Chapter 10

An Analysis of Bone/Muscle Movement

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Contents

Introduction

This laboratory exercise gives students the opportunity to investigate how the skeletal and muscular systems *work*. By manipulating a simple kinematic model representing the leg and foot, students can get hands on information about the interaction of bones and muscles in humans. Having worked with the model, they then are able to predict and analyze the properties of bone/muscle systems in other vertebrates and understand how these systems have become modified during the course of evolution for a particular life style.

Notes for the Instructor

Materials and Equipment

From the point of view of materials and equipment, this lab can be divided into five parts, each related to the main theme of evolution, specifically how intimately linked structure and function are in biological systems.

1. *Structure of bone and muscle:* Microscopes with slides of ground bone and muscle tissue (cardiac, striated, and smooth) are on demonstration so students can see how structure and function relate even at the cellular level.

2. *Kinematic model*: A wooden foot and lower leg with three spring scales per pair of students. The use of this simple biophysical model that can adjust to new situations, introduces the concept of models, whether they be mathematical or mechanical, and their value as tools for investigating biological processes. (See Appendix A.)

3. *Evidence for evolution in homology*: Frog, bird, cat, and human skeleton. You can substitute diagrams if these skeletons are not available. However, the more skeletons and individual bones of different animals accessible for study, the more evidence the student can gather.

4. *Taxonomy of vertebrates*: This lab offers an opportunity to emphasize evolutionary concepts by setting up a museum-type display. This display might include taxonomical information, photographs of the animals, an assortment of artifacts such as birds eggs and nests, taxidermic or preserved specimens, and so forth.

5. *Structure and function*: Skeletons of a runner and leaper (cat), a digger (mole), and a flier (bat). If these particular skeletons are not available, any that exhibit differences in structure due to varying life styles can be substituted.

By the end of the lab period, students have learned both traditional information (cellular structure, names of bones, taxonomy), and something of far greater pedagogical and heuristic value. They have learned how to project the knowledge they gained from working with a model to the biological world and how to look at the structure of a skeleton and see how it has become modified to suit a particular animal's way of life.

Student Outline

Introduction

The ability of animals to move about depends upon the interaction of bone and muscle. The skeleton provides the framework that supports the body and gives it its characteristic shape. Muscles, which make up 50% of the body's mass, are responsible for the final form. They use the bones as levers and by contracting, cause the many complex movements of which animals are capable, such as throwing or fetching a ball, jumping over a fence or simply taking a breath of fresh air. In this lab, you will study:

1. The structure of both bone and muscle.
2. How muscles and skeletons interact as demonstrated by a kinematic model.
3. The application of your new found knowledge to the theory of evolution and to locomotory behavior in various vertebrates.

The Structure of Bone and Muscle

The Structure of Bone

Bone is one of nature's strongest materials. One cubic inch can bear loads of 19,000 pounds. This strength rivals that of light steel, but a steel skeleton would be five times heavier.

Bone is made up of the protein collagen and minerals   (calcium and phosphate). Collagen fibers are amazingly strong, but too flexible and elastic to support the body. The minerals give the bone its hardness and rigidity. Together they make a matrix that provides maximal strength in a lightweight form.

Bone is composed of structural units called Haversian systems. Each system is made up of concentrically arranged layers of hard, inorganic material surrounding a microscopic central Haversian canal. Blood vessels and nerves pass through this canal. The living bone cells (osteocytes) lie along the interfaces between adjoining concentric layers of the hard matrix. Materials are exchanged between the living cells and the blood vessels in the Haversian canal by way of radiating canaliculi.

Most bones are not solid, compact structures, or they would be unnecessarily heavy in proportion to the strength requirements. The large bones are therefore hollow. Sufficient bone bars and braces extend from the solid bone exterior into the hollow interior to provide reinforcement similar to the engineering of bridges. So wisely is the order of nature arranged that this space in the bone shaft is not wasted, but filled with bone marrow, which is used as a factory for red blood cells.

The Structure of Muscle

Vertebrates have three types of muscles:

1. *Cardiac*: Cardiac muscle cells make up the heart. Their contraction creates the force that propels blood through the body.

