

# Cornell Institute for Biology Teachers

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**Title:**

**PHYSIOLOGY; PHYSICS; “PHOOT”**

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**Appropriate Level:**

Life Science, High School, Honors, or Advanced Placement Biology. The level of the lab can be increased by covering more complex background material on Biomechanics.

**Abstract:**

In this lab students will investigate the application of physical principles to a living organism. Students will analyze the foot and its function as a machine by applying lever mechanics to the “walking” foot. Analysis will incorporate anatomical terms for some of the muscles and bones involved in plantigrade motion.

**Special Notes:**

“It has been our experience that many instructors of biology, (whether they be at the junior high level all the way up to the college level) have a ‘natural’ aversion to physics. We, the authors, believe it is especially important that the teachers implementing this exercise should try not to let this aversion (should one exist) carry over into the classroom. Since this is probably the place that the students will first learn how to approach the sciences, one can see that the teacher’s attitude is as important as the students’. Also, it is important to remember that the students (usually) have no preconceived notions about physics except what they hear from teachers like yourself. Hopefully, any physical principals presented here are relevant enough to apply to a biological setting and they are presented in a way that is interpretable enough so that both the teacher and the student have an educationally profitable experience.”

**Time Requirement:**

Two 45-minute periods are required to complete this laboratory exercise. This time will also include discussion of principles with your students.

# Additional Teacher Information

## Objectives

- Students will view the body as a complex, mechanical machine.
- Students will learn about anatomical structures involved in ankle joint mechanics.
- Students will describe three classes of levers.
- Students will apply lever mechanics to the functioning of the foot in the process of walking.

## Materials

A balanced “see saw” model, designed by Young Hui Chang and obtainable from the Cornell CIBT lending library is an integral component of this laboratory exercise. An articulated skeleton would be ideal to have available but is not a necessity. A videotape used in the “These Boots Are Made for Walking” section is also available through CIBT lending library.

## Per lab team

- bathroom scales that measure kilograms, a block of wood to fit on scales (large enough to accommodate one foot)
- 1-100g mass and 1-50g mass
- 2 spring scales (ideally measuring newtons but grams would also be OK)
- see saw model
- 2 different colored pencils or crayons
- calculator

## Background Information

- Students must have an opportunity to review the technical names for the anatomical directions used in this laboratory protocol. Terms in question include anterior, posterior, lateral, superficial, longitudinal, plantarflexion (flexion), dorsiflexion (extension), medial, and dorsal.
- Students must recognize that good science begins with observations of the natural world.
- For greatest impact, the students should be exposed to the concept that all the sciences are connected to each other in some way.

## Extensions

As extensions of this laboratory exercise you may wish to investigate the field of biomechanics, development of running shoes, medical treatment for diabetics who are prone to ulcers of the foot in pressure areas or how other animals are adapted to walking.

You are a plantigrade animal in that you walk and you stand on the soles of your feet. Your foot must withstand as well as transmit stresses associated with its contact with the ground in standing, walking, and running. Each foot is comprised of 26 separate bones. Your heel bone, (calcaneus) can act as a very useful lever as well as the posterior contact point of the foot.

The bones of your foot are tightly bound by ligaments that allow adequate movement despite the requirements of weight bearing and shock absorption. Compared to other primates, man's foot has gained strength at the expense of mobility. This is probably a reasonable trade for the continued use of an upright posture.

The muscles which control the position of the body's weight over the foot can have, indirectly, a marked effect in weight bearing.

When working, the heel and the ball of the foot are the striking points. The path of weight bearing begins with the striking heel and passes forward (slightly off-center). The ball of the foot is the site of rapid weight transfer from lateral to medial. This now places the burden on the big toe to push off. The arch of the foot absorbs the shock of weight bearing and locomotion. The energy of shock source is shared by many small bones of the foot.

A lever whose effort arm is the longer of the two, whether it be a first or second class lever, favors force. Less effort is required to overcome a resistance than it would take to overcome without the lever. It gains this advantage at the expense of speed and range of movement. On the other hand, a lever whose resistance arm is longer, whether it be a first or third class lever, favors speed or distance.

