Structural/Functional Relationships in the Muscle/Skeletal System

Preparation: lever web tutorial - read page 17

Animals run, jump, swim, climb and dig. Their ability to perform these complex movements depends of the structural relationships of skeletal elements and the development of the muscular system that provides for movement. The types of joints that connect bones to each other will limit the range of motion, but the speed, direction and efficiency of that motion will depend on the way the muscles attach to the skeletal elements as well as their size.

Many of the skeletal elements you examined last week function as levers. These levers are under the control of muscles. By understanding the underlying mechanics of lever systems it will be easier to understand the adaptations that have evolved in skeletal design to allow vertebrates to exploit a variety of habitats and food sources. In this laboratory you will be exploring the structural and functional relationships of the muscle/skeletal systems that affect both feeding and locomotion.

Levers are made up of two components: a stiff rod and a fulcrum about which the rod rotates. Many of the long bones in the body function as levers with the joint between the bones serving as the fulcrum. In order for bones to move a force must be applied that overcomes the tendency of the bone to stay at rest. In animals this force is exerted through the contraction of muscles that attach to bones by tendons. The location of the fulcrum with respect to the point of muscle attachment will influence the speed a bone can move and the efficiency with which muscular force is translated at the moving end of the bone.

Functionally muscles have three important regions. The **origin** attaches the muscle to a relatively stable bone and the **insertion** attaches it to a relatively more mobile bone (Figure 1). Between the tendons of the origin and insertion lie the contractile fibers of the muscle. The length of the muscle may change as much as 30% during contraction and a pull is exerted at both ends of the muscle. If the force of contraction is sufficient to overcome the resistance to motion the bone at the insertion will move. Explore this idea by placing your arm on the table with the palm up. Contract your biceps to move your palm toward you mouth. Now place your hand under the table and do the same thing. What is happening. Why are the results different?

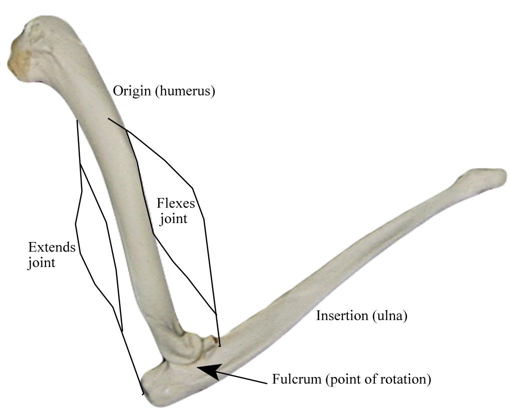


Figure 1. A simple lever system as represented by the junction between the humerus and ulna. In this example, the humerus is the more stable of the two bones and serves as the origin for the two muscles shown. The ulna is the more movable bone and functions as the insertion. The two muscles shown function in opposition. When the flexor contracts the ulna moves towards the humerus. When the extensor contracts the ulna moves away from the humerus.

Skeletal levers are simple machines that translate forces from one point to another. The contraction of a muscle creates an **in-force** that is translated into an **out-force** as the bone at the insertion moves. The limbs and jaw provide examples of simple levers, where a bone rotates about a fulcrum. The efficiency with which the force of the contracting muscle is transmitted will depend on the structural arrangement of bones in relation to the point of muscle attachment.

I. How does the position of muscle attachment affect the efficiency of force transmission?

The experimental system

We will use a simple experimental system to explore the mechanics of how muscles and bones act together to produce force. The experimental set-up is similar to the muscle/skeletal elements that extend the forearm (figure 1). In the model (figure 2), the spring creates an **in-force** that is directed upwards. This creates an **out-force** that is directed downwards. You can apply a specific amount of in-force by tightening a spring-loaded scale. This represents the contraction of a muscle attached to the **in-lever arm** by clamps rather than a tendon. The amount of out-force generated at the **out-lever arm** can be measured using a force transducer connected to a computer data acquisition system. You can explore the effects of changing the location where the **in force** is applied by loosening the clamps and sliding them along the ruler. Increasing the distance between the fulcrum and the **in-force** would be like lengthening the elbow.

