

The Human Arm

Prepared by Dr. Kristin Domike as part of the HHMI Biophysics Initiative

Topics

- Muscles
- Levers and Torque
- Investigating the Elbow
- Looking at an Artificial Elbow Joint

Muscles

- Skeletal Muscles

- Composed of thousands of parallel fibers wrapped in a flexible sheath along a bone
 - Narrows at both ends into tendons

- Muscle/Tendon Properties

- Most muscles taper to a single tendon that is attached to a different bone
- Some muscles taper to two or three tendons
 - These muscles are called “biceps” and “triceps”
- Generally, two bones attached by muscles can freely move with respect to each other at the *joints* where they are in contact

Leonardo Da Vinci was correct in saying “The muscles always begin and end in the bones that touch one another, and they never begin and end on the same bone...”

Muscles

- Contraction of Muscles/Tendons

- Muscle fibers contract after receiving an electrical stimulus from the nerve endings attached to them
 - As result, the muscles *shorten* and a *pulling force* is felt by the two bones to which the muscle is attached.

- Forces in Muscles

- The maximum force a muscle is capable of exerting is proportional to its cross-section
 - This makes sense if you think about how much you can lift using your legs (larger cross-section) vs. your arms (smaller cross-section)
- The estimated maximum force a muscle can exert is approximately $7 \times 10^6 \text{ dyn/cm}^2 = 7 \times 10^5 \text{ Pa} = 102 \text{ lb/in}^2$

Once again, Leonard Da Vinci was correct when he stated, "...It is the function of the muscles to pull and not to push..."

To compute the forces exerted by muscles, we can conveniently view the various joints in the body as levers

What is a lever?

- A lever is a rigid bar free to rotate about a fixed point called the fulcrum
- Levers are used:
 - To advantageously lift loads
 - To transfer movement from one point to another
- For a lever, the force, F , required to balance a load of weight W is:

$$F = W \frac{d_1}{d_2}$$

Where d_1 and d_2 are the lengths of the lever arms (shown on the next slide)

Levers

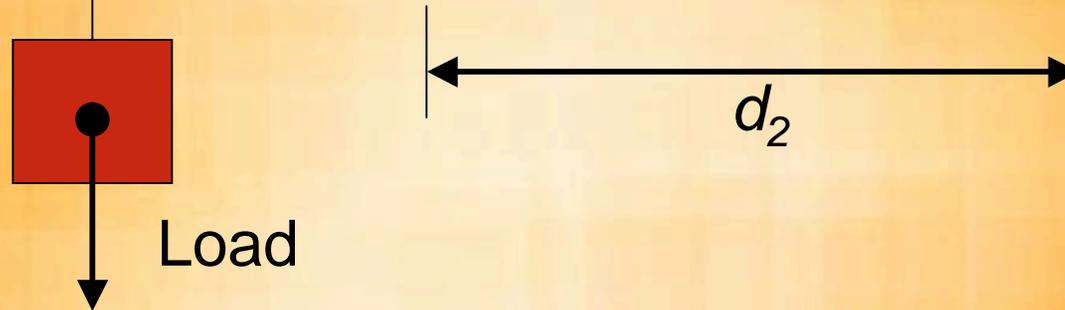
Force required to balance Weight $F = W \frac{d_1}{d_2}$

Classes of Levers

1.



2.



3. The Mechanical Advantage, M , of the lever is defined as:

$$M = \frac{W}{F} = \frac{d_2}{d_1}$$

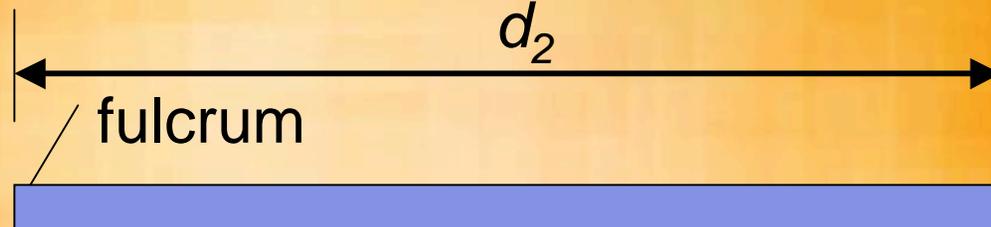
If the load is close to the fulcrum, the mechanical advantage is large ($d_1 < d_2$). If the load is far from the fulcrum, the mechanical advantage is small ($d_2 > d_1$). Depending on the distances from the fulcrum, the mechanical advantage can be greater or smaller than one.

Levers

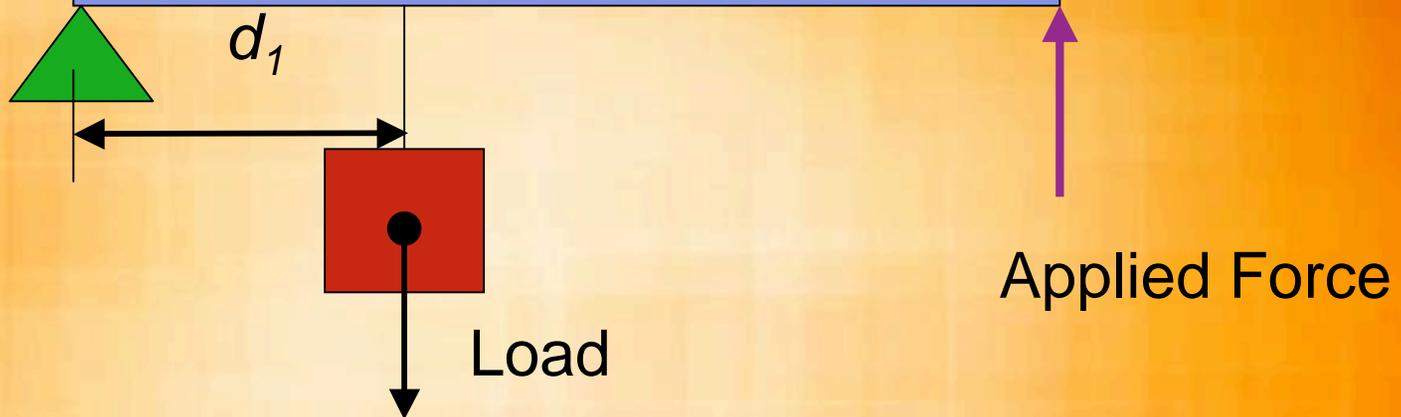
Force required to balance Weight $F = W \frac{d_1}{d_2}$