In levers, the ratio between the effort applied to the lever and the resistance overcome by the lever is known as the MECHANICAL ADVANTAGE which is shown by the following equation:

$$\text{Mechanical Advantage (M.A.)} = R/F \text{ or } FA/RA$$

If the resistance is close to the fulcrum and the effort is far from the fulcrum, a small effort exerted over a relatively large distance can be used to move a large resistance over a small distance. This lever operates at a mechanical advantage. Systems that function at a mechanical advantage are slower, more stable, and used when strength is important. Third class levers always operate with great speed and mechanical disadvantage. In lever systems that operate at a mechanical disadvantage, effort is lost but speed is gained which in some cases can be a distinct advantage.

## Answers to questions

### Step I These Boots Are Made For Walking

*Some possible observations that your students might make include:*

- *comments on a stance and a swing phase for a given leg*
- *flexing of the ankle joint in early swing stage and extending in stance phase*
- *knee straightens as leg swings forward, heel hits ground first, then the front of the foot hits, leg rotates about the ankle, heel rises first, weight supported by the ball of the foot (for some people not used)*
- *knees go up when foot is lifted; and a myriad of other comments.*

*It would probably be best to simply show the tape at the beginning of the lab and re-show at the end, having students make their observations at that time.*

### Step II Foot and Leg Diagrams

*Students will color various bones and connective tissue on drawings of the human leg. This will help them focus on muscle and bone structure.*

### Step III Walk On By

*Try to encourage students to enlist some of the anatomical terms that they have been introduced to in the Step II activity. Students should be cautioned to use good descriptors that help visualize the actions of the foot in walking.*

### Step IV What Is A Lever?

**Class I Lever** *For a 100g mass acting as the resistance load at a distance of  $x$ , a 50g mass on the other side must be twice as far away ( $2x$ ) from the fulcrum to balance the “see-saw.”  $FA = (R \times RA)/F$*

**Class II Lever** *For 100g resistance load at distance  $x$ , an effort force at a distance greater than  $x$  will be smaller than 100g. For example, at an effort arm of  $2x$ , the effort should be 50g. As the 100g resistance load gets closer to the fulcrum the  $R \times RA$  term decreases(!), thus, the effort force should also decrease.  $F = (R \times RA)/FA$*

**Class III Lever** *With a 100g resistance load at the end of the “see-saw” (distance  $x$  away), the spring scale at  $x$  should be 200g. As the scale moves towards the fulcrum, the effort arm is decreasing so the effort force must increase in order to keep the  $(F \times FA)$  term constant to balance the “see-saw.”  $F = (R \times RA)/FA$*

## Step V My Lever Systems

*The distance between the ankle drop line and the metatarsal should be approximately twice that of the distance to the calcaneus.*

## Step VI and VII Forces In Action

*In both cases, the toes are to the left of the page, and the heel is to the right of the page.*

*Case A depicts the foot as a Class I Lever. The fulcrum is the dark triangle which represents the ankle joint. The resistance load is the force under the metatarsal which is  $F_S$ , or the body weight read by the bathroom scale. The effort force is at the right of Diagram A, which shows the muscle force ( $F_M$ ), of the gastrocnemius. The resistance arm is the distance between the metatarsal and the ankle drop line, and the effort arm is the distance between the ankle drop line and the calcaneus. So,  $F \times FA = R \times RA$  translates into:  $F_M \times FA = F_S \times RA$ .*

*Case B depicts the foot as a Class II Lever. The metatarsal resting against the ground acts as the fulcrum (dark triangle). The resistance load is the force of the tibia pushing down on the ankle joint ( $F_B$ ). It acts at a resistance arm equal to the distance between the metatarsal and the ankle drop line. The effort force is further from the metatarsal and is represents the gastrocnemius muscle force ( $F_M$ ). The effort arm is the distance between the metatarsal and the calcaneus.  $F_M \times FA = F_B \times RA$ .*

