteins called actin and myosin within the myofibril. This interaction is explained by the sliding filament theory, which suggests that myosin forms cross bridges with actin. These cross bridges pull the actin filaments over the myosin filaments during a power stroke, thus causing the contraction (shortening) of the muscle (see Fig. 2).

2) Maximum force is generated when the maximum number of cross bridges form between the actin and myosin filaments.

3) Active and passive insufficiency are similar in that they both occur in muscle that crosses more than one joint. However, active insufficiency occurs when a muscle shortens to a length at which the muscle can no longer create tension, whereas passive insufficiency occurs when muscle fibers can no longer lengthen. Another difference is that the passive insufficient muscle is not the contracting muscle.

4) Synergy is when two or more elements work together to achieve a result not possible by each of the components acting alone. The muscles can also have actions that are antagonistic but still work together to perform a function. The action of extending your wrist is the result of synergistic muscles. The two muscles involved are the extensor carpi radialis and extensor carpi ulnaris. These two muscles have opposite and similar components. The opposite component cancel out, and thus only the similar motions occur.

5) The advantage of having a muscle insertion farther from its associated joint is that it increases the distance MA, the perpendicular distance from the muscle line of action to the joint. By increasing MA, you decrease M, the force needed to lift the same weight. This effect can be observed in the moment of force equation where $M \times MA = R \times RA$.

Teacher's Copy of the Answers: Protocol I

1) Answers vary, but the angle should be in the midrange of motion around 90°.

2) The angles of mechanical advantage for the biceps muscle are those angles beyond 90° in which the muscle is contracting. However, at these angles, the muscle is near its limit of shortening and cannot exert much force.

3) The 0° angle is the angle at which there is a maximum length-tension advantage. This is because when the arm is fully extended, the biceps is at its maximum length.

SUMMARY: TIPS FOR INSTRUCTORS

The format outlined is only a suggestion and may be modified to suit the individual situation of the instructor and the class. We recommend that students chosen as volunteers vary in size, gender, and strength. This will provide a range of data for comparison.

The exercise is designed to provide students with the opportunity to actively participate in a laboratory experiment as investigators and subjects. Students are challenged to use the scientific process to solve problems. The interaction of students during the exercise also provides an opportunity for students to share ideas and help each other learn. Questions are also interspersed throughout the text and exercise to encourage thought and discussion.

Our goal in creating this exercise was to develop a laboratory experience that would provide an opportunity for students to appreciate scientific research. In completing this exercise students will have augmented their knowledge of physiology and, we hope, will have gained a vision of science for the future.

Suggested Readings

1. **Bonwell, C. C., and J. A. Eison.** *Active Learning: Creating Excitement in the Classroom.* Washington, DC: George Washington Univ., 1991.
2. **Chan, V., J. Pisegna, R. Rosian, and S. E. DiCarlo.** Model demonstrating respiratory mechanics for high school students. *Am. J. Physiol.* 270 (*Adv. Physiol. Educ.* 15): S1–S18, 1996.
3. **Collins, H. L., and S. E. DiCarlo.** Physiology laboratory experience for high school students. *Am. J. Physiol.* 265 (*Adv. Physiol. Educ.* 10): S47–S54, 1993.
4. **Dolmans, D. H., and H. G. Schmidt.** What drives the student in problem-based learning? *Med. Educ.* 28: 372–380, 1994.
5. **Elliot, D. D.** Promoting critical thinking in the classroom. *Nurs. Educ.* 21: 49–52, 1996.

6. **Hudson, P.** Active learning in large class settings: acting out muscle contraction. *Am. J. Physiol.* 269 (*Adv. Physiol. Educ.* 14): S75–S76, 1995.

7. **Johnson, D. W., R. T. Johnson, and K. A. Smith.** *Active Learning: Cooperation in the College Classroom.* Edina, MN: Interaction Book, 1991.

8. **Modell, H. I.** Why am I teaching this course? Setting educational objectives for course activities. *Ann. NY Acad. Sci.* 701: 27–35, 1993.

9. **Modell, H. I.** Active learning in large class settings: preparing students to participate. *Am. J. Physiol.* 269 (*Adv. Physiol. Educ.* 14): S73–S74, 1995.

10. **Modell, H. I.** Preparing students to participate in an active learning environment. *Am. J. Physiol.* 270 (*Adv. Physiol. Educ.* 15): S69–S77, 1996.

11. **Modell, H. I. and J. A. Michael.** Promoting active learning in the life science classroom: defining the issues. *Ann. NY Acad. Sci.* 701: 1–7, 1993.

12. **Rangachari, P. K.** Active learning: in context. *Am. J. Physiol.* 268 (*Adv. Physiol. Educ.* 13): S75–S80, 1995.

13. **Richardson, D.** Active learning: a personal view. *Am. J. Physiol.* 265 (*Adv. Physiol. Educ.* 10): S79–S80, 1993.

14. **Richardson, D., and B. Birge.** Teaching physiology by combined passive (pedagogical) and active (andragogical) methods. *Am. J. Physiol.* 268 (*Adv. Physiol. Educ.* 13): S66–S74, 1995.

15. **Silverthorn, D. U.** Active learning in large class settings: mapping techniques for physiology. *Am. J. Physiol.* 269 (*Adv. Physiol. Educ.* 14): S74–S75, 1995.

16. **Silverthorn, D. U.** Diverse methods of active learning. *Am. J. Physiol.* 268 (*Adv. Physiol. Educ.* 13): S100, 1995.

17. **Vander, A. J.** The excitement and challenge of teaching physiology: shaping ourselves and the future. *Am. J. Physiol.* 267 (*Adv. Physiol. Educ.* 12): S3–S16, 1994.

18. **Yucha, C. B.** Understanding physiology by acting out concepts. *Am. J. Physiol.* 269 (*Adv. Physiol. Educ.* 14): S50–S54, 1995.

References

1. **DiCarlo, S. E., E. Sipe, J. P. Layshock, and R. L. Rosian.** *Experiments and Demonstrations in Physiology.* Upper Saddle River, NJ: Prentice Hall, 1998.

2. **Kreighbaum, E.** *Biomechanics, A Quantitative Approach for Studying Human Movement.* Minneapolis, MN: Burgess, 1981.

3. **Lister, M. J.** *Biomechanics.* Alexandria, VA: American Physical Therapy Association, 1985.

4. **Low, J. L., and A. Reed.** *Biomechanics Explained.* Boston, MA: Butterworth-Heinemann, 1996.

5. **Nigg, B. M., and W. Herzog.** *Biomechanics of the Musculo-Skeletal System.* Chichester, UK: Wiley, 1994.

6. **Valenta, J.** *Biomechanics.* New York: Elsevier, 1993.