2. *Smooth*: Smooth muscle cells are long and tapered and have only one nucleus. They line the walls of many internal organs and are responsible for pushing food through the digestive system and regulating blood pressure.

3. *Skeletal (striated)*: the only type under the animal's
    voluntary control. A typical skeletal muscle, such as the biceps in the upper arm, has three main areas:

    (a) *Origin*: attached by tendons to a stationary bone.

    (b) *Insertion*: attached by tendons to a more moveable bone.

    (c) *Belly*: the enlarged center section of the muscle containing the fibers that contract, thus pulling the bone attached at the muscle insertion.

    A skeletal muscle is made up of many multinucleate muscle fibers (cells), each of which runs the entire length of the muscle and is innervated by at least one motor neuron. Each muscle fiber is made up of a bundle of myofibrils which in turn are made up of units called sarcomeres, strung out in single file along the length of the fibril. Here is where the contraction occurs with the thin filaments (actin) sliding between the thick filaments (myosin) as proposed by the sliding filament theory.

Bone/Muscle Systems as Lever Machines

The interaction of muscles, bones and joints to generate movements form a biological lever. A *lever* is a rigid structure, such as a crowbar or a bone, that can transmit forces by turning at a *fulcrum*, in this case a joint. The *force* that moves the levers is supplied by the muscles. The product of the force that the muscle exerts *(F)* and the length (or *D*istance) of its bone-lever *(D)* equals the *torque (T)* produced: $T = FD$. In other words, small differences in the distance can make a big difference in strength. The distance we are concerned with in this lab is the insertion point of the calf muscle on the heel bone.

As you take a forward stride while walking, notice that the force exerted by your weight and being counteracted by the contraction of the lower leg muscle or gastrocnemius, does not act at just one point, but rather shifts progressively forward.
At each point: $F_1D_1 = F_2D_2$ where:

> F_1 = the force produced by the gastrocnemius,
> D_1 = the distance from the ankle joint to the muscle insertion of the gastrocnemius,
> F_2 = your weight (the force of the earth upward), and
> D_2 = the distance from the ankle to the point of contact with the earth.

At equilibrium (when the bone is stationary), the torque produced by F_1D_1 is equal to the opposite torque, produced by F_2D_2.

The Kinematic Model
(adapted from S. C. Brown)