*Since the distance from the ankle drop line to the metatarsal is about twice the distance to the calcaneus, the gastrocnemius muscle force ( $F_M$ ) should be about twice the body weight in order to maintain a balanced equilibrium when standing on the wooden block (following lever mechanics for a first class lever). Since the calcaneus is about 1.5 times further from the metatarsal than the ankle, the force of the tibia on the ankle joint ( $F_B$ ) should be about three times body weight (following lever mechanics for a second class lever). The reason that the tibia can produce that much force is not because one gets "heavier," but because the gastrocnemius muscle attaches above and below the ankle it compresses the tibia into the ankle joint with a force much greater than body weight. Remember, this is for simply standing on the wooden block, imagine the high forces produced in your bones when you walk, run and jump!*

*The foot can be classified as either I or II depending upon the fulcrum, resistance and effort used. See above descriptions for the foot as first and second class levers.*

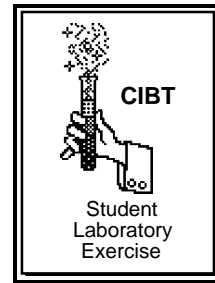
## Step VIII What Does Carrying A Backpack Have To Do With My Foot?

*Adding an extra weight ( $W$ ) to the body weight will result in the gastrocnemius muscle force being increased by  $2W$  ( $F_M = 2F_S + 2W$ ). Thus, the tibial bone-force would increase by  $3W$  ( $F_B = 3F_S + 3W$ ). Since many teens may be self-conscious about their weights, if you would like to have a class list in order to run a statistical analysis, etc. you may consider simply finding  $F_M$  and  $F_B$  in terms of  $F_S$ . In fact, this method is a good tool that allows for a much easier comparison of individuals that may be very different on an absolute scale, but very similar physiologically.*

## Step IX Some Evolutionary Thoughts

*Students will color in the hind limbs of a cat, a horse, and a human (leg) and compare structure and function of the various bones. A discussion of the fossil record and comparative anatomy as it relates to evolution can follow.*

# Physiology, Physics, Phoot



## Introduction

The human body is an amazing machine designed over thousands of years to work at its optimal level. One of the most amazing feats of the body is movement. This movement occurs through the concerted action of striated muscle, tendons, ligaments, and bones. With the amount of force exerted by our muscle onto our bones, its amazing that our bones don't break every time we walk, much less run! The purpose of this exercise is to introduce you to the science of biomechanics, the application of physical principles to biological specimens. You will examine the human foot and its function as a tool for walking. You will apply the principles of levers to determine the force exerted on some of the foot bones when we walk.

## Objectives

In this lab you will:

- view the body as a complex, mechanical machine
- learn about anatomical structures involved in ankle joint mechanics
- describe three classes of levers
- apply lever mechanics to the functioning of the foot in the process of walking

## Materials (Per lab team)

- bathroom scales that measure kilograms, a block of wood to fit on scales (large enough to accommodate one foot)
- 1 100g mass and 1 50g mass
- 2 spring scales (ideally measuring Newtons but grams would also be OK)
- see-saw model
- colored pencils or crayons
- calculator

## Procedure

### Step I—"These Boots Are Made For Walking"

You will be watching a short videotape that shows people walking. Please observe their lower legs and feet and write down any observations that you make in the space below. Exclude footwear and clothing and attend to what you see the feet and legs doing in the process of walking or standing.

### Step II--Foot and Leg Diagrams

Included in your lab packet are several anatomical plates from "The Anatomy Coloring Book" by Kapit and Elson. At the top of each plate there is a list of anatomical structures, each has a small case letter to the lower right. Additionally, there are some paragraphs of information. Before doing the tasks below, look at the key and read the paragraphs to help you orient yourself on the page. The purpose of this part is to get you to focus on specific parts of the leg for some later work that you will do.

- Color the **tibia** labeled "B" in plate 30, anterior and posterior view
- On plate 31, color the tibia (with the same color as in plate 30) on the lateral, posterior, and medial views
- On plates 57 and 58 color the **Gastrocnemius** muscle.
- On the same plates, using a different pencil, color the **Calcaneal** (Achilles) tendon.
- Plate 31 shows the foot bones. Color the Calcaneus bone labeled "B" in all views.
- Color the **metatarsal** bones labeled "F" in the four large views.

Make careful observations of the lateral and medial longitudinal arches.