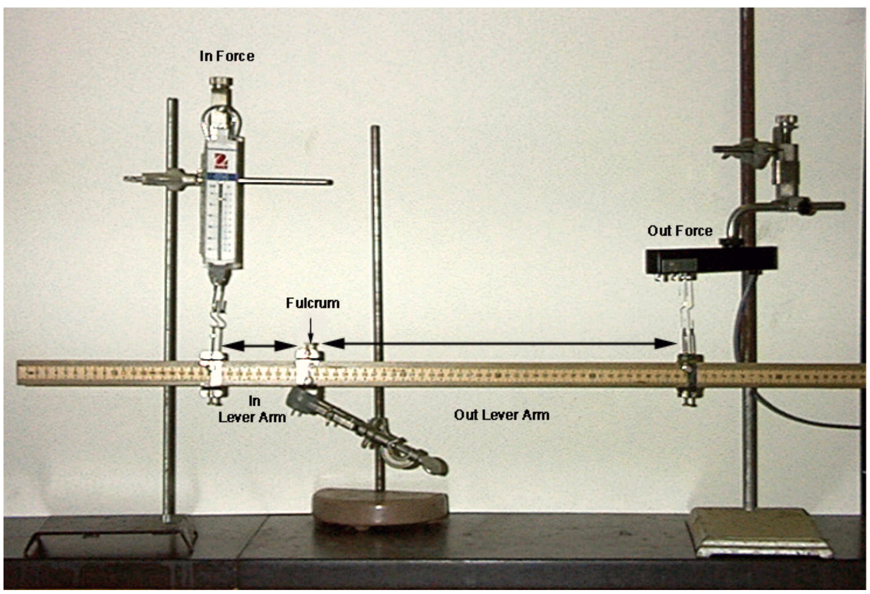


Figure 2. Set up for exploring how the length of the in and out lever arms affects the efficiency with which the in-force is translated into an out-force

Here are some points to keep in mind as you work with the lever system.

- **When changing the length of the in-lever arm, unhook the ruler from the out-force transducer. Otherwise, you may break it.**
- Be sure that all of the devices are set at right angles to the rulers, otherwise the forces will not be accurately measured.
- Be sure that there is no friction at the fulcrum, if the ruler is not free to move at the fulcrum, the forces will not be accurately measured.
- Initially you will need to apply some force at the in-force scale to hold the ruler in place vertically. Start with an in force of 50 grams. This will create an “initial” out-force that can be measured by the force transducer.

- Attach the out-lever arm and start the data acquisition system prior to increasing the in force. This will allow you to record the "initial" and "final" out-force and **calculate the change in out-force that results from a known change to the in-force.**

How to use the data acquisition system.

Before starting the experiment familiarize yourself with the data acquisition system.
→**Start menu**→ select: **programs - BIOPAC → bsl student lab pro v 3.6.7**
→**Open File** → select: **p:/data /biology/biol10/lever.acq**
→**Click on full screen toggle.** What you see is a record for a lever experiment that was collected previously. Note the positions of the various buttons that will allow you to modify the data display (Figure 3.).

