NAME PERIOD DATE

11. ROTATIONAL STATICS

STRUCTURED

Driving Question | Objective

What must the net force and net torque on an object be if the object is in static equilibrium (translational and rotational)? Experimentally demonstrate that the sum of the forces acting on an object in static translational equilibrium is equal to zero, and the sum of the torques acting on an object in static rotational equilibrium is equal to zero.

Materials and Equipment

- Data collection system
- PASCO High Resolution Force Sensor with rubber bumper[1]
- PASCO Tension Protractor (2)[2]
- Table clamp or large base (2)
- Support rod, 60-cm or longer (2)
- Support rod, 90-cm or longer
- Hooked mass set
- AA-cell battery or similar cylindrical object
- Right angle clamp (2)
- Thread
- Meter stick
- Tape
- Scissors

[1] www.pasco.com/ap22

PASCO High Resolution Force Sensor

[2] www.pasco.com/ap06

PASCO Tension Protractor

Background

An object at rest, experiencing zero changes to its motion, is said to be in *static equilibrium*. This equilibrium describes both the translational and rotational motion of the object. For an object to remain in static equilibrium, the forces and torques acting on the object must satisfy certain conditions that are easily derived using Newton's Second Law.

If an object is at rest and experiencing zero changes to its translational motion, its acceleration $\vec{a}$ must equal zero, and according to Newton's Second Law:

$$\sum \vec{F} = \vec{F}_{\text{net}} = m\vec{a} = 0 \tag{1}$$

the sum of the forces $\vec{F}_{\text{net}}$ (net force) acting on the object must also be zero.

If an object is at rest and experiencing zero changes to its rotational motion, its angular acceleration $\vec{\alpha}$ must equal zero, and according to the rotational equivalent of Newton's Second Law,

$$\sum \vec{\tau} = \vec{\tau}_{\text{net}} = I\vec{\alpha} = 0 \tag{2}$$

the sum of the torques $\vec{\tau}_{net}$ (net torque) acting on the object must also be zero.

In this lab activity, you will investigate the forces acting on a suspended mass and demonstrate that static equilibrium in translational motion occurs when the sum of forces acting on the mass is zero. You will also investigate the forces and torques acting on a balanced rigid system, and demonstrate that the system experiences zero rotational motion if the sum of the torques acting on it is zero.

RELEVANT EQUATIONS

$$\sum \vec{F} = \vec{F}_{\text{net}} = m\vec{a} = 0 \tag{1}$$

$$\sum \vec{\tau} = \vec{\tau}_{\text{net}} = I\vec{\alpha} = 0 \tag{2}$$

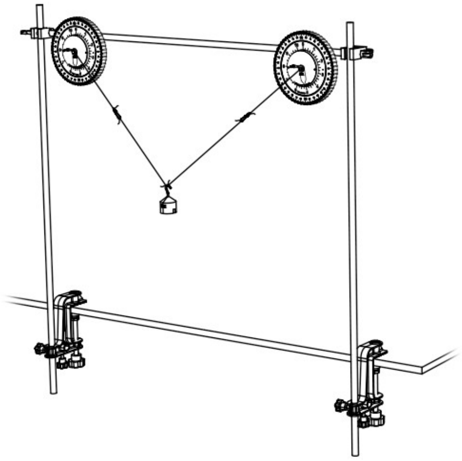
$$\tau = r_{\perp}F = r\left(F\sin\theta\right) \tag{3}$$

Equation 3 indicates that torque is equal to the product of the lever arm $r_{\perp}$ (sometimes referred to as the moment arm) and the force F being applied, where the lever arm is defined as the perpendicular distance between the axis of rotation and the line of action of F. This equation simplifies to the product of the distance from the axis of rotation r to the point at which the force is applied and the component of force acting perpendicular to r: $F \sin \theta$.

Procedure

Part 1 – Net Force on an Object in Static Equilibrium

SET UP

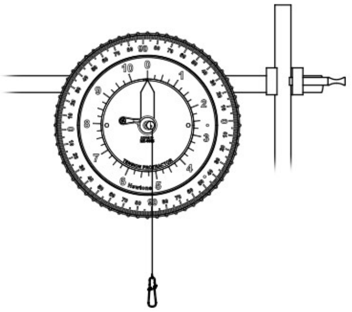


1. Set up the three support rods and two tension protractors similar to the diagram at right:

   a. Assemble the two shorter rods vertically using the table clamps or rod bases, and place them about 80 cm apart. Attach a right-angle clamp to the top of each rod.

   b. Slide the protractors onto the third rod using the rod clamp on the back of each, and then use the right-angle clamps to connect the third rod horizontally to the two vertical rods.

   c. Once the third rod is connected, slide each protractor along the horizontal rod so they are as far apart as possible, adjust each protractor so its face points out perpendicular to the top of the lab table, and then tighten the thumbscrew on the each protractor's clamp to lock it in place.



   d. Zero the force scale of each tension protractor: Without anything attached to the tension protractor string, adjust the thumb screw in the back until the force scale reads zero.

   e. Zero the angle scale of each tension protractor: Hang a small mass (10-g) from the hook so the string hangs straight down. Rotate the outer ring to align the 90° mark with the string (refer to the diagram).