Classes of Levers

1.



2.



3.

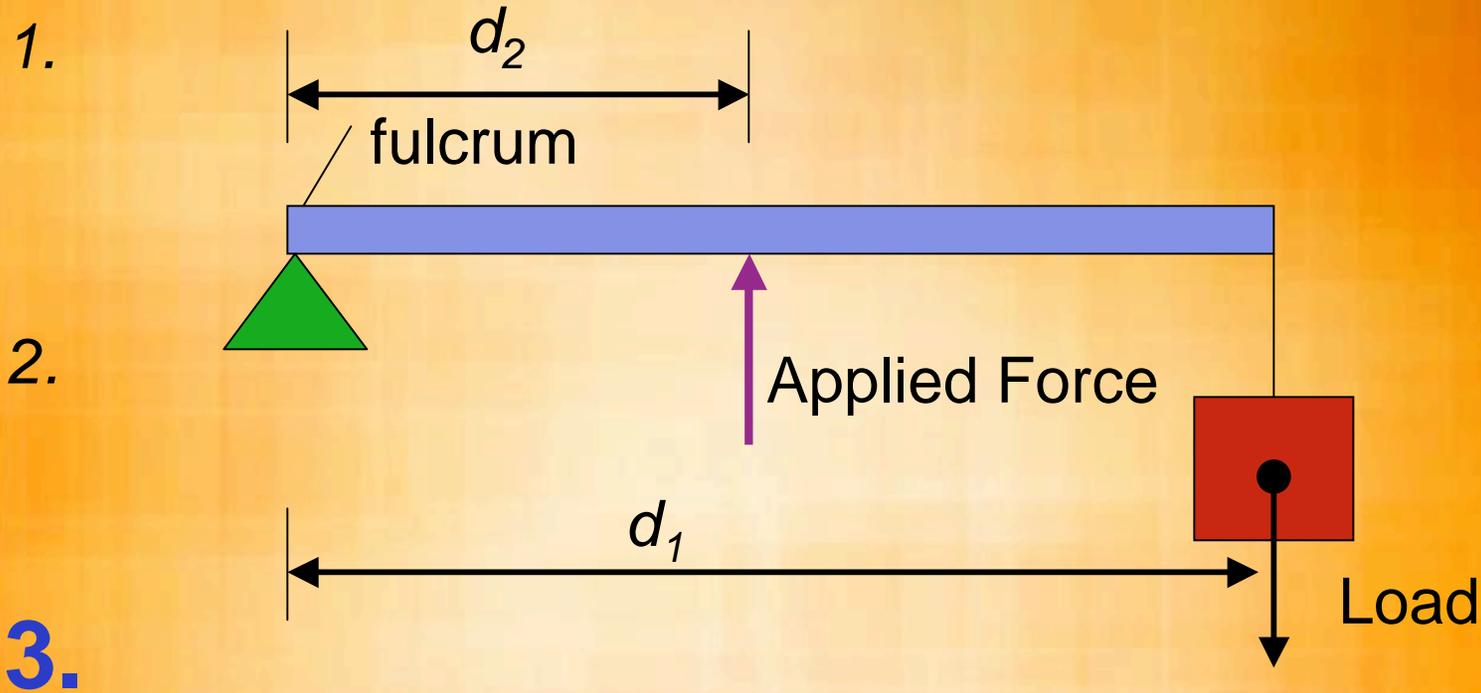
$$M = \frac{W}{F} = \frac{d_2}{d_1}$$

For Class 2, d_1 is always smaller than d_2 ; therefore the mechanical advantage of a Class 2 lever is greater than Class 1.