### **Step III—“Walk on By”**

You and your partner will take turns being walker and writer. For two to three minutes you will observe your partner’s walking motions. You may wish to change positions occasionally as you write. You will watch the lower leg and foot and write down what you see the walker doing. Pay particular attention to the heel strike and ball of the foot take-off during the walking steps. Watch for flexion and extension as well as signs that the gastrocnemius muscle and Achilles tendon are “working”. Some individuals have more pronounced muscle outline than others. The walker may switch speed periodically. (Although a nice slow walk is best for observing.) Try to incorporate some of the anatomical terms that you learned from the coloring exercise. It is best to roll up pant legs for this observation. If possible, remove footwear to make observations easier.

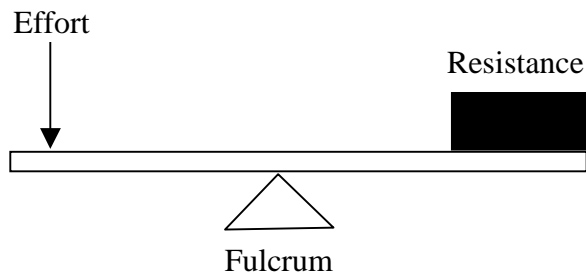
## Step IV--What is a Lever?

A reminder from your foot! A machine is a device for doing work. One simple machine is a lever. All machines are concerned with at least two forces. One force is that put **into** the machines. The other **opposes** the operation of the machine, that is, the force the machine is designed to overcome. This is known as **resistance**.

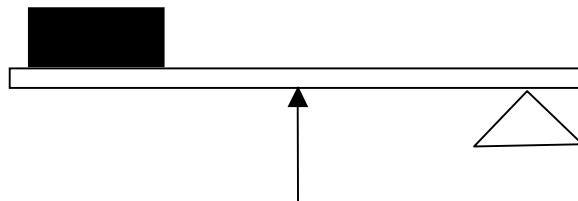
A lever is a bar turning about a fixed point, axis or **fulcrum**. There must be a force to operate the lever and there is a resistance to overcome. When applied to body mechanics, the foot is the lever, the force for operating it is produced by muscular contraction and the resistance can be internal or external depending upon one's perspective on the situation.

A lever is a rigid bar that moves on a fixed point, or **FULCRUM**, when a force is applied to it. The applied force, or **EFFORT**, is used to move a **RESISTANCE**, or weight. Depending on the relative position of the effort, fulcrum, and the resistance, the lever belongs to one of 3 classes.

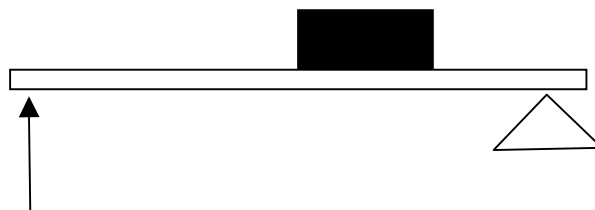
In the **FIRST CLASS LEVER**, the effort is applied at one end of the lever and the resistance is at the other end, with the fulcrum somewhere between them.



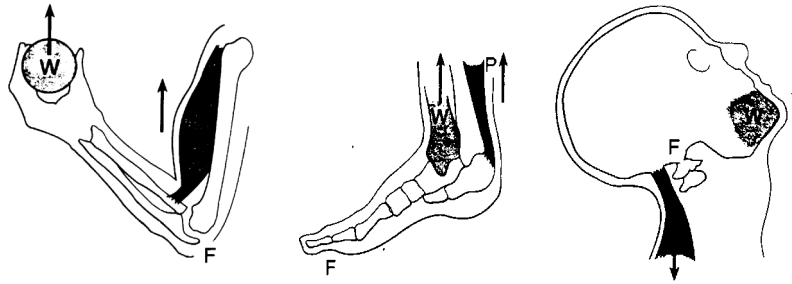
In **SECOND CLASS LEVERS**, the effort is applied at one end of the lever and the fulcrum is located at the other with the resistance at some intermediate point between them.