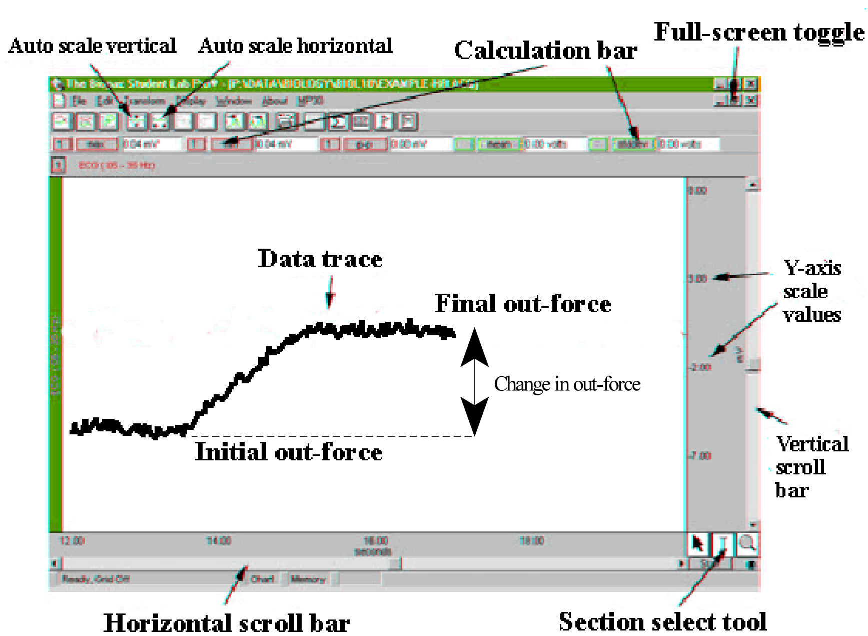


Figure 3. Sample image from the BIOPAC Student Pro software. A typical data trace from this experiment is shown.

- Time is on the x-axis (horizontal).
- Magnitude of response, in grams, is on the y-axis (vertical).
- Scroll horizontally through the data trace using the **horizontal scroll bar**
- Move the record up or down vertically with the **vertical scroll bar**

To Collect Data

Using a constant in-force of 50 gm, evaluate the effects of changing the length of the in-lever arm on the force that can be generated at the out lever arm. This is similar to animals having different proportions in their skeletal systems or muscles attaching closer to the fulcrum of the lever.

- Set up a table to record in-lever arm length and the change in out-force. Use a 50gm change in in-force and keep the out-lever arm length constant. Document these two parameters in the table caption.

- Begin with the in-force (point of muscle attachment) close to the fulcrum and record the length of the in-lever arm.
- Attach the out-lever arm to the force transducer by lifting the ruler.
- →**Click the "start" button** (lower right corner) on the data acquisition unit and increase the in-force by tightening the spring scale 50gm.
- →**Click the "stop" button** (lower right corner). Lift the ruler to release the out-lever arm from the transducer.
- To determine the change in the out-force:
  - Set the horizontal and vertical scales so that you can see the entire data trace. Click on **"auto scale horizontal"** or **"auto scale vertical"**
  - Choose the section select tool (lower right corner).
  - Begin at a point in the trace where the initial out force is recorded. Click and hold the mouse button as you drag over the data trace and through the point of maximum out-force.
  - The change in force will automatically be calculated in the **p-p box** in the calculation bar (figure 3). The program calculates the difference between the minimum and maximum values recorded across the highlighted region of the trace. Record the change in out- force in your table.
- For successive measurements move the spring scale away from the fulcrum, record the length of the in-lever arm, reset the initial force on the spring scale, reattach the out-lever arm and repeat the above steps. Be sure you change the in-force the same amount for each step of the experiment.

<u>To analyze the data:</u>

The change in out-force can be used to calculate the force efficiency of the lever. It is a measure of how much of the 50 gm in-force is translated into an out-force. By calculating the ratio of the out-force to the in-force you have a measure of the mechanical efficiency of the lever.

- Calculate the Force Advantage (FA) and record it in your table.

$$\textbf{Force Advantage} = \textbf{Force}_{out}/\textbf{Force}_{in}$$

- Use Excel to graph the the relationship between the length of the in-lever arm and the FA. The figure caption should include the out-lever length and the magnitude of the in-force.

II. How does the position of muscle attachment affect range or speed of movement?

The speed advantage of a muscle/lever system depends on the amount of movement achieved at the working end of the bone in relation to the amount of movement in the muscle. Systems in which a small muscle contraction results in a large range of bone motion would be considered efficient. Speed Advantage (SA) is the ratio of the distance moved by the bone compared to amount of muscle contraction. When working with skeletal elements the ratio of the length of the in-lever arm to the out lever arm provides a good approximation of the SA

$$\textbf{Speed Advantage (SA) = Distance Bone moves/ muscle contraction} = L_{out}/L_{in}$$

Consider the muscle/skeletal lever on the right. **Circle the L_{in} position at which a muscle contraction of 1cm would result in the greatest bone movement at L_{out}**

➤ Sketch a graph that would represent the relationship between the SA of a lever and the length of the in-lever arm.

