Lab 7

Torque and the Human Arm

Continuing Objectives

4. Be able to make careful measurements to ensure reproducible results.

5. Know how to keep a clear and organized record, including an introduction (with purpose of lab and appropriate laws or equations), apparatus sketch, table of raw data and calculated quantities, and a good conclusion or summary.

7. Know how to make comparisons: are two measured quantities equal? Is a measured quantity statistically equivalent to a theoretical value?

10. Be able to work with physical vector quantities.

Lab-specific Objectives

1. Use a physical model to study how the human arm moves.

2. Explore and understand rotational motion via the study of a physical model.

Introduction

Torque is a topic that has applications in a wide variety of fields. Automotive mechanics need to understand torque in order to change your tires, doctors need to understand torque on different parts of the human body in order to repair damaged joints (such as knee and hip replacement surgeries), and biomedical engineers need to understand how torque affects movement when designing prosthetic limbs. In this lab, you will focus on a biological application of torque in order to understand how it works and affects daily life.

Theory

Torque refers to the application of force on an object that can result in a rotation of that object. The object will rotate about some pivot point, and the resulting rotation depends on the force applied, where it is applied relative to that pivot, and the angle at which it is applied. The equation for torque is given as

$$\vec{\tau} = \vec{r} \times \vec{F}, \tag{7.1}$$

where $\vec{r}$ is the vector pointing from the pivot point to the location at which the force is applied, $\vec{F}$ is the applied force, and the "×" symbol represents a cross product. Based on the definition of a cross product, the magnitude of the torque can be written as

$$|\vec{\tau}| = rF\sin(\theta), \tag{7.2}$$

where r and F are the magnitudes of the vectors and θ is the angle between those vectors. Figure 7.1 shows the physical relationship between these variables. The direction of motion caused by torque is given by the right hand rule (RHR) of the cross product. In this case the rotation can be either clockwise or counterclockwise with respect to the pivot point.

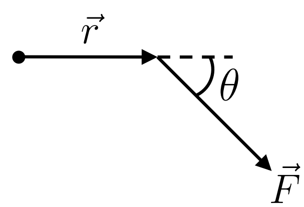


Figure 7.1: Graphical description of the relationship between the variables in the equation for torque.

We will consider a case of static equilibrium in this lab to determine the force applied by the bicep muscle in order to hold up the forearm and hand. We will also explore how that force changes when mass is added to the system by something held in the hand. Figure 7.2 shows a simplified version of the average human forearm-hand system, which we will use throughout this lab. The bicep muscle connects to the forearm at a point relatively close to the elbow joint, which is our pivot. The center of mass (COM) of the forearm is not geometrically centered, but is positioned closer to the elbow than the hand. The hand is included in this setup as well, and is factored into the COM calculation.

Part I: Qualitative Motion of the Forearm

Let's start by making some qualitative observations of the motion of our forearm.

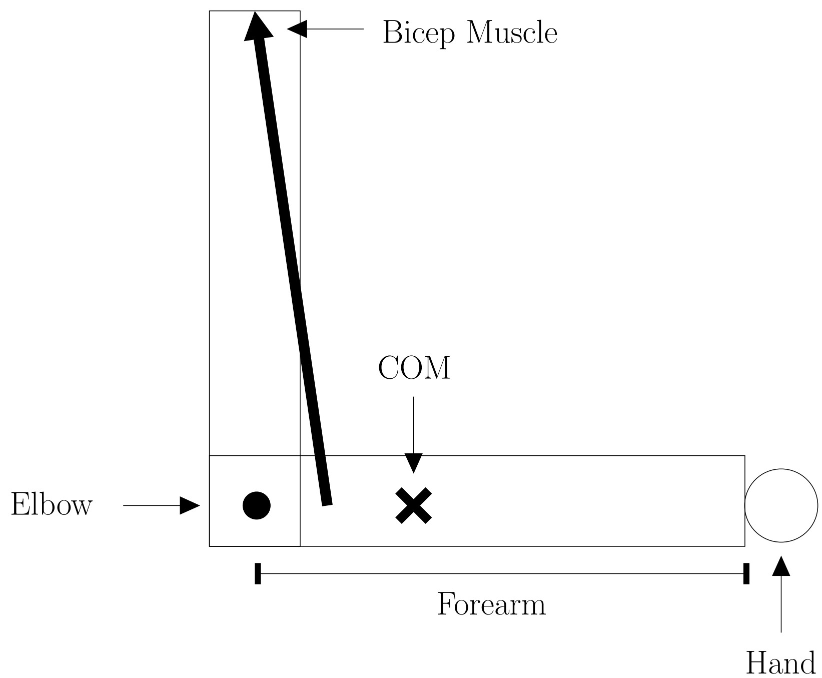


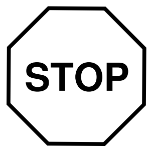
Figure 7.2: Simplified diagram of the human forearm. The forearm and hand are shown with the position of the elbow, COM, and connection of the bicep muscle. Figure not to scale.