Levers

Force required to balance Weight $F = W \frac{d_1}{d_2}$

Classes of Levers



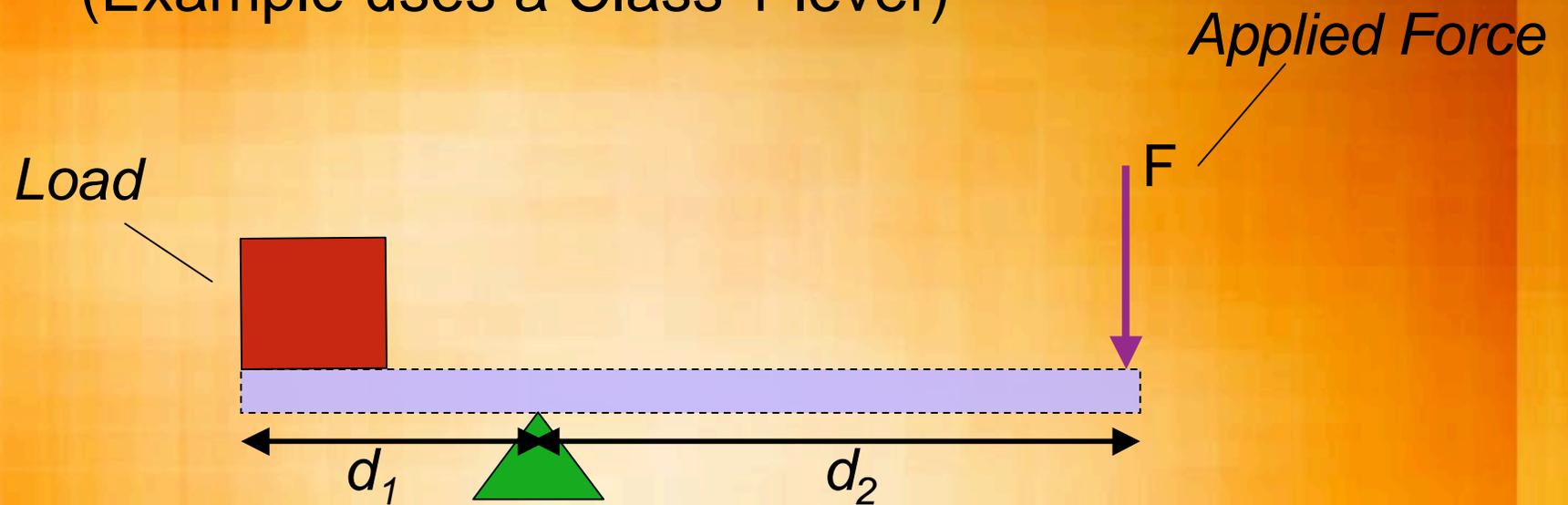
$$M = \frac{W}{F} = \frac{d_2}{d_1}$$

For a Class 3 lever, d_1 is larger than d_2 (opposite of Class 2), therefore, the mechanical advantage is always less than 1.

** Note: These equations are only valid when forces are applied \perp to the lever*

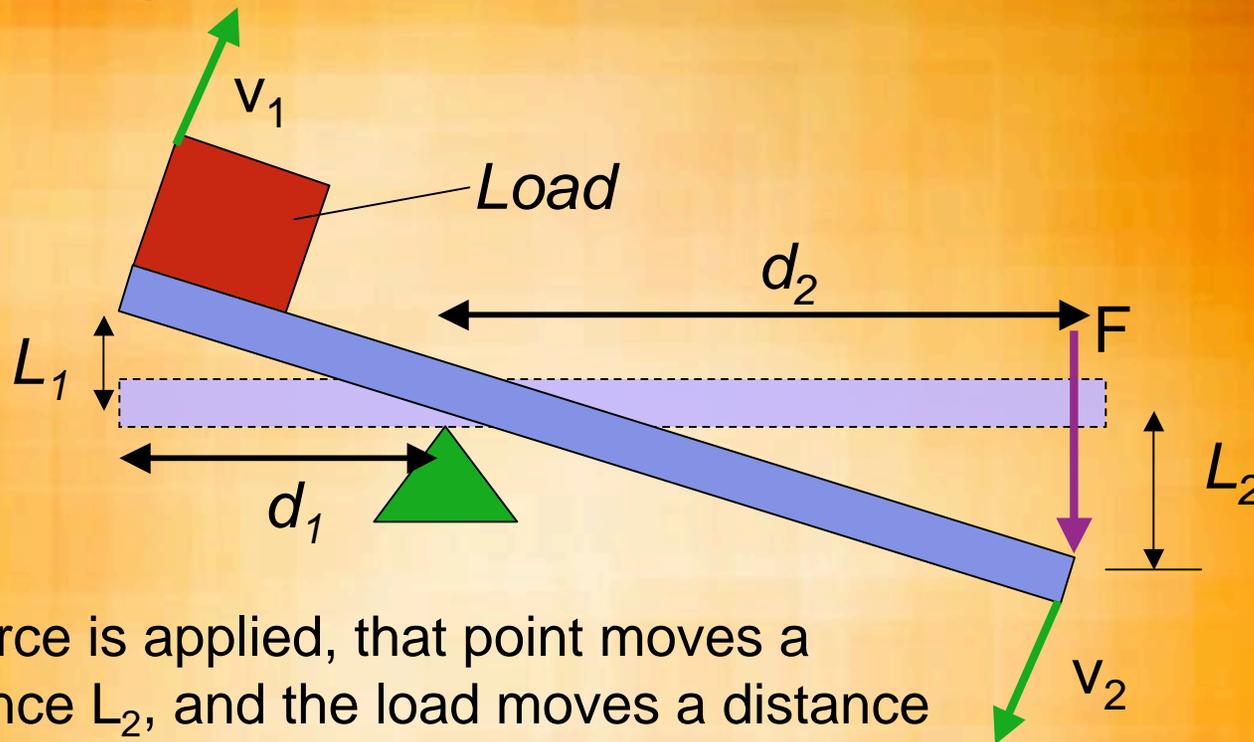
Motion of a lever arm

(Example uses a Class 1 lever)



Motion of a lever arm

(Example uses a Class 1 lever)