2. Cut four lengths of thread: two 25-cm lengths, one 45-cm length, and one 65-cm length.

3. Use the two 25-cm pieces of thread to suspend a 500-g hooked mass from the wire hooks of the tension protractors: Tie one end of each thread to each protractor hook and tie the other end of each thread to the mass.

COLLECT DATA

4. With the mass hanging motionless, read the magnitude of tension T and the angle θ for each thread. Record the tension and angle for the left thread into Table 1 and the tension and angle for the right thread into Table 2, in the Data Analysis section.

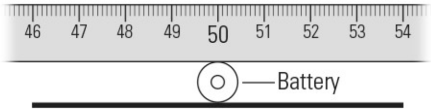
5. Remove one of the 25-cm threads and replace it first with the 45-cm thread, and then with the 65-cm thread, recording the tension and angle for each new thread configuration into Tables 1 and 2.

Part 2 – Net Torque on an Object in Static Equilibrium

SET UP

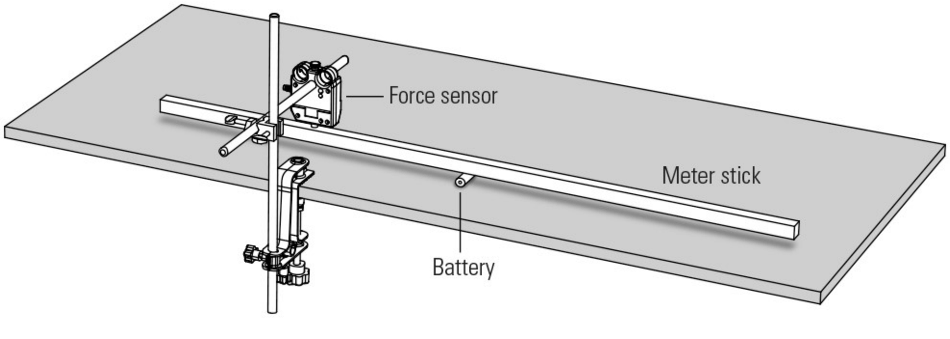
6. Place the battery, or other small cylindrical object, near the edge of the lab table and tape it in place so it does not roll.

7. Find the balance point of the meter stick by placing the center of the meter stick across the battery. Adjust the meter stick until it balances (or nearly balances).



8. Assemble the table clamp or base, two support rods, right angle clamp, and force sensor with bumper similar to the picture below. Adjust the position and height of the force sensor so that it is *just* in contact with the meter stick at some distance between the balance point, or *pivot point*, and the end of the meter stick.

   NOTE: In order to display the scale on the meter stick, the illustrations show the meter stick balancing on its narrow edge, but the wider side of the meter stick should be placed on the cylinder for contact with the force sensor, and so it can support the mass that will be set on it.



9. Connect the force sensor to the data collection system, and then press the Zero button on the top of the force sensor.

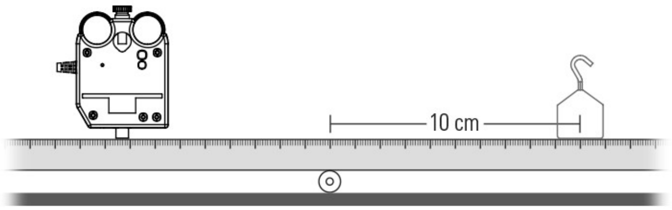
10. On the data collection system, create a digits display of force measured by the force sensor.

    NOTE: The force measured by the force sensor will be equal to the downward force applied by the sensor to the meter stick.

COLLECT DATA

11. Measure the distance between the pivot point and the point where the force sensor makes contact with the meter stick. Record this distance in the space above Table 4 in the Data Analysis section below.

12. Begin recording data, and then place a 100-g hooked mass on the meter stick so that its center is 0.10 m from the pivot point, opposite the force sensor.



13. When the force measurement has stabilized, record it and the horizontal distance from the mass to the pivot point into Table 4.

14. Repeat the same collect data steps four more times, moving the mass an additional 0.10 m from the balance point in each trial. Record the force and horizontal distance for each trial into Table 4.

15. Stop recording data after the fifth trial.

NOTE: If the meter stick becomes unbalanced at any time, stop data collection, re-establish the balance, and begin a new data set.

