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, it's 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)
- seesaw model
- colored pencils or crayons
- 1 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 on the next page. (Exclude footwear and clothing; 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 then 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.

![First Class Lever Diagram](image_url)

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.

![Second Class Lever Diagram](image_url)
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:

\[ F \times FA = R \times RA \]

**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 9.8m/sec$^2$ to find the answer.

________________ Newtons

Find the distal end of your tibia (you call this your anklebone) and drop an imaginary vertical line from your tibia to the floor (see diagram below).

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= ______

Which acts as the resistance force? R= ______

\[ F \times F_A = R \times R_A \]

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_A, R, R_A, 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.

\[ F \times F_A = R \times R_A \]

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?
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 which 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:

\[
\text{Mechanical Advantage (M.A.) } = \frac{R}{F} \quad \text{or} \quad \frac{FA}{RA}
\]

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.
III. SKELETAL SYSTEM / LOWER LIMB
THIGH & LEG BONES
FEMUR. TIBIA. FIBULA. PATELLA.

The hip (coxal) joint (multiarticulated, ball and socket synovial joint) is concerned with the transmission of considerable weight-bearing forces; the head of the femur is particularly subject to pathologic changes with any significant alteration of blood supply (avascular necrosis). The greater trochanter is the site of attachment for several important muscles crossing the hip joint.

The knee (genual) joint consists of two condylar-type, synovial (bipartite) joints between the condyles of the femur and the flat, plateau-like articular surfaces on the condyles of the tibia. The principal movements at these joints are flexion and extension. The knee joint includes the saddle-type synovial (patellofemoral) joint between the patella and femur. The deep surface of the patella is cartilaginous and exhibits medial and lateral facets (note patellar surface of the femur). Premature wear of the patellar cartilage is common (chondromalacia patellae). The patella is a sesamoid bone which develops in the tendon of the quadriceps femoris muscle; as such, it resists the stress imposed on that tendon during knee movements.

The stability of the knee joint comes from ligaments and the muscles crossing the joint. The collateral ligaments resist sideward displacement and rotation. The cruciate (crossing) ligaments resist hyperextension (anterior cruciate) and hyperflexion (posterior cruciate) of the joint. The C-shaped menisci (the medial larger than the lateral) deepen the articular surfaces of the tibial condyles. Often torn by misuse of the knee joints (rotation and adduction/abduction with weightbearing), the menisci can often be repaired by arthroscopy.

CN: Do not use the color used for the ilium on Plate 29. Use light colors and a bright color for F (1) Color the two large views of the lower limb. (2) Next color the femur and the six directional arrows for the hip joint. (3) Color the extension/flexion views of the knee joint. (4) Color the two views of the major ligaments and the menisci of the knee joint.
The foot is a mobile, weight-bearing structure. The ankle joint (hinge-type synovial joint) between tibia, fibula, and the talus forms a mortise, permitting only flexion (plantar flexion) and extension (dorsiflexion) here. With excessive rotation of this joint, characteristic fractures and torn ligaments occur. The foot can adjust to walking/running on tilted surfaces by virtue of the subtalar (talocalcaneal) and transverse tarsal (talocalcaneonavicular and calcaneocuboid) joints. Here inversion and eversion movements occur. The ankle has strong medial ligamentous (deltoid ligaments) and weaker lateral ligamentous support. The relatively high frequency of inversion sprains (tearing the lateral ligaments) over eversion sprains seems to reflect this fact.

The bony architecture of the foot includes a number of arches that are reinforced and maintained by ligaments and influenced by muscles. The medial longitudinal arch transmits the force of body weight to the ground when standing and to the great toe in locomotion, creating a giant lever that gives spring to the gait. Both longitudinal arches function in absorbing shock loads and balancing the body.
V. MUSCULAR SYSTEM / LOWER LIMB
MUSCLES OF ANTERIOR & LATERAL LEG

ON: Begin with the attachment sites of the anterior leg. Note that the muscles A, B, and C arise from the interosseous ligament as well as the tibia and the fibula. Do not color the attachment sites of the thigh muscles (in small italics). Attachment sites on the planlar surface of the foot are shown at upper right.

The muscles of the leg are arranged into anterior-lateral, lateral, and posterior compartments. The bony ridge (anterior margin) of the tibia creates two oblique surfaces the anteromedial of which relates to the anterior leg muscles; the anteroepicondylar surface is bony (such) and devoid of muscle. The lateral compartment muscles largely arise from the fibula and the interosseous ligament between tibia and fibula.

ANTEOR LEG:
TIBIALIS ANTERIOR,
EXTENSOR DIGITORUM LONGUS,
EXTENSOR HALLUCIS LONGUS,
PERONEUS TERTIUS.

All of the anterior leg muscles are dorsiflexors (extensors) of the ankle; extensors hallucis and digitorum longus are toe extensors; tibialis anterior is an invertor of the subtalar joints as well, and peroneus tertius (the 5th tendon of extensor digitorum) is an evertor. Due to rotation of the lower limb during embryonic development, these extensors are anterior to the bones in the anatomical position (unlike the upper limb wrist extensors). Tibialis anterior is particularly helpful in lifting the foot up during the swing phase of walking to avoid striking the toes.

LATERAL LEG:
PERONEUS LONGUS,
PERONEUS BREVIS.

The peroneal muscles are principally evertors of the foot, and are especially active during plantar flexion, as in walking on the toes or pushing off with the great toe. Peroneus tertius arises in the peroneal compartment but is actually part of extensor digitorum.
V. MUSCULAR SYSTEM / LOWER LIMB
MUSCLES OF POSTERIOR LEG

TIBIALIS POSTERIOR;
FLEXOR DIGITORUM LONGUS;
FLEXOR HALLUCIS LONGUS;
POPLITEUS;
PLANTARIS;
SOLEUS;
GASTROCNEMIUS

ATTACHMENT SITES
DEEP VIEW
INTERMEDIATE
SUPERFICIAL

POSTERIOR VIEW
(right leg)

The muscles of the posterior leg form two groups: a deep group of four muscles, and a superficial group (gastrocnemius, soleus, and plantaris). The two compartments are separated by a fascial septum (deep transverse fascia, not shown). The fascial compartments are fairly non-expandable, muscle swelling secondary to vascular insufficiency may result in serious muscle compression/muscle death (compartment syndrome) without fascial decompression.

The major calf muscle is gastrocnemius which flexes the knee and, with its two fellows, plantarflexes the ankle joint. In knee flexion it is aided by popliteus which also rotates the tibia medially. The other deep flexors plantarflex the ankle joint (both toe and great toe flexors and tibialis posterior), flex the toes (the flexors), and invert the foot (tibialis posterior).

CN: The muscles to be colored on this plate are labeled G-M. Any other letter label found here (A-F on Pl. 57; N-Y on Pl. 59) is for identification only, and those muscles should be left uncolored. You may repeat colors used for muscles on Plate 57 on this plate and/or the next plate. 1. Color one muscle at a time in each of the posterior views. Note that the plantaris (K), the soleus (L), and the gastrocnemius (M) all insert into the same tendon (tendocalcaneus) which receives the color M. 2. Color the upper and lower medial views.