In **THIRD CLASS LEVERS**, the effort is applied at a point between the resistance and the fulcrum.



In the drawings below, label the effort force (E) and the resistance force (R), then identify which class of lever is represented by the drawings. Explain why.



The length of the lever between the fulcrum and the effort (F) is known as the **EFFORT ARM** (FA). Similarly, the portion of the lever between the fulcrum and the resistance (R) is the **RESISTANCE ARM** (RA). In a second class lever the effort arm is always longer than the resistance arm. In a third class lever the resistance arm is always longer than the force arm. In the first class lever, however, the arms may be equal or different lengths depending upon the position of the fulcrum. Any lever balances when the product of the effort and the effort arm equals the product of the resistance and the resistance arm as shown by the following equation:

$$\mathbf{F \times FA = R \times RA}$$

## Practice Questions

### Class I Lever

Using the *balanced* “see-saw” model, hang a 100g mass halfway between the fulcrum and the end of one side of the “see-saw.” Note the distance between the fulcrum and the mass. Let us arbitrarily call this distance the resistance arm. Find the effort arm (on the other side of the fulcrum) at which a 50g mass would balance the see-saw.

\*\*(Special Note: the model you are using is not a sensitive instrument therefore there may not be a *standard* answer.)

### Class II Lever

Again hang a 100g mass on one side of the fulcrum. Now attach a spring scale *at the end* of the “see saw” *on the same side* of the fulcrum. Note the Effort required by the spring scale to balance the “see-saw.” \_\_\_\_\_ Now move your mass closer towards the fulcrum and repeat. \_\_\_\_\_

Did the scale reading go up or down? \_\_\_\_\_ Why?

### **Class III Lever**

Hang the 100g mass at the end of the “see-saw.” Now attach the spring scale at a point approximately half-way between the fulcrum and the mass. What does the spring scale read? \_\_\_\_\_ Now move your scale towards the fulcrum. What does it read now?

\_\_\_\_\_

Did your scale reading go up or down? \_\_\_\_\_ Why?

(As the model is not a sensitive instrument, the important point is “up or down.”)

### **Step V--My Lever Systems**

Weigh yourself on the bathroom scales provided. What is your mass?

\_\_\_\_\_ Kg (If your scale is calibrated in pounds, divide your mass in pounds by 2.2 to get your mass in Kg.)

Now find your force, which is the effect of gravity on your mass. Multiply your mass by  $9.8\text{m/sec}^2$  to find the answer.

\_\_\_\_\_ Newtons

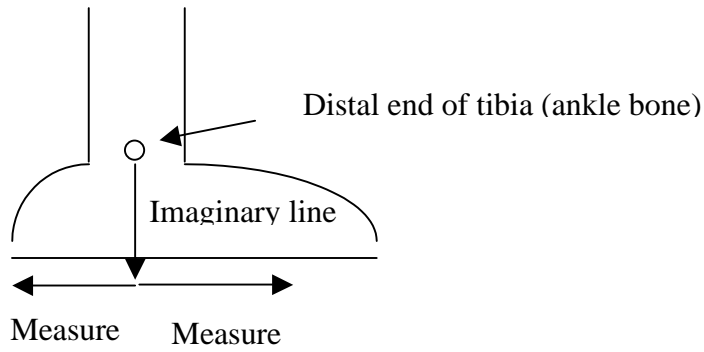
Find the distal end of your tibia (you call this your ankle bone) and drop an imaginary vertical line from your tibia to the floor (see diagram on the following page).

Measure the distance from that point to the edge of your heel bone, the calcaneus.

\_\_\_\_\_ cm

Measure the distance from the tibia point to the edge of your metatarsal, the ball of your foot.