Introduction

The kinematic model is a simple lever system representing the lower leg and foot (see Figures 10.1 and 10.3). The pivot bolt represents the ankle and should be loose enough for the foot to be able to rotate. Positions 1 and 2 represent two possible points of insertion of the Achilles tendon from the gastrocnemius muscle into the heel bone (calcaneus), as might be found in different species that have heel bones of different lengths. A cat or deer has a calcaneus that is short relative to the rest of its of its foot (position 2), compared to the human or bear whose heel is relatively longer (position 1). Positions 3, 4, and 5 represent points along the foot where forces are exerted, corresponding to positions at the proximal and distal ends of the metatarsal bones and end of toes, respectively. They can also be considered feet of different lengths as you would find in different species. Position 5 represents a deer that walks on the end of its toes; position 4 represents a cat that walks on the ball of its foot.
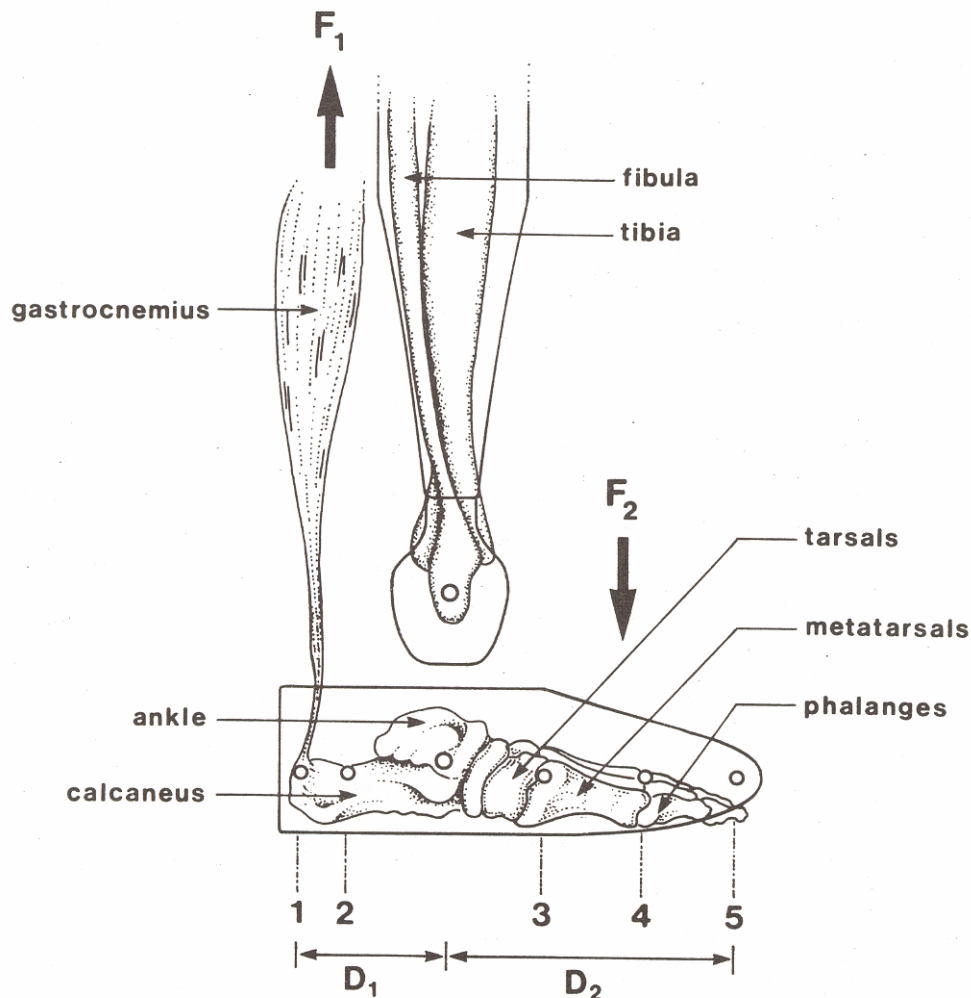

Figure 10.1. The kinematic model and the human lower leg and foot (also see Figure 10.3).

1. Attach the spring scales to positions 2 and 3 and adjust the tension so that each scale reads 8 oz. Are the torques equal (does $F_1D_1 = F_2D_2$)? Record your answers on the work sheets.

2. Move the bottom end of the scale so that it is attached to position 4. Does F_1 change? Are the torques still equal? (Keep in mind that these scales have been pulled by many students so don't expect perfection.)

3. Re-attach the scale to position 3. Remove the pivot bolt at the ankle joint so the foot swings free and place a third scale on the pivot bolt. Pull down on the third scale until it reads 2 pounds. What is the relationship among the three forces exerted? Why does this seem reasonable and predictable?

Measurement of Muscle Force

Remember that even though the force exerted by your weight shifts forward as you take a step, the torques at each point in the stride must remain equal.

1. Which two of the parameters (F_1, F_2, D_1, D_2) remain constant when you walk? The other two must change so that equilibrium is maintained. F_1D_1 *must* always equal F_2D_2 .

2. However, between different species of animals, all four parameters can vary. For a species that weighs 1 pound (F_2) with its gastrocnemius inserted as position 1 (D_1), measure the muscle forces (F_1) required for equilibrium as this constant weight of 1 pound (F_2) is exerted at positions 3, 4, and 5 (D_2). (Detach the top of the second scale and pull up until it reads 1 pound.) Enter the F_1 values in Table 10.1 (Species 1).

3. Repeat this procedure for a 1 pound species that has a shorter heel; its gastrocnemius is inserted at position 2. Enter these F_1 values in Table 10.1 (Species 2).

Table 10.1. F_1 values.

Species	Position of weight force		
	Position 3	Position 4	Position 5
1			
2			

4. Calculate (solve for) F_1 mathematically for Species 1 and compare with the experimental values that you just measured. Enter these calculated F_1 values in Table 10.2.

5. Calculate F_1 for Species 2 and compare with the experimental values. Enter these calculated F_1 values in Table 10.2.