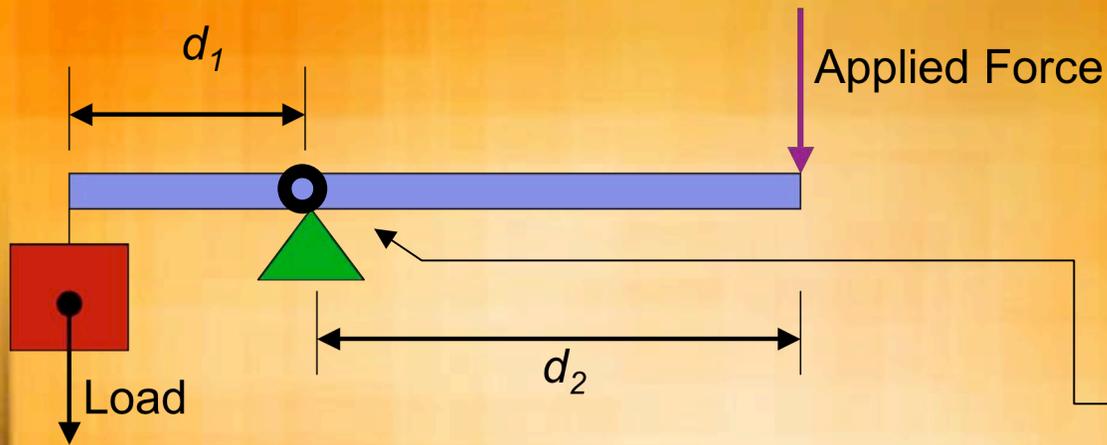


As force is applied, that point moves a distance L_2 , and the load moves a distance L_1 . The relationship is: $L_1/L_2 = d_1/d_2$

The ratio of velocities of the moving lever is: $v_1/v_2 = d_1/d_2$

** These relationships apply to all types of levers **

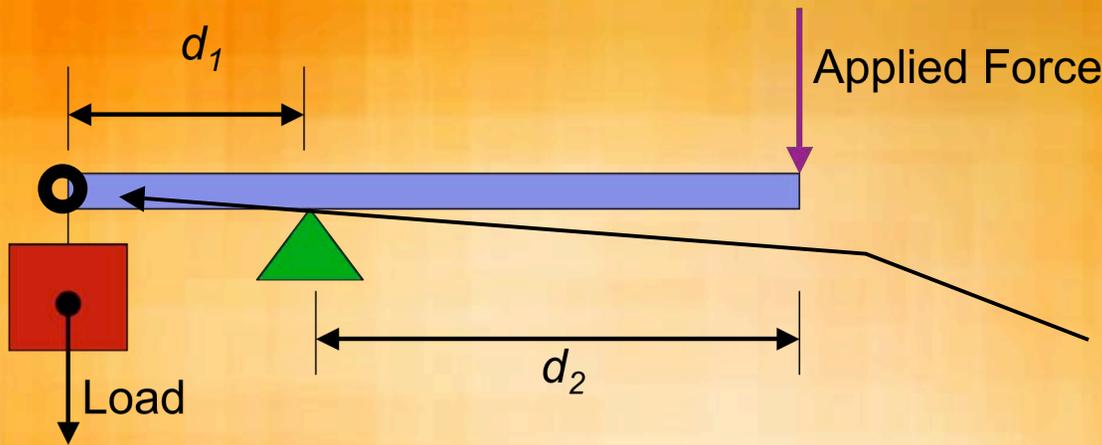
Torque about a point



You can choose a location to be the “joint” or point about which we will measure torque

For example:

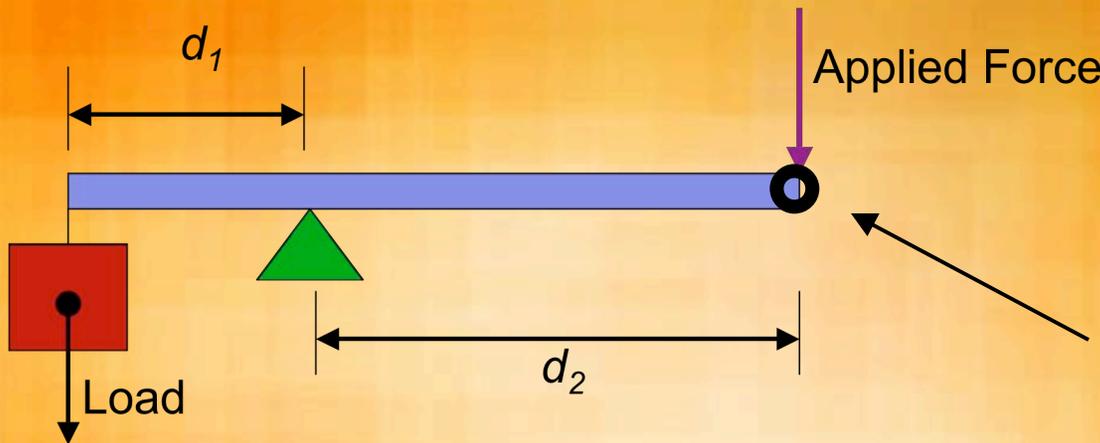
Torque about a point



You can choose a location to be the “joint” or point about which we will measure torque

Or:

Torque about a point



You can choose a location to be the “joint” or point about which we will measure torque

Or:

Torque, τ , is calculated from the following equation:

$$\tau = FR \sin \theta$$

F = force
 R = distance from the location force is applied to the joint
 θ = angle between the force and the radial line

At Equilibrium,

$$\sum \tau = 0$$

about a point

This allows us to solve for any unknowns (like forces, R distances, or angles)

Investigating the Elbow

- The two most important muscles used to produce elbow movement are:
 - Triceps
 - Contraction of triceps causes an extension (opening) of the elbow
 - Biceps
 - Contraction of biceps closes the elbow

We will only consider these two main muscles, but obviously there are many other muscles that play a role, some stabilize the elbow, some stabilize the shoulder joint.