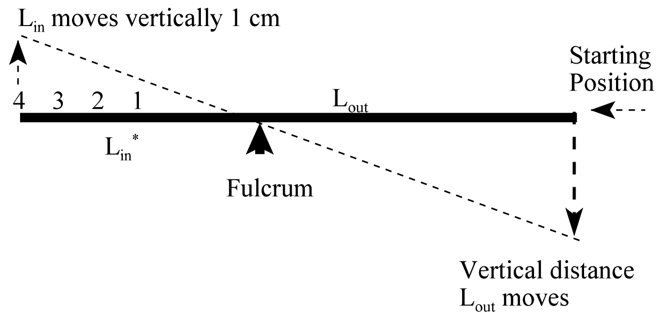
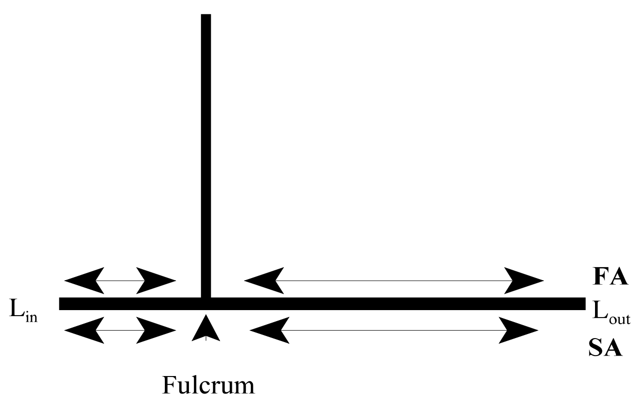


Figure 4. The effect the position of muscle attachment along L_{in} has on the vertical movement of L_{out}.

➤Before proceeding, examine your graphs of the relationship between the point of muscle attachment (length of in-lever arm) and the force or speed advantage of a lever. Then examine the diagram below. Indicate with a + or - at the point of each arrowhead the change in FA or SA that would result if the length of the lever arm was modified in the direction of the arrowhead.



Use your knowledge of lever mechanics to make predictions about structure of vertebrate forelimbs and jaws.

➤Using the same length for $\mathbf{L_{out}}$ sketch two forelimbs: one with a high FA and one with a high SA. For simplicity consider only the muscle that would extend the joint (Figure 1).

➤Using the same length for $\mathbf{L_{out}}$ sketch a jaw that would have a high FA at the molars and one that would have a low FA (Figure 5). How could you might modify L_{out} to increase SA at the incisor.

To test your predictions about how the structure of vertebrate jaws and forelimbs have evolved to meet the needs of the organism, proceed to either part III (jaws) or part IV (forelimbs)

III. How have vertebrates modified the structure of the jaw to increase force or speed advantage?

The jaws of vertebrates function as levers and the amount of force or speed that can be exerted at the point where food is captured or shredded depends in part on the structure of the lever system. You will be examining the jaws from two orders of mammals: Carnivora and Rodentia. Carnivores are meat eaters and rodents are primarily herbivores.

As you work with the carnivore jaws carefully examine the articulation between the jaw and the skull. Note the elongate nature of the condyloid process. When the jaw moves up and down the condyloid process can also slide laterally. The small incisors in the front of the jaw hold food, while the long, pointed canines are adapted for piercing and tearing. The sharp premolars and molars are designed for cutting. The first molar in the lower jaw, the **carnassial** is greatly enlarged for shearing, cutting and/or crushing food. Move the jaw up and down and note from both lateral and ventral orientations how the carnassial and premolars in the lower jaw slide past the teeth in the upper jaw as the mouth closes.

Compare a carnivore jaw to that of a rodent. Note the differences in the shape of the jaw and condyloid process as well as the size and shape of the teeth. The ball shaped condyloid process allows a rotary action during chewing. The jaw can slide forward and backward or from side to side. Note how the large incisors fit together and slide past each other as you rotate the jaw. The incisors are designed for gnawing and grow throughout a rodent's life. They are continually worn down and sharped as they slide past each other. The remaining teeth are used to grind the food.