6. At what position in the power stride must the gastrocnemius exert the most force to counteract a constant weight? The least?

7. What material composes the actual surfaces of articulation in a vertebrate ankle? What is the advantage of this covering?

Table 10.2. Calculated F_1 values.

Species	Position of weight force		
	Position 3	Position 4	Position 5
1			
2			

Measurement of Power Efficiency

Now that you understand the relationship of the forces involved, you can estimate the mechanical power efficiency *(PE)* of the system. To do this, divide the force of the animal's weight (F_2) by the balancing force exerted by the gastrocnemius muscle (F_1, from Table 10.2).

$$PE = \frac{F_2}{F_1} = \frac{animal's\ weight}{gastronemius\ balancing\ forces}$$

1. Calculate the power efficiencies from your F_1 calculations 10.2 for the species with its gastrocnemius inserted at position 1. Enter these data in Table 10.3.

2. Calculate the power efficiencies for the second species and enter these data in Table 10.3.

3. In each case, at what point along the foot is the greatest power efficiency achieved (i.e., position 3, the proximal metatarsals; position 4, the distal metatarsals; or position 5, the toes)?

4. Which of the two species has the greatest power efficiency, the one with longer or the one with the shorter calcaneus?

5. Lift a relatively heavy object, such as a chair or lab stool. Which foot position (3,4, or 5) is the most natural stance for this action? Does this agree with your calculations?

Table 10.3. Power efficiency.

Species	Position of weight force		
	Position 3	Position 4	Position 5
1			
2			

Measurement of Speed Efficiency

Efficient movement is the ultimate goal of the bone/muscle system. Maximum efficiency is achieved when the distance moved by the muscle is low compared to the distance moved by the business end of the bone. Thus, speed efficiency equals the distance moved by the business end of the bone *(B)* divided by the distance of muscle contraction *(M)*.
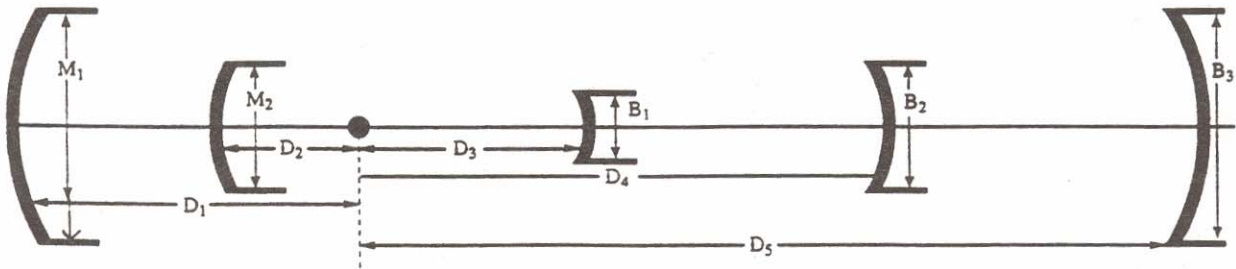
$$speed\ efficientcy = \frac{B}{M}$$

Figure 10.2. Diagram showing the relationships in a simple lever system. *M* = distance of muscle contraction; *B* = distance moved by business end of bone; *D* = distance from the ankle.

1. Insert five pencils in the five holes of the foot model. These correspond to the gastrocnemius insertion into the calcaneus at positions 1 and 2 and the two metatarsal and toe positions. Simultaneously record on a piece of paper the distance moved by the bones at the various positions along the foot, as the model rotates about the ankle joint. Measure these distances. Also measure the distance *(D)* from the ankle joint to the various positions. Results similar to those in Figure 10.2 following should be achieved.

2. At what point along the foot is the greatest speed efficiency achieved? The least?

3. How does the speed efficiency of a species with its gastrocnemius inserted at position 1 compare with that of a species whose muscle insertion is at position 2?

4. Suppose we examine species whose gastrocnemius inserts an equal distance from the axis of rotation (ankle) but whose feet are of different lengths. Which species would have the greatest speed efficiency?

5. How does the mechanical power efficiency compare with the mechanical speed efficiency at the various points along the foot/leg lever?