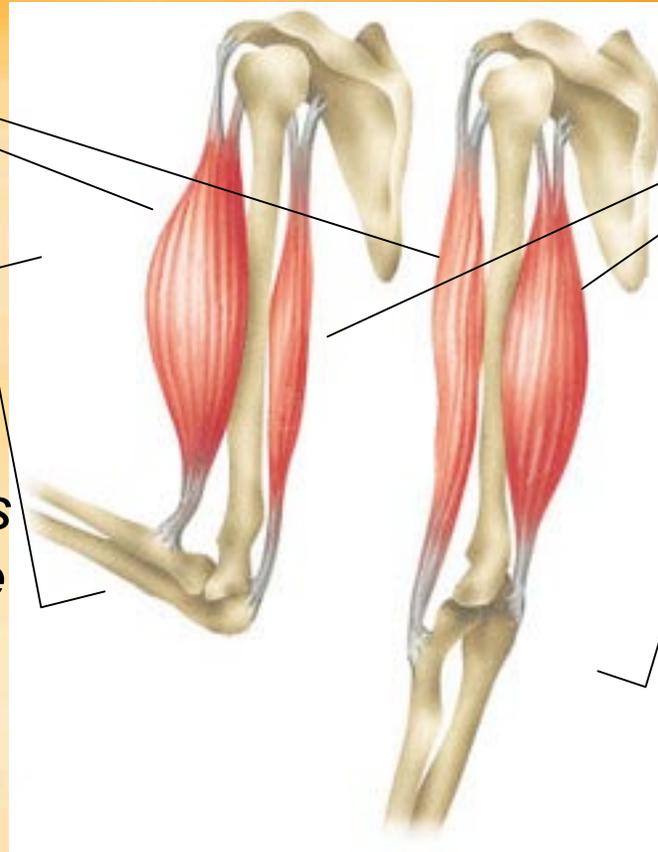
Investigating the Elbow

Biceps muscle

Triceps muscle

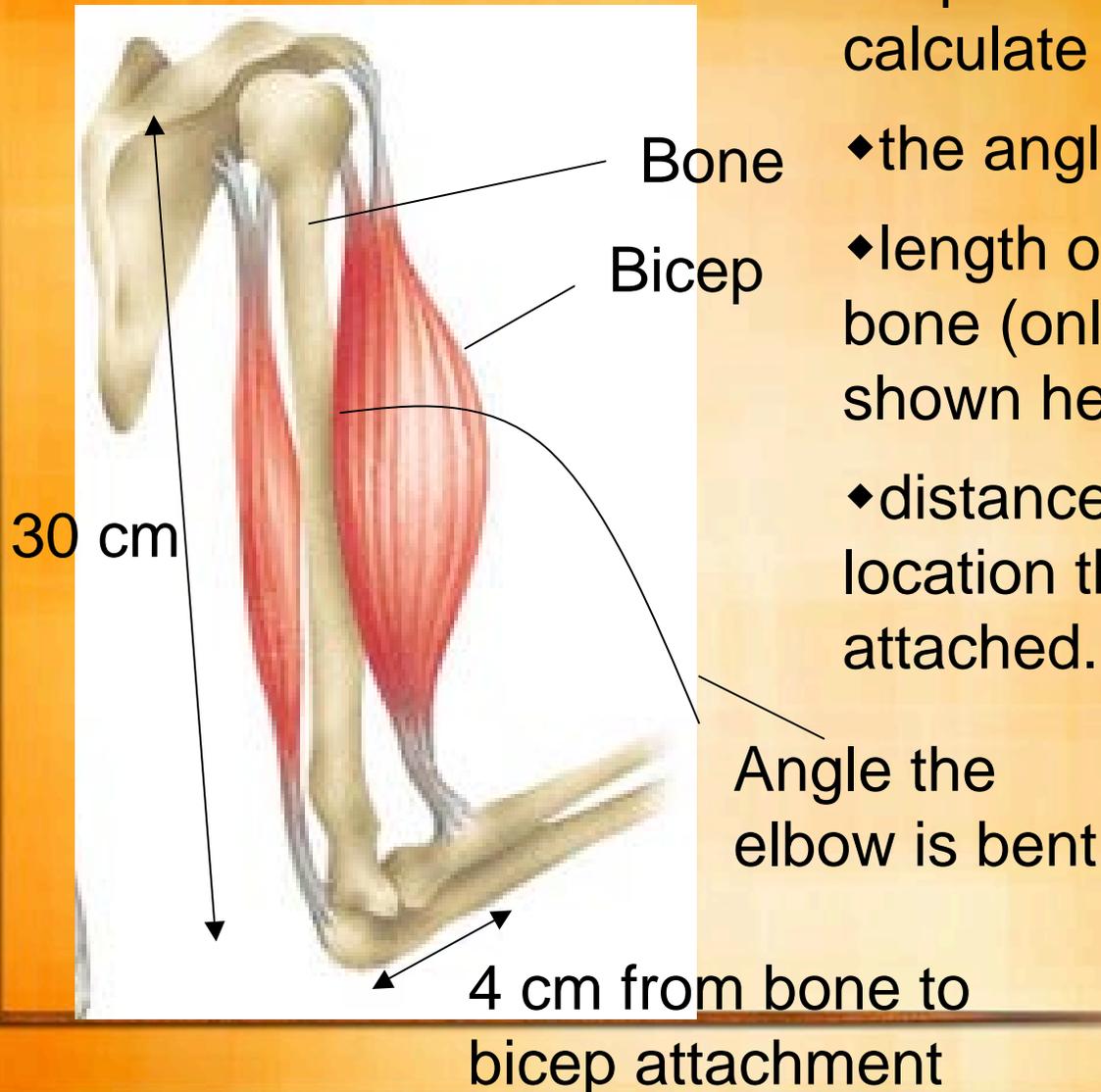
Biceps muscle contracted
Notice this causes the elbow to close

Triceps muscle contracted
Notice this causes an extension of the elbow



Notice how the ends of each muscle are attached to a different bone.