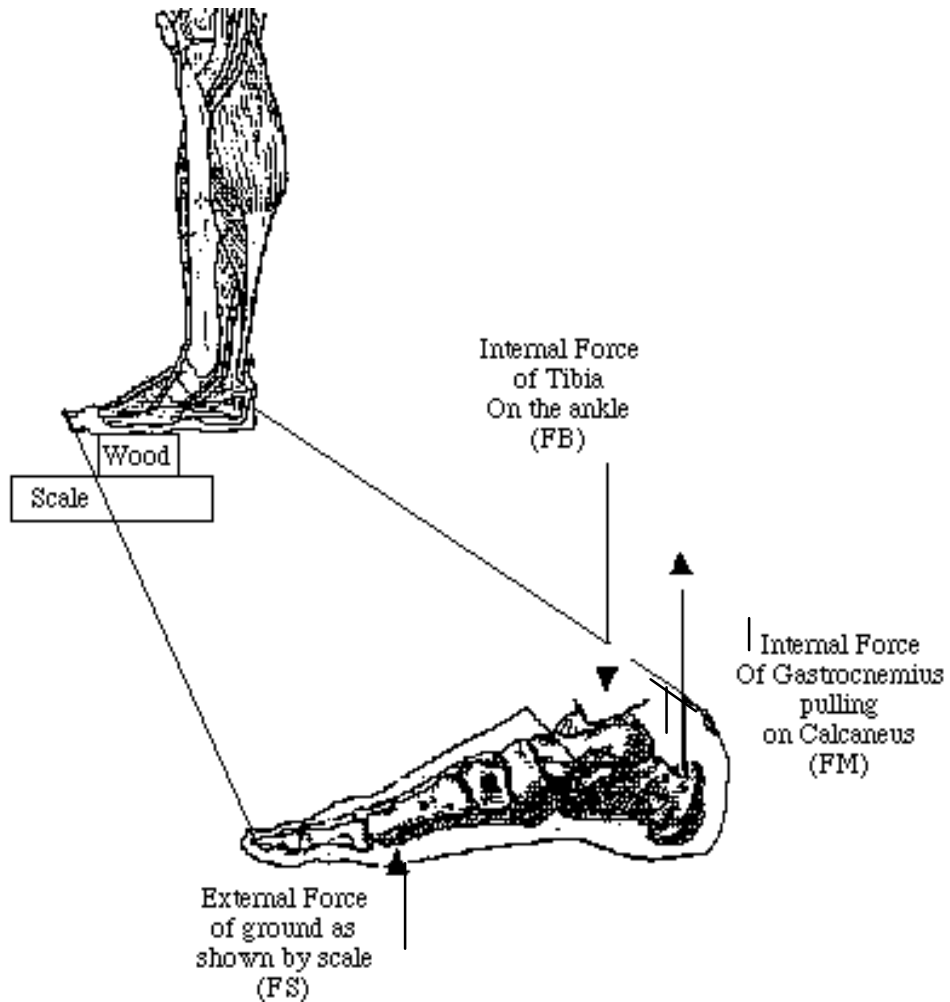
\_\_\_\_\_ cm



You may wish to go back and look at your anatomical drawings to "get your bearings."

### Step VI—Forces in Action

Study the following diagram:

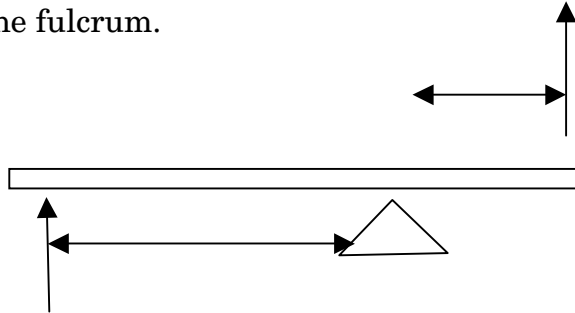


## Step VII—How Forces Act on My Foot

Use diagrams A and B to show what forces are acting on your foot when you are being supported by the ball of your foot. In both cases, the “see-saw” represents your foot. However, the resistance and effort forces are in different places in each case because we can view the ankle as the fulcrum in one case, and the ball of the foot as the fulcrum in the other. Fill in the appropriate blanks with the data that you have recorded.

A. Class of Lever \_\_\_\_\_

Label  $F$ ,  $F_A$ ,  $R$ ,  $R_A$ , and the fulcrum.