Measurement of Work Output of a Muscle

The work output of a muscle *(W)* equals the force exerted by the muscle *(F)* times the distance moved by the muscle *(M)*. Thus, if muscles A and B exert equal forces, but muscle A contracts by 1 cm and muscle B by 2 cm, muscle B has done twice as much work as A.

Using your data from Table 10.1 on the muscle force (F_1) needed to counteract a given weight force (F_2) and the data on distances moved by muscles at positions 1 and 2 $(M_1$ and $M_2)$, calculate:

1. The work output of muscle $(W = FM)$ for Species 1.

2. The work output of muscles for Species 2.

Table 10.4. Work output.

Species	Position of weight force		
	Position 3	Position 4	Position 5
1			
2			

3. Stand flatfooted and then on the tips of your toes, like a ballet dancer en pointe. Which position is more difficult and takes more muscle work to maintain? Does your experience agree with your calculations?

Now that you have developed some insight into the mechanics of bone/muscle systems, you can apply this knowledge to the real world. The skeletons of a number of different vertebrates (human, fish, frogs, snakes, turtles, birds, cats, salamanders, etc.) are available for study.

Evolutionary Aspects

All vertebrates evolved from a common ancestor that lived in the Paleozoic Era, about 500 million years ago. Throughout evolution, the skeletal structures have been modified to fit the life style of each species. Various bones and teeth have taken on new forms and functions in relation to locomotor patterns, food habits, weight of animals, and many other parameters.

Similarities in Skeletal Structure

One of the main lines of evidence substantiating the theory of evolution is the similarity in basic skeletal structure found in fossil remains as well as exhibited in the living animals of today. Examine the skeletons on display, looking for similarities. Pay particular attention to the homology seen in the limb bones of various vertebrates. Using the human skeleton diagram as a guide, label the bones on diagrams of the frog, chicken, and cat skeletons.

Structure and Function

Having worked with the kinematic model, you are now able to predict and analyze the properties of leg/ankle/foot lever systems in vertebrates that have become modified during the course of evolution for producing powerful lifting forces versus providing rapid locomotory movements. Compare the skeletons of three mammals that have different life styles: a runner and leaper (cat), a digger (mole), and a flier (bat). Visualize the movements of the bones as they would operate in the living animal. What adaptations in relation to gait and life style of each particular animal can you observe in the skeletal structure? Also note the prominent bumps and knobs on each of the bones. These protuberances serve as attachment points for the skeletal muscles. More than just limb bones have been modified to adapt to the animal's way of life. Give specific details on how the following bones are adapted in each of the animals and why:

- skull, jaws, and teeth (head);
- vertebral column (back);
- ribs, sternum, and clavicle (chest);
- scapula, humerus, radius, ulna, metacarpals, carpals, and phalanges (forelimb); and
- pelvis, femur, fibula, tibia, metatarsals, tarsals, and phalanges (hindlimb).

APPENDIX A
Construction of the Kinematic Model

The kinematic model that is shown in Figure 10.3 is constructed from three pieces of 3" × 1" pine. Both the top crosspiece and "foot" are 10" long and connected by a 16 1/2" leg. The top cross-piece is nailed and glued to the leg using a lap joint. The foot is connected to the leg at the "ankle" by a 1/4" bolt that is 1 1/2" in length. Screw five hooks into the top crosspiece, and five 1/2" screw eyes into the foot at a height of 1 1/2". Directly below each of the eyes and at a height of 3/4", drill a 5/16" hole through the foot, large enough for a pencil to be inserted.

Hooks, eyes, and holes are spaced as follows: Distance between Positions 1 and 2: 1". Position 2 and "ankle" bolt: 2". "Ankle" bolt and position 3: 2". Positions 3 and 4: 2". Positions 4 and 5: 2".

To allow for mobility of the foot in the ankle region, cut a V-shaped groove that is 3/8" deep on the back of the foot. In order for the bottom of the leg to fit into this groove, the end must be rounded and a 3/8"-thick layer removed from the bottom 3" of the front.