Both types of jaws function as levers (Figure 5). We will consider only the vertical components of a bite. Keep in mind that the actual movements associated with food processing are much more complex. The condyloid process which articulates with the skull functions as a fulcrum. The large masseter muscle provides the **in-force** to elevate the jaw. It originates on the zygomatic arch and inserts along the masseteric fossa and angular process. The length of the **in lever arm** can be measured as the distance from the articular surface of the condyloid process to the base of the angular process where the in-force is exerted by contraction of the masseter. For simplicity we will consider the distance from the condyloid process to the middle of the premolar/molar tooth row as the length of the **molar out-lever arm** and the distance from the condyloid process to the anterior surface of the incisors as the length of the **incisor out-lever arm**. These represent the location where the out forces of biting and processing food could be measured.

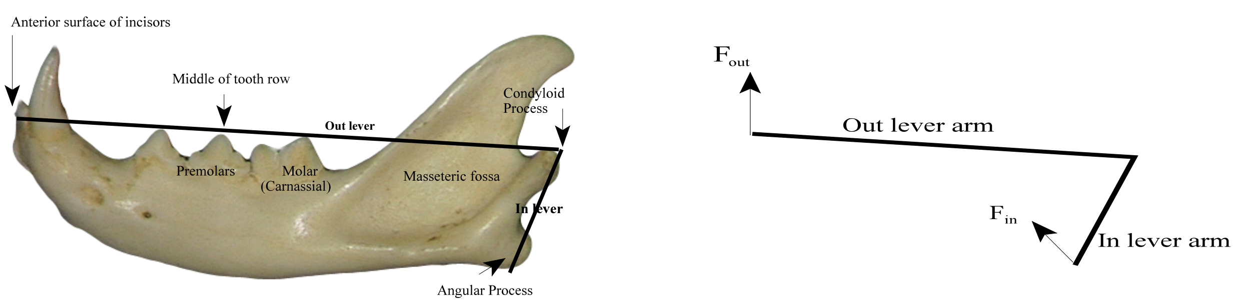


Figure 5. The lever arms of a cat jaw. Contraction of the masseter muscle creates an in-force that elevates the jaw and is translated into an out-force that results in the teeth of the lower jaw moving past the teeth of the upper jaw.

Since we do not have living organisms from which we can measure in and out forces, we will make use of the fact that the out-force generated by a lever system depends on the lengths of the respective lever arms.

$$\mathbf{FA = F_{out}/F_{in} = in\text{-}lever\ arm/out\text{-}lever\ arm}$$

A force efficient lever will have a FA >1 and an inefficient lever will have a FA < 1. If the FA =1 the system is mechanically neutral and muscle force is not lost in translation through the lever.

Data Collection:

For each order (Carnivora, Rodentia) begin with the smallest individual. Use either a caliper or ruler to measure the lever arms as shown in figure 5 and record your data in a carefully labeled table. Make a separate table for each order.

- Measure the length of the **in-lever arm** and the **two out lever-arms** at the positions shown in figure 5. Check with the instructor/TA if you have questions.
- Chose one of the "unknown" mammals from the side bench and make similar measurements. Later you will determine if it's jaw characteristics are more similar to those of a rodent or carnivore.

Data Analysis: *Excel*

1. Enter the data. Column one should be the common name of the organisms you measured. You will also have columns for the length of the **in-lever, molar out-lever, and incisor out-lever**. Do not leave a space between carnivores and rodents within the column.

2. You are now ready to graphically explore the data. Begin by determining the relationship between the length of the **in-lever arm** (y-axis) and **molar out-lever arm** (x-axis) for each order of mammal. If the slope ($\Delta y/\Delta x$) is linear it represents the FA (in length/out length) at the middle of the molar/premolar tooth row.

Graph carnivores and rodents on the same graph. A few hints follow:

- for carnivores **block the data for the y-axis ➤ insert chart ➤ x y scatter ➤** select the option that only graphs points **➤ next ➤ series ➤ x values** (block molar out-lever arm data) **➤ Name** (enter the word carnivores).
- **series ➤ add ➤ block the data for the y-axis for rodents ➤ x values** (block molar out-lever arm data) **➤ Name** (enter the word rodents).

Do a linear regression to determine if the relationship is predictable.

- **RC** on a data point
- **Add trendline ➤** trend/regression (chose **linear**) ➤Options (✓ equation on chart, ✓ R^2 on chart) **➤ ok**.
- Identify the species to which each data point belongs (this can be done using the text box option in Excel or by hand after the figure is printed).