Investigating the Elbow



Properties which can be used to calculate forces are defined:

- ◆ the angle the elbow is bent
- ◆ length of upper and lower arm bone (only the length of upper is shown here)
- ◆ distance from the bone to the location the muscle(s) is attached.

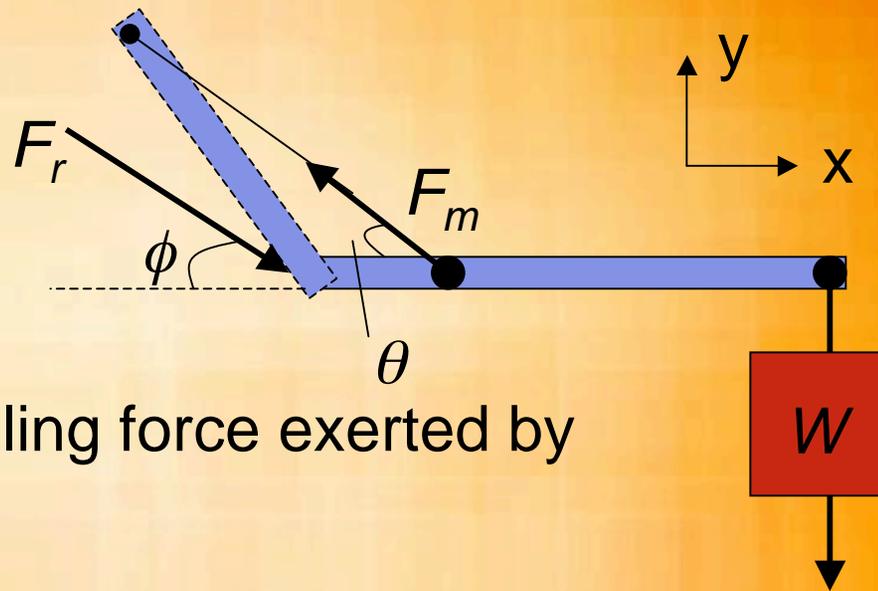
Looking at the Elbow

Let's imagine a weight is held in the hand and you're contracting the bicep muscle to lift the weight up
We can draw this using lever representation



Looking at the Elbow

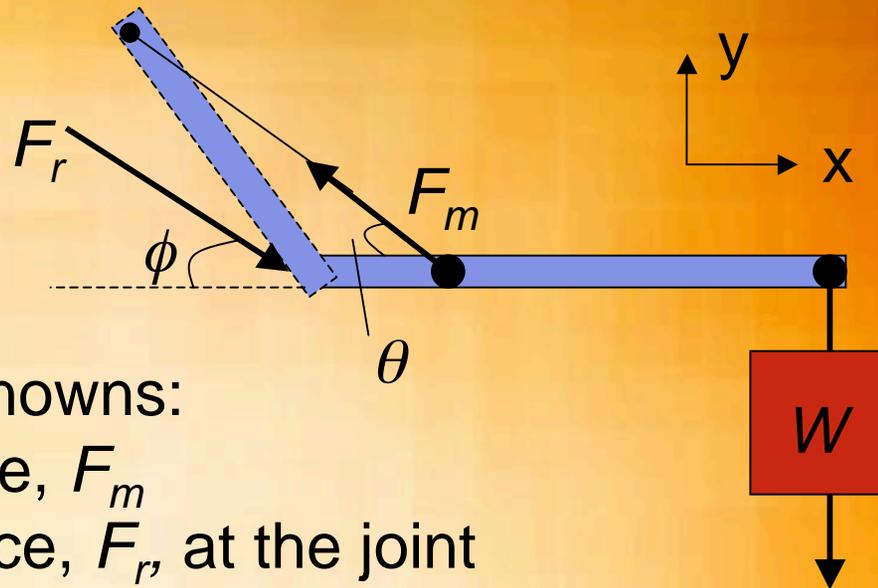
Let's imagine a weight is held in the hand and you're contracting the bicep muscle to lift the weight up
We can draw this using lever representation



Where F_m is the pulling force exerted by the biceps

And F_r is the direction and magnitude of the reaction force at the joint

Looking at the Elbow



We have three unknowns:

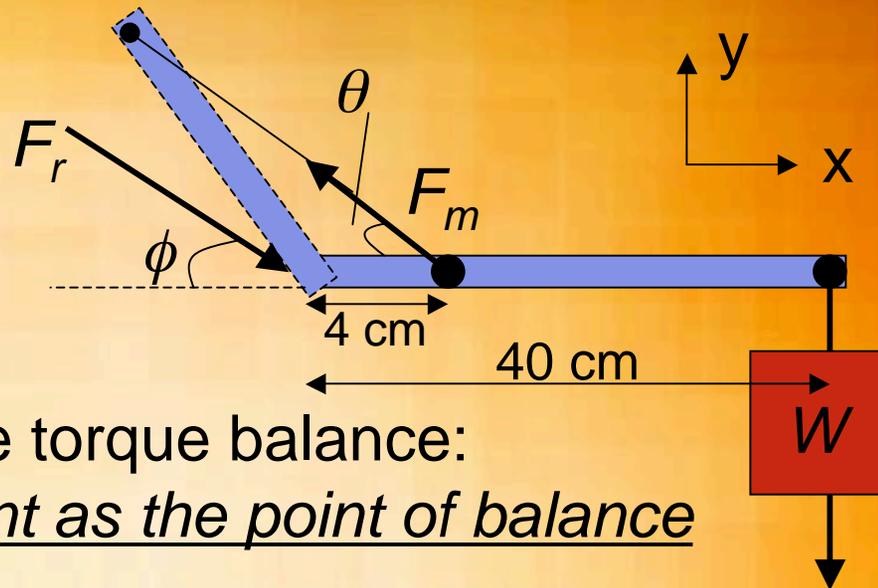
1. The muscle force, F_m
2. The reaction force, F_r , at the joint
3. And the angle of F_r

For equilibrium, the sum of the x and y components of the forces must be zero:

x components of the forces: $F_m \cos \theta = F_r \cos \phi$

y components of the forces: $F_m \sin \theta = W + F_r \sin \phi$

Looking at the Elbow



Let's also look at the torque balance:

We'll choose the joint as the point of balance

The two torques are:

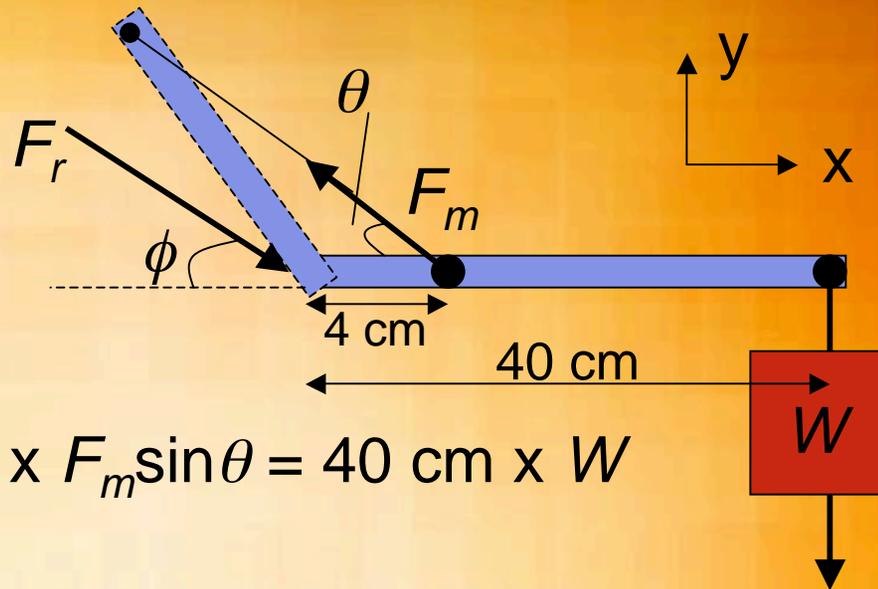
1. The clockwise torque due to the weight
2. The counterclockwise torque due to the vertical y component of the muscle force

(F_r acts at the joint, so it doesn't produce torque at this point)

Using the dimensions shown above,

$$4 \text{ cm} \times F_m \sin \theta = 40 \text{ cm} \times W$$

An Example Solution



(from last slide) $4 \text{ cm} \times F_m \sin \theta = 40 \text{ cm} \times W$

If $\theta = 72.6^\circ$,

Then the muscle force $F_m = 10(W)/0.954 = 10.5 \cdot W$

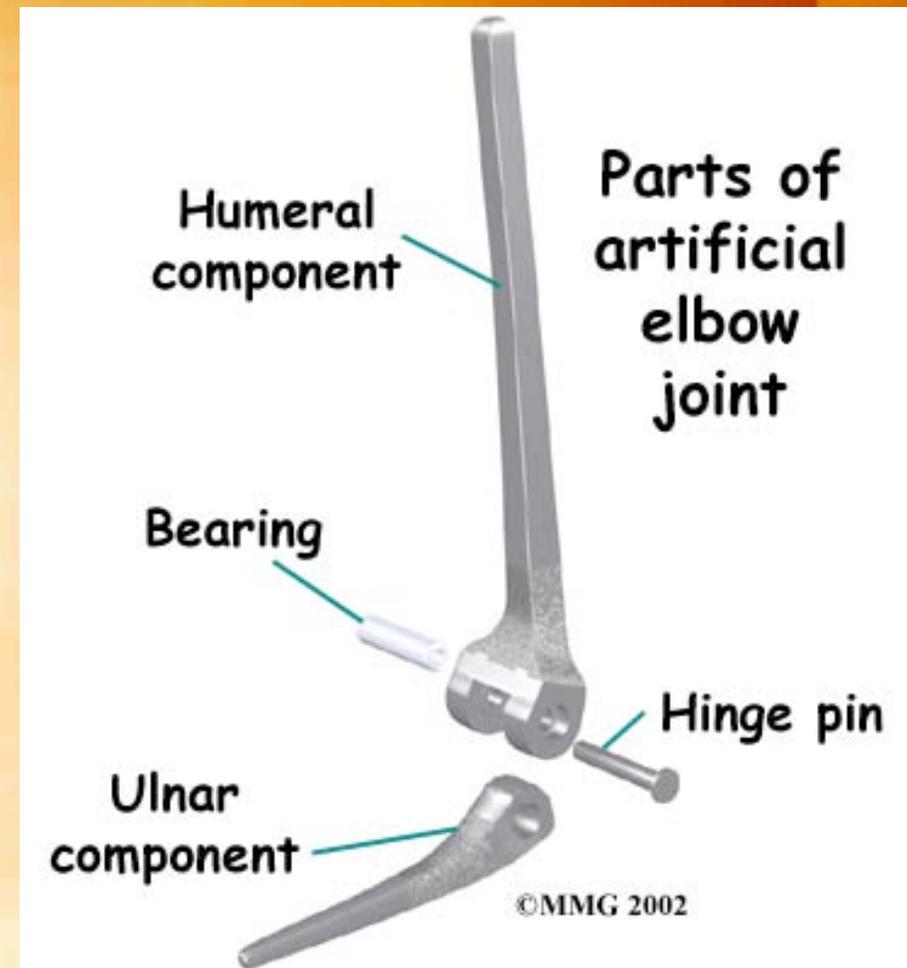
If you hold a 14-kg weight in the hand, the force exerted by the muscle is,