Three spring scales are required for each model and can be ordered from Carolina Biological Supply Company (Ohaus pull-spring scales). The bottom end of the scale is hooked to the screw eyes on the foot. Force is applied by pulling on a chain that connects the top of the scale to the hooks on the cross-piece.
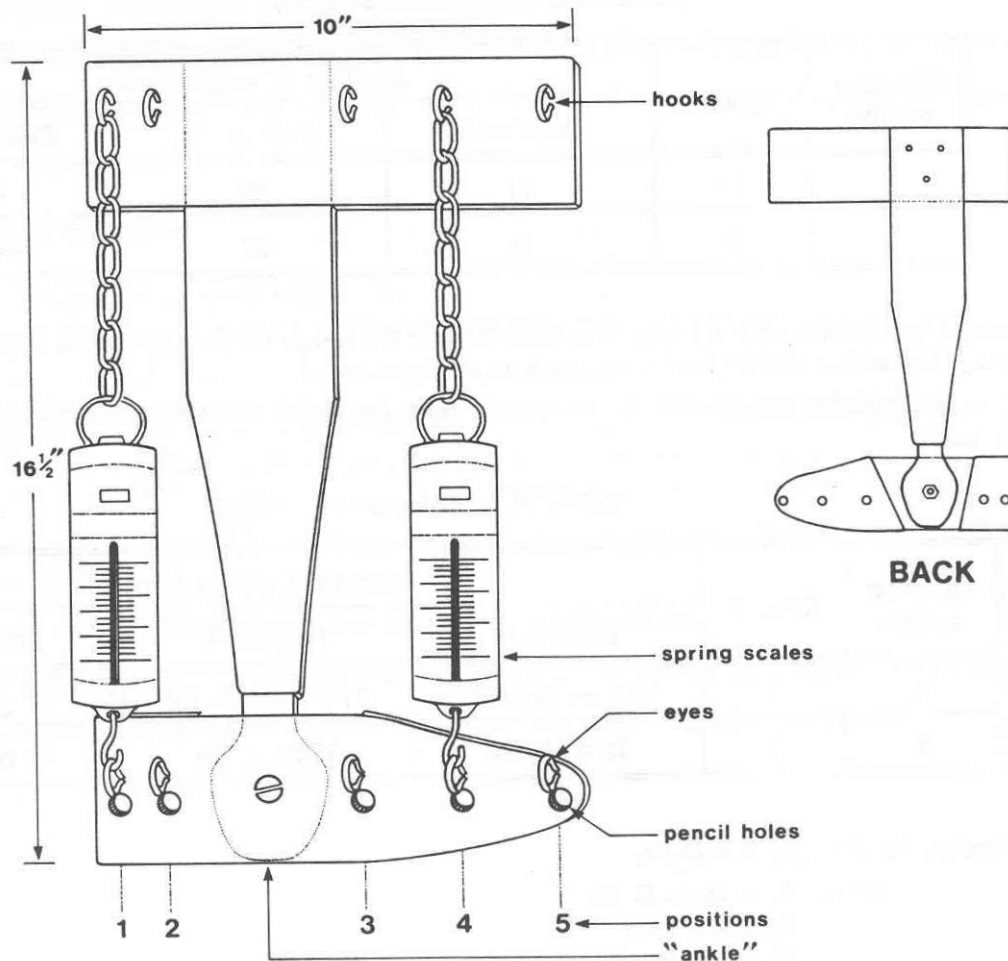

Figure 10.3. Plan of the kinematic model.

APPENDIX B

Possible Answers to Worksheets

Introduction to the Kinematic Model

1.   Yes. $F_1D_1 = F_2D_2$ (8 oz × 2" = 8 oz × 2"). These values *must* be equal at the start. If they are unequal, adjust the top of the scale.

2.   Yes. As F_1 increases, F_2 decreases. (For example, 12 oz × 2" = 6 oz × 4"). Do not expect perfection. Students should be looking for trends.

3. $F_1 + F_2 = F_3$ (16 oz + 16 oz = 32 oz).

Measurement of Muscle Force (F_1)

1.   The two parameters that remain constant are D_1 (the insertion of the muscle onto the heel) and F_2 (the animal's weight).

Table 10.1. F_1 values (readings from scales).

Question number	Species	Position of weight force		
		Position 3	Position 4	Position 5
2.	1*	11	22	32
3.	2	16	32	44**

*Species 1 is a species with a longer heel bone relative the rest of the foot, such as a human or bear. Species 2 is a species with a shorter heel bone, such as a deer or cat.