Examine the figure. If the relationship is linear the slope represents the FA or multiplier effect of the lever at the middle of the premolar/molar tooth row for the order the jaws were from.

➤**Compare the slopes of the regression equations for the two groups. Which group has the highest FA and the most force efficient jaw lever? How has each family adapted their lever system and tooth structure to accommodate their diets?**

➤ **If the jaw lever is not force efficient, how can an organism increase the amount of force that is exerted at the premolar/molar surface?**

3. Based on your knowledge of levers and the life styles of the two orders of mammals, which order of animals do you expect to have the highest SA at the level of the incisors? Would this order also have the highest FA? Graphically explore the relationship between SA and FA at the incisors.

Begin by calculating the FA and SA

FA = Lever-in/Lever-out **SA = Lever-out/Lever-in**

Place cursor in the cell where you would like the first calculation to be inserted

- Enter an = sign
- Click the cell containing the data you want divided - it will appear as an active cell and the code for this cell will appear in the cell with the equal sign.
- Enter a / (this is the division term)
- Click the cell you want to divide by - it will appear as the active cell and the code for this cell will be added to the equation you are building.
- **ENTER** - you will see the result of the division in the cell

Place cursor in the cell that contains the result of the division

- Control C
- Block the additional cells in which you want the same calculation done
- **ENTER**

Plot the relationship between the FA (y-axis) and the SA (x-axis) for the two orders of mammals on the same graph. Instructions follow:

- Block the FA for carnivores and begin graphing as in 1 above
- **Series ➤ x Value** (block the carnivore SA data) **➤ Name** (type the word carnivores into the name box)
- **Add series ➤ y Values** (block the FA data for rodents) **➤ x Values** (block the rodent SA data) **➤ Name (** insert the word rodents into the name box).
- Finish the figure and save as a separate sheet
- Add trendlines to each series as done in two above
- By hand or using the text box function identify the various species.

➤ **Examine your figure of FA vs. SA. How are these characteristics related? Which order of mammal maximizes SA? Is this consistent with the feeding habits of the groups?**

➤ **Which group does the jaw mechanics of your unknown mammal most closely resemble**?

➤ **Do the differences you see in jaw levers fit the models you drew on page 21?**

IV. How have vertebrates modified the structure of their forelimbs to increase either force or speed?

Animals can adapt skeletal structures to maximize force or speed by altering the length of bones and the point of muscle insertion. Since several muscles control joint movement the actual interplay of force and speed can be very complex. We will begin by examining the forelimbs of a variety of animals that have different life styles. As you examine the bones of the forelimb note the similarities and differences in the bone structure. The bones you will examine come from animals that burrow, run, swim or are generalized. How do the Speed Advantage (SA) and Force Advantage (FA) of the forelimb lever systems compare for animals with different life styles?

Recall: **SA = out-lever arm /in-lever arm** **FA = F_{out}/F_{in} = in-lever arm /out-lever arm**.

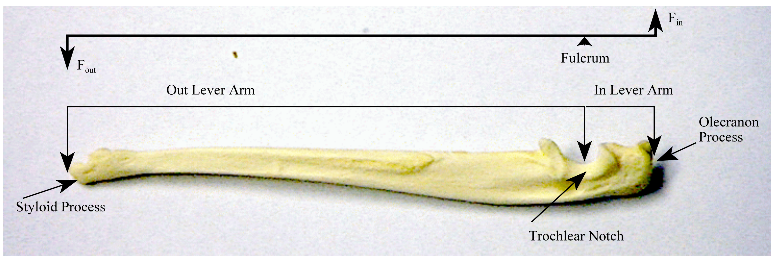


Figure 6. Lever system of a cat ulna (lateral view).

You will determine the FA and SA for the ulna, one of the two bones that form the lower portion of the forelimb. The major muscle group responsible for straightening (extending) the forelimb is the **triceps** which originates along the posterior margin of the humerus and inserts on the olecranon process of the ulna (Figure 6). It's action is opposed by the **brachialis** muscle which bends (flexes) the forelimb. It originates on the humerus and inserts on the lateral surface of the ulna distal to the trochear notch. While examining the ulna you should also note the way the radius articulates with it. The radial tubrosity of the radius is the point where another major flexor of the forelimb, the **biceps brachii** inserts. For this analysis we will focus only on the force that extends the forelimb.