Consider the three forces acting on the foot ( $F_s$ ,  $F_B$ ,  $F_M$ ):

Which force ( $F_s$ ,  $F_B$ ,  $F_M$ ) acts as the effort force?  $F = \underline{\hspace{2cm}}$

Which acts as the resistance force?  $R = \underline{\hspace{2cm}}$

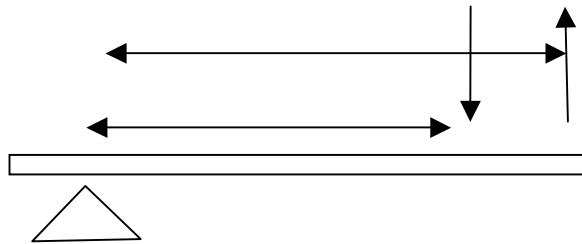
$$\mathbf{F \times F_A = R \times R_A}$$

Rewrite this equation substituting your answers for  $F$  and  $R$  from above.

Using your Body Weight ( $F_s$ ) and the measurements you made on your foot, can you solve for the unknown(s) in this equation? What does this number correlate to in real life?

B. Class of Lever \_\_\_\_\_

Label F, F<sub>A</sub>, R, R<sub>A</sub>, and the fulcrum.



Which force acts as the effort force?

F=\_\_\_\_\_

Which force acts as the resistance force?

R=\_\_\_\_\_

Using the equation as you did for Case A, substitute your answers for F and R.

$$\mathbf{F \times F_A = R \times R_A}$$

Now using the information gained from solving case A, you should be able to go to case B and solve for the unknown(s).

What does this information tell you about the forces acting on your bones?

What class lever is your foot? Justify your answer.

### Step VIII—What does Carrying a Backpack Have To Do With My Foot?

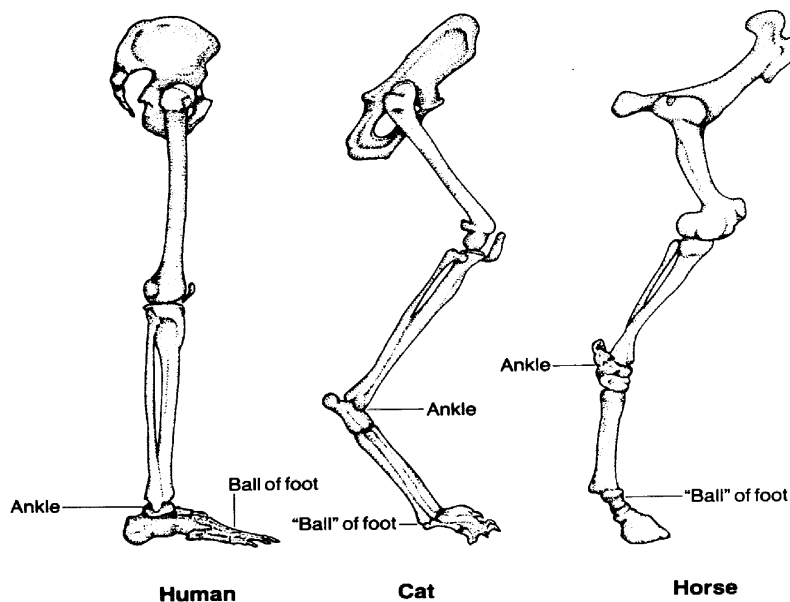
Now that you are an expert at ankle joint mechanics, repeat Step V while holding an additional known weight ( $W$ ). Your bodyweight should now be increased by  $W$ .

How does this increase in body weight affect the muscular force required of the gastrocnemius ( $F_M$ )? The load on the tibia ( $F_B$ )? Repeat the calculations performed in Step VII for this *new* bodyweight.

### Step IX--Some Evolutionary Thoughts

Shown below are drawings of the hind legs of a human, a cat, and a horse. For each animal:

- Color the pelvis blue
- Color the femur red
- Color the tibia orange
- Color the fibula green
- Color the ankle yellow
- Color the foot bones brown



Contrast the shape and orientation of the pelvis in each of these three animals.

Contrast the shape and length of the foot relative to the overall length of the leg.

Large, bulky muscles are attached to thick, heavy bones. What can you say about the upper leg muscles of the three animals above?

What do you think these three features have in relation to the speed and agility of the animals above?