**Again, the students should look for tendencies, since the scales lose some accuracy when stretched to the higher values.

Table 10.2. Calculated F_1 values.

Question number	Species	Position of weight force		
		Position 3	Position 4	Position 5
4.	1	10.6 oz (0.66 lb)	21.3 oz (3.66 lb)	32 oz (2 lb)
5.	2	16 oz (1 lb)	32 oz (2 lb)	48 oz (3 lb)

To calculate for F_1: $F_1 = F_2D_2/D_1$

where: $F_2 = 16$ oz (1 lb)
$D_2 = 2", 4", 6"$
$D_1 = 3"$ (at position 1) or 2" (at position 2)

6. Position 5: The most power (force) must be exerted when the distance involved at the end of the stride is furthest from the ankle joint. Position 3 requires the least power.

7. Cartilage. It is tough but slippery so reduces friction.

Measurement of Power Efficiency

<p align="center">**Table 10.3.** Power efficiency.</p>

Question number	Species	Position of weight force		
		Position 3	Position 4	Position 5
1.	1	$16/10.6 = 1.5$	$16/21 = 0.75$	$16/32 = 0.5$
2.	2	$16/16 = 1.0$	$16/32 = 0.5$	$16/48 = 0.33$

To calculate: $PE = F_2/F_1 = 16$ oz$/F_1$ values from Table 10.2

3. Position 3. The power efficiency is greatest at the proximal metatarsals.

4. Species 1 has the most power efficiency; it has the longest calcaneus relative to the rest of the foot.

5. It is easier to lift a heavy object standing in position 3. You don't try to move a refrigerator standing on tiptoe.

Measurement of Speed Efficiency

1. Calculation and comparison of speed efficiencies:

	B_1	B_2	B_3
M_1	$B_1/M_1 = 20/32 = 0.63$	$B_2/M_1 = 30/32 = 0.94$	$B_3/M_1 = 34/32 = 1.06$
M_2	$B_1/M_2 = 20/16 = 1.25$	$B_2/M_2 = 30/16 = 1.88$	$B_3/M_2 = 34/16 = 2.13$

2. The greatest speed efficiency (B/M) is at B_3, at the toes for either species. The least speed efficiency is at B_1, close to the ankle.

3. Species 2 (the one with the shortest heel) has the greatest speed efficiency.

4. The species with the longest foot (from ankle to toe) and the shortest heel has the greatest speed efficiency.

5. Inversely proportional. As the power efficiency increases the speed efficiency decreases.

Measurement of the Work Output of a Muscle

Table 10.4. Work output.

Question number	Species	Position of weight force		
		Position 3	Position 4	Position 5
1.	1	2/3(1) = 0.66	11/3(1) = 3.66	2(1) = 2
2.	2	1(0.5) = 0.5	2(0.5) = 1	3(0.5) = 1.5

To calculate: $W = FM$

where: F = data from Tables 10.1 or 10.2
M = distance the muscle moves.

3.   It takes more work to stand on ones toes (position 5) than flat footed (position 3)

APPENDIX C
Further Reading

Alexander, R. McN. 1968. Animal mechanics. Sidgewick and Jackson, London, 346 pages.

Gans, C. 1974. Biomechanics: An approach to vertebrate biology. Lippincott, Philadelphia, 261 pages.

Gordon, J., E. 1988. The science of structures and materials. Scientific American Books.

Gray, J. 1953. How animals move. Cambridge University Press, 144 pages.

———. 1968. Animal locomotion. W. W. Norton, New York, 479 pages.

Hildebrand, M. 1960. How animals run. Scientific American, 202(5):148–157.

———. 1974. Analysis of vertebrate structure. John Wiley and Sons, New York, 710 pages.

McMahon, T. A. 1984. Muscles, reflexes, and locomotion. Princeton University Press, 331 pages.

Schmidt-Nielson, K. S. 1972. How animals work. Cambrdige University Press, 114 pages.

Vogel, S. 1988. Life's devices: The physical world of animals and plants. Princeton University Press, 367 pages.