Data Collection: collect the following data on the ulna in tabular form.

- Determine the length of the **in-lever arm** by measuring from the middle of the trochlear notch to end of the olecranon process, where the triceps inserts.
- Determine the length of the **out-lever arm** by measuring from the middle of the trochlear notch to the end of the styloid process, where the out-force is produced.

Data Analysis: *Excel*

- Enter the data. Column one should be the common name of the organisms you measured. You will also have columns for the length of the **in-lever** and **out-lever**.
- Calculate the **SA** (out-lever/in lever) and the **FA** (in-lever/out-lever) as done in part 3 on page 24.
- Block the columns containing the SA and FA data. Make an x y scatter plot using only points to illustrate the tradeoff between SA (x-axis) and FA (y-axis) in the ulnas of the

various species of mammals you measured.

- **Do not add a trendline**
- By hand or using the text box function identify the species the data points correspond to.

➤What is the relationship between FA and SA? For which species is the SA for the ulna highest? Does this fit with it's lifestyle. For which species is the FA for the ulna highest? Does this fit with it's lifestyle? Do the results fit with your predictions about the design of force or speed efficient forelimbs? Do the animals sort by order?

See optional foot exercise on page 28.

Assignment:

1. Submit all tables made during this laboratory (do not recopy them), but make sure that they have appropriate captions and column headings with units of measure. The captions should contain enough information that a reader can understand the data they contain. These tables are not to be used in the results section you write, rather they will allow us to check the manner in which you are collecting laboratory data.

2. **Write a results section.**
    - Organize the graphs you have made into a **results section**.
    - What are the important features of the data you want the reader to notice? The text should point out the major features of the graphs and the interesting relationships shown by the data.
    - Organize the text so it provides answers to the questions posed **in bold** at the beginning of sections **I-IV**. Additional questions posed **in bold** throughout this exercise will help you think about the important features of your data. Please note that you are being asked to write a results section and not a discussion. As you address the questions posed in sections I-IV be careful to phrase them as a result by stating what you found from the data.

3. Include all the graphs you made during class in the results. Each graph should be carefully labeled and have an appropriate caption.
    - Graph of the relationship between the length of the in-lever arm and the FA (pg 20).
    - Graphs of the relationship between L_{in} and L_{out} for carnivores and rodents (pg 23)
    - Graph of the relationship between FA and SA in carnivore and rodent jaws (pg 24)
    - Graph of the relationship between the FA and SA of the ulna (pg 25).

4. Make sure you include a statement on the unknown jaw. Which order is it most likely from?

Types of Lever Systems

Three types of levers can be defined based on the relationship between the position of the in force (power arm) and out force (load arm) with respect to the fulcrum (pivot point). Examine the three levers shown below. Note that in type 1 levers the fulcrum is between the in and out forces. In type 2 and 3 levers the in and out forces are on the same side of the fulcrum. In the type 2 lever the out force is closer to the fulcrum and in a type 3 lever the in force is closer to the fulcrum. Now consider how these types of levers might be employed in the skeletal system.

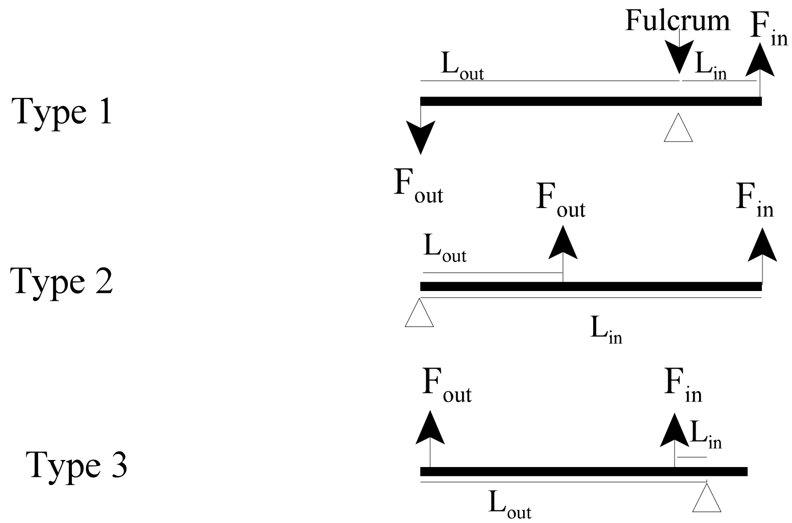


Figure 4. Types of lever systems based on the location of the fulcurm and the position of the in lever arm and the out lever arm.