1. Hold your arm loosely at your side, and then bring your forearm up until it is parallel with the ground. As you do this, hold your other hand on the inside of your upper arm, just above the elbow joint. You should feel your bicep muscle engage as you raise your forearm. As you hold your forearm parallel to the ground, you should feel the muscle stay tense as it holds up your forearm. This is the situation that we will be considering in this lab.

2. Choose something around you that is relatively light to hold in your hand, like a notebook or a few of the masses on the table. Start with your arm loose at your side again, and then slowly bring your forearm up through the parallel position you explored in the previous step until your hand is near your shoulder. What are the points along this motion at which it feels easiest to hold the object for a while (about 15 seconds)? When is it hardest to hold the object?

3. Now find something heavier like a stack of books or a backpack to hold and repeat the steps above. There may be larger masses on the front desk for you to borrow for this step. Identify when it is easiest and hardest to hold these objects.

4. Considering the (simplified) diagram of the human forearm in Figure 7.2, why do you think it is harder to hold objects at some positions? Discuss your thoughts with your lab partner and record your results in your lab notebook.



Discuss your results with your instructor or TA.

Part II: Quantitative Measurements of Forearm Motion

Now you will make some quantitative measurements to go along with the qualitative observations above. A physical model of the human forearm is attached to the end of your desk, and Figure 7.3 shows a schematic of the setup. A metal rod acts as a combination of the forearm and hand, and is able to pivot up and down. There are holes or pins in the rod that indicate where the bicep muscle connects, where the COM is, and where the hand would hold an object.

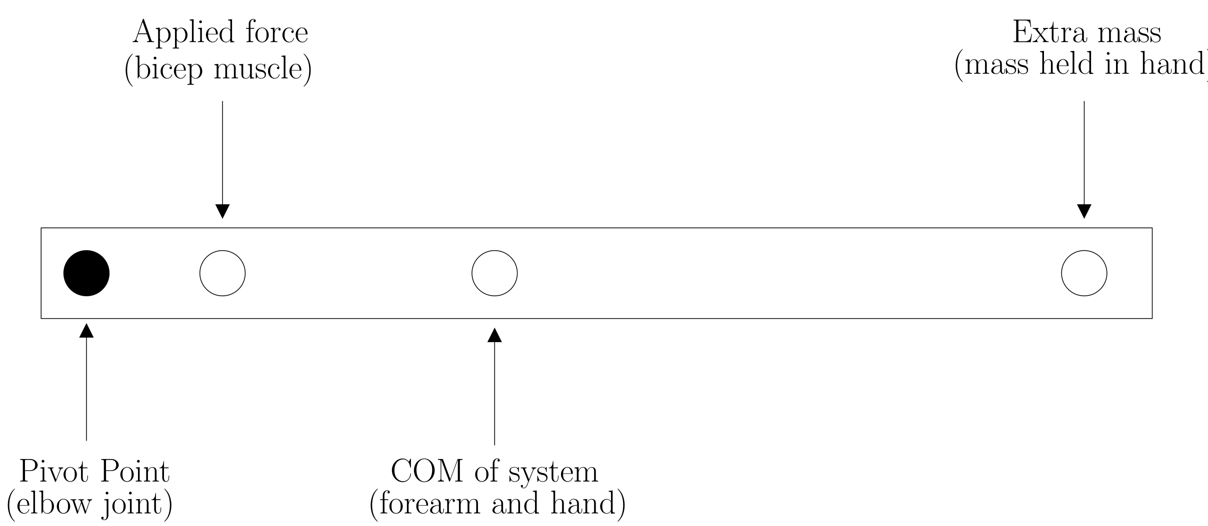


Figure 7.3: Experimental setup of the human forearm and hand system. The holes indicate locations where forces may be applied on the system. Figure not to scale.

We will consider the case where the forearm-hand system is parallel to the ground. The spring scale will attach at the bicep hole and serve as the muscle in our setup. We will attach mass to the COM hole to mimic the mass of the forearm.