Data Analysis

Part 1 – Net Force on an Object in Static Equilibrium

Table 1: Tension components on the mass from the left thread

Configuration	Left Thread Tension (N)	Left Thread Angle (°)	T_x (N)	T_y (°)
1				
2				
3				

Table 2: Tension components on the mass from the right thread

Configuration	Right Thread Tension (N)	Right Thread Angle (°)	T_x (N)	T_y (°)
1				
2				
3				

1. Calculate the x-component of the tension force T_x from each thread on the suspended mass ($T_x = T\cos\theta$). Record the results into Tables 1 and 2.

   NOTE: If you choose the positive x-direction to be directed toward the right, the leftward pointing tension force will be negative.

2. Sum the component tension forces T_x from both threads to determine the net force ΣF_x in the x-direction. Record this net force in Table 3 for each configuration.

3. Calculate the downward force from the suspended 500-g mass and record it here:

   Force from hanging mass (N): ______________________________

4. Calculate the y-component of the tension force T_y from each thread on the suspended mass ($T_y = T\sin\theta$). Record the results into Tables 1 and 2.

5. Sum the component tension forces T_y from both threads, plus the force from the hanging mass, to determine the net force ΣF_y in the y-direction. Record this net force in Table 3 for each configuration.

Table 3: Net force on the mass

Configuration	Net Force, *x*-direction (N)	Net Force, *y*-direction (N)
1		
2		
3		

Part 2 – Net Torque on an Object in Static Equilibrium

Horizontal distance from the force sensor contact point to the pivot point (m): ____________________________

Table 4: Torques due to the mass added on one side of the pivot point

Trial	Horizontal Distance from Mass to Pivot (m)	Force Applied by Sensor (N)	Torque Applied by Sensor (N·m)	Torque Applied by Mass (N·m)	Net Torque (N·m)
1					
2					
3					
4					
5					

6. Calculate the torque τ applied by the force sensor in each trial using the equation

$$\tau = r_\perp F \tag{3}$$

where $r_\perp$ is the horizontal distance from the force sensor contact to the pivot point, and F is the force applied by the sensor. Record your results for each trial into Table 3.

NOTE: Torques applied in a clockwise direction about the pivot point are negative, while torques applied in a counterclockwise direction are positive.

7. Use Equation 3 to calculate the torque applied by the mass in each trial, where $r_\perp$ is equal to the horizontal distance from the mass to the pivot point, and F is the weight (in N) of the 100-g mass. Record your results for each trial in Table 3.

8. Calculate the sum of the torques (the net torque) in each trial. Record your results into Table 3.

Analysis Questions

1. Draw a free-body force diagram of the setup you used to demonstrate that the net force acting on an object in static translational equilibrium is zero. Indicate the direction and magnitude of the forces involved in your experiment.

2. Explain how your data demonstrates that the net force acting on an object in static equilibrium is zero.

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3. How would your experiment have been different had you used an object that was three times as massive? Justify your answer.

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4. Draw a free-body force diagram of the setup you used to experimentally demonstrate that the net torque acting on an object in static rotational equilibrium is zero. Indicate the direction and magnitude of the forces involved in your experiment.

5. Explain how your data demonstrates that the net torque acting on an object in static equilibrium is zero.

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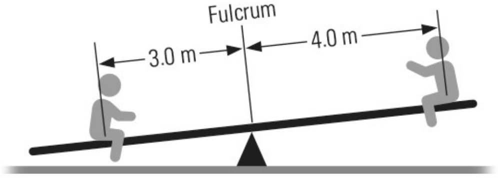
Synthesis Questions

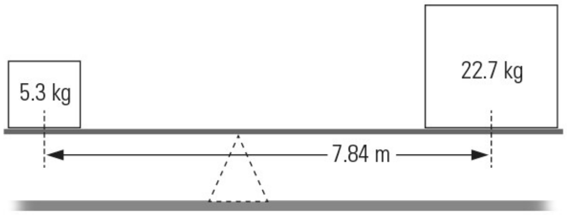
1. Describe the relationship between static equilibrium and net torque.

2. Can you assume that a larger force always produces a greater torque? Why? Justify your answer.

3. Two children are sitting on a seesaw. If the child on the left has a mass of 31.0 kg and sits 3.0 m from the fulcrum, and the child on the right has a mass of 25.0 kg and sits 4.0 m from the fulcrum, what is the net torque on the seesaw? If the seesaw is initially at rest, which way will it rotate? Assume that the fulcrum is directly below the center of mass of the seesaw. Show your work.



4. A student is trying to balance a long beam on a fulcrum so that the beam does not rotate. If the beam has two masses on it that are 7.84 m apart (a 5.3-kg mass on the left end, and a 22.7-kg mass at the opposite end), where should the student place the fulcrum so the system will be in static equilibrium? (Assume the beam is massless.) Show your work.



❷ 5. A log weighing 510 N is laid across cinder block supports (L and R) on each bank of a stream to form a bridge, as shown in the diagram. The length of the log is 2.0 m, and 0.5 m of the log hangs past the R block to the right. What is the magnitude of the normal force on each block? Assume the log has uniform density.