- As you bend (flex) your forearm place two fingers on the tendon that crosses the junction from the upper arm bone (humerus) to the bones in the forearm. This tendon attaches the muscles that flex the forearm to either the radius or ulna. What type of lever is represented by this type of movement? _______________
- Place your fingers at the back of the elbow and straighten (extend) the forearm. What type of lever was employed in this movement? _______________
- Place your palm on the table. Keeping your finger tips on the table and arm straight, lift from the shoulder to move you palm off the table. What type of lever was employed in this movement? ___________
- Cross your legs and flex your ankle by drawing your foot toward your knee. What type of lever was employed in this movement? _______________
- With your legs crossed point your toes toward the floor (extend ankle). What type of lever was employed in this movement? _______________
- Stand on your tip toes. The fulcrum is under your toes and the out force is moving your lower leg (tibia) vertically. What type of lever is employed in this movement?________

Optional **Lever System of the Hindlimb**

We will now focus on the action of the ankle joint when an animal walks and compare the trade off between force advantage and speed advantage. One way that animals can alter speed is by moving from a plantigrade (flat-footed) to a digitigrade (toe-walking) posture. This change means that the lever action of the ankle joint can be added to the action of the limb. This effectively increases the length of the stride. Complete analysis of modifications for force or speed would require analysis of the entire limb and of the bones associated with the hip, knee and ankle joints. For simplicity we will just examine the ankle joint. As you do this keep in mind that some of the feet you are analyzing are from plantigrade as opposed to digitigrade walkers.

The **talus** (one of the tarsal bones) is enlarged to provide a surface for articulation with the tibia and fibula of the lower leg (Figure 7). It also serves as the fulcrum about which the foot rotates as the animal flexes and extends its foot. For simplicity we will consider only the potential extension of the foot as the animal strides forward. The calf muscle or **gastrocnemius** is the major muscle that controls this movement. It inserts on the calcaneus or heel. The fulcrum for this motion is the talus.

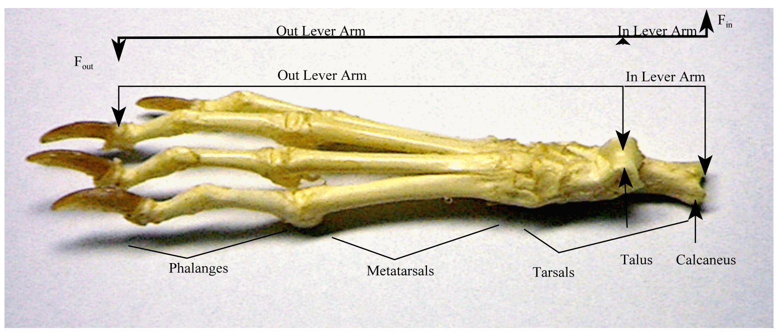


Figure 7. Lever system of a rabbit foot

➤ **Examine the feet that are available on the side bench. What modification(s) of the foot result in greater speed advantages? Which species would you expect to have the greatest SA ---- the greatest FA? Does this fit with the lifestyle of the organisms studied?**

For your information:*

A rabbit can run 64-72 km/hr.

A human can run 37 km/hr for short distances and 19.5 km/hr for longer distances.

A red fox can run 72 km/hr.

A cheetah can probably run 110 km/hr although it will rarely run more than ½ km.

A horse has been clocked at 69.7 km/hr for 0.4km and 18.2 km/hr for 80 km.

**Source*: Hildebrand, Milton. 1974. Analysis of Vertebrate Structure.John Wiley & Sons, New York, 709 pp.