1. Using the same approach that you learned in your lecture and problem session for problems with rotation, identify the forces that cause rotation. Then, draw a torque diagram of the forearm and hand apparatus. Assume that there is no extra mass in the hand and that the forearm is stationary and parallel to the ground.

2. Using the fact that the net torque on an object in equilibrium is zero, derive an expression for the force applied by the bicep muscle. We will assume that the bicep acts perpendicular to the forearm.

STOP Show your results to your instructor or TA.

3. Using the expression you just derived, predict the necessary force that must be applied by the "bicep muscle" (spring scale) in order to keep the forearm-hand system at your desk parallel to the ground. In other words, measure the necessary masses and distances for your setup. Add 150 g to the COM location using the mass hanger at your desk. There should be rulers on your desk and scales in the back of the room for determining the mass of the forearm system. Report your final value for the force in your lab notebook.

4. Now use the spring scale to test how accurate your calculations were: attach the spring scale to the bicep muscle location and experimentally determine the force required to hold the forearm and hand parallel to the ground. Estimate the uncertainty in your measurement and report your result in your lab notebook in correct scientific form. Is this consistent with the calculations that you did? Be sure to note sources of error in your measurements in your lab notebook.

STOP Discuss your results with your instructor or TA.

5. Calculate the force of gravity on the forearm-hand system. How does the force applied by the bicep muscle compare to the force of gravity on this system? Are they equal? Explain your answer in your lab notebook.

6. It turns out that the mass of the average human forearm and hand is 1.5 kg, which is more than the mass of your apparatus. Using the expression from step 2, estimate the actual force applied by the bicep muscle. How does this

compare to your experimentally determined value from step 4 (don't actually measure this)?

The elbow joint is actually a fairly strong one due to muscles like the biceps! It is estimated that the elbow endures loads around 300 N doing activities such as eating or getting dressed, and loads up to 1700 N when supporting the body in order to get out of a chair.

7. Now add some mass to the system such that the hand would be holding it. (Keep the COM masses attached as well.) You should add no more than 250 g, including the mass hanger. Repeat steps 1 and 2 in order to derive a new expression for the bicep muscle force. Calculate the required applied force in this case, and then experimentally test your predictions. Report the force applied with the uncertainty, and determine whether the calculated value is consistent with your results.

8. In the human body, the bicep muscle does not actually pull perpendicularly to the forearm. The angle with which it pulls varies from person to person, but we will assume an average angle of 65° with respect to the forearm. Without the additional weight on the hand, once again repeat steps 1 and 2 to determine the appropriate expression for the bicep muscle force in this case of 65°. Make sure that the forearm is still parallel to the ground! Use your derived expression to calculate what the applied force of the bicep should be if pulling at this angle.

9. Now we estimate the uncertainty in this prediction. Determine the uncertainty in the angle θ_{bicep} and use uncertainty propagation to determine the uncertainty in your calculated value of F_{bicep}. (We assume that the uncertainty in the COM mass and the r measurements are negligible.) The steps you need are the ones outlined in Appendix A.1 (see also Lab 2). Report your result for the predicted F_{bicep} and uncertainty. To report your result use the format you learned at the end of Lab 2 (also described in Appendix A.2.)

10. Test your predictions for the bicep force pulling at an angle of 65° with respect to the forearm using your setup. Record your result with your experimental uncertainty in your lab notebook, and compare it with the predicted result and uncertainty from the previous step. Are your results consistent?

STOP Discuss your results with your instructor or TA.

Reflection and Activity

In the back of the lab room, you should find a setup that models the knee joint. There is only one of these models, so if you are waiting for your chance to work with it, please take this time to reflect on today's lab in your notebook.

Look back at today's lab-specific objectives (beginning of the lab).

1. What activities did you do today that helped practice those objectives?
2. How has your understanding of the concepts covered in this lab changed over the course of today's lab?
3. Today you used a physical model to explore the forces and torques on a typical human arm. Think of an example of another system that might be better understood by modeling it and studying the model. How does modeling help with the study of physics?

Knee Model

1. In the back of the lab room, you should find a setup that models the knee joint. In the human knee, tendons attach over your kneecap and allow your muscles to tense and loosen, thus straightening or bending your knee. The setup you see allows the kneecap to be removed. Try to move the lower part of the apparatus (below your knee) with and without the kneecap in place. Then, talk with your partner and explain in your notebook why we need kneecaps and how this relates to torque.
2. Summarize the steps and conclusions from this lab in your lab notebook. You should be able to explain how $\vec{r}$ and $\vec{F}$ contribute to torque and how torque applies in the specific case of the human forearm. Before leaving, remove any mass hangers or spring scales from the apparatus.