$$F_m = 10.5 \times 14 \times 9.8 = 1440 \text{ N (or 325 lb)}$$

You can now solve for F_r , $F_r = 1320 \text{ N (for these conditions)}$

Artificial Elbow Joint

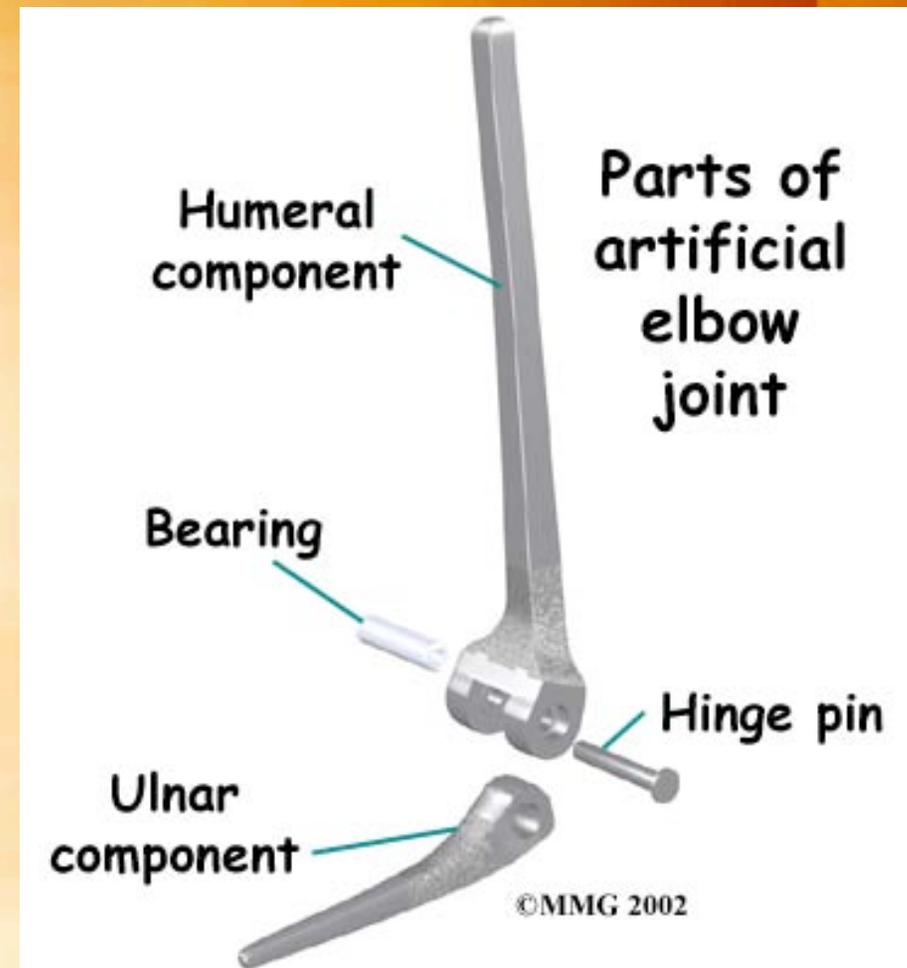
- The most common types of artificial elbow joints are ones with a hinge
- The prosthesis has two main metal components
 - The humeral component
 - Replacing the upper bone
 - The ulnar component
 - Replacing the lower bone
- The hinge is made of a hard plastic and metal
 - It allows the two main metal components to glide easily against each other



Schematic of an artificial elbow joint with hinge

Artificial Elbow Joint

- The humeral and ulnar component are typically fitted *inside* existing bone and then held in place using one of the following two methods:
- There are two ways to hold the prosthesis in place
 - Using epoxy glue creates a **cemented prosthesis**
 - Using a fine mesh on the surface of the prosthesis creates a **uncemented prosthesis**
 - These prosthesis are designed to allow surrounding bone *grow* into the prosthesis over time



Schematic of an artificial elbow joint with hinge

Potential Complications of an Artificial Joint

- Anesthesia
 - Rare; but some patients may react to the anesthesia
- Nerve or Blood Vessel Injury
 - Uncommon, but nerves or blood vessels do have a chance of being stretched or pinched during the operation
- Infection
 - Low chance, 1-2% after elbow joint replacement
 - Often you will be given antibiotics if there is chance infection may spread to the joint location
- Loosening
 - The **major** reason for joint failure!
 - Knee joints typically last 12-15 yrs, but elbow joints tend to loosen sooner
 - Loosening, if it occurs, it's often where metal or cement (epoxy) meets the bone
 - Another operation may need to be performed if the pain becomes unbearable