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FORCE, TORQUE, AND THE ELECTROMYOGRAM: A STUDENT LABORATORY EXERCISE

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ABSTRACT

This paper describes a muscle physiology laboratory exercise that uses electromyography to emphasize the concepts of force and torque and the role of limb position. Students perform a simple laboratory exercise that enables them to relate the angle of a joint with the concepts of force, torque, and the moment arm. Students observe the combined effects of motor unit recruitment and the variation of action potential frequency on the amount of electrical activity a muscle generates. They note that the amount of force a muscle generates also depends on motor unit recruitment and spike frequency. Here, I provide detailed protocols that students may follow. For the instructor, I provide background information, representative results, an explanation of technical matters, a list of pitfalls students may experience, and settings files for LabChart and LabScribe software. The exercise described here provides an excellent complement to, or serviceable replacement for, other muscle physiology labs while it also illustrates some principles of kinesiology.

Keywords: EMG, electromyography, moment arm, lever arm

INTRODUCTION

A wealth of resources is available to anyone that plans to teach electromyography to students. Many student laboratory exercises are made available by manufacturers of physiology hardware and software. To my knowledge, however, none of those protocols allows students to explore the topics of limb position, force, the moment or lever arm, and torque. Since a number of parties have recently advocated for more cross-disciplinary biology curricula (National Research Council 2003; Steen 2004; Association of American Medical Colleges and Howard Hughes Medical Institute 2009; Brewer and Smith 2010), a laboratory exercise that integrates aspects of biology, physics, and mathematics would have a place in a modern science curriculum. For many years, my students have investigated limb position, force, the moment arm, and torque in a laboratory exercise which is described in this paper. Here, I provide everything you need to run this exercise with either of two popular platforms: LabChart by ADInstruments and LabScribe by iWorx. Other digitally-based platforms should also be suitable. In short, students record the electrical activity of their biceps brachii muscle while holding no mass, a 2.28 kg mass, and a 4.55 kg mass, all at two different arm positions: with the forearm nearly full extended and with it partly flexed. Students quantify the amount of electrical activity in each of their six recordings and create a graph that shows how that quantity depends on arm position and mass held. They answer questions that require them to think through the concepts they should have learned. They calculate force and torque based on the masses they held and their own physical dimensions. The exercise integrates the topics of

muscle physiology, mathematics, and physics. It can also be used to show how digitized data can be manipulated in a spreadsheet. Because of its simplicity, the exercise can serve as the first in a series, to acquaint students with the principles of electrophysiological recording, or it can stand alone. It can complement other labs, such as the classic frog gastrocnemius muscle exercise, or replace them. Settings files for LabChart and LabScribe are available below the abstract here <http://digitalcommons.gaacademy.org/gjs/vol75/iss2/12/>. Student protocols are also available. Instructors are free to use these materials provided they adhere to the requirements that are described in the footnote on the second cover page.

The Physics of Holding a Mass

Imagine holding a 1 kg mass in your hand while your forearm is partially flexed so that the arm and forearm are at a right angle (Figure 1). The 1 kg mass exerts a downward force (F) equal to its mass (m) multiplied by the acceleration due to gravity (a). (For the sake of argument, we will ignore the mass of the arm itself.)

$$\begin{aligned} F &= ma \\ F &= (1 \text{ kg})(9.8 \text{ m/s}^2) \\ &= 9.8 \text{ N (Newtons)} \end{aligned}$$

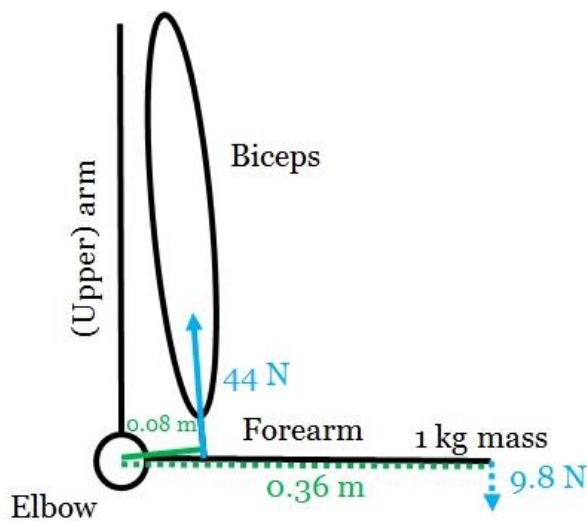


Figure 1. The physics of holding a 1 kg mass. The forearm is flexed to form a 90° angle with the arm. The mass exerts a downward force of 9.8 N. Because the forearm is perpendicular to the direction of the downward force, the moment arm is the distance from the elbow to the mass, in this case 0.36 m. The biceps brachii muscle exerts an upward force on the forearm to prevent it from falling. Because the biceps inserts close to the elbow, its moment arm is only 0.08 m long (solid green line). The biceps must generate 44 N of force to create the same amount of torque as the 1 kg mass but in the opposite direction.

The magnitude of the force is 9.8 N (Figure 1, dashed blue arrow). This force generates a tendency to rotate at the elbow (clockwise in Figure 1). This tendency to rotate is termed *torque*, which is defined as follows:

$$\tau = Fd$$

where τ represents torque, F is force, and d is the length of the *lever arm* or *moment arm*. The moment arm is the shortest distance between the pivot point and a line parallel to the direction of the force (Figure 1, dashed green line). With the arm and forearm at a right angle, the length of the moment arm is the distance from the elbow to the center of mass

of the mass being held. Suppose that distance is 0.36 m. The magnitude of the torque would be as follows:

$$\begin{aligned}\tau &= Fd \\ \tau &= (9.8 \text{ N})(0.36 \text{ m}) \\ &= 3.5 \text{ N}\cdot\text{m}.\end{aligned}$$

To hold the mass steady, the biceps brachii muscle must generate the same amount of torque but in the opposite direction, in this case counterclockwise. To generate that torque, the biceps exerts an upward force at its insertions on the forearm. With the limb in this position, the moment arm may be just 0.08 m (Figure 1, solid green line). The force that the biceps must exert to generate 3.5 N·m of torque in the counterclockwise direction can be determined as follows:

$$\begin{aligned}\tau &= Fd \\ 3.5 \text{ N}\cdot\text{m} &= F(0.08 \text{ m}) \\ 44 \text{ N} &= F.\end{aligned}$$

Because of its short moment arm, the biceps must create 44 N of force to counter the effect of a 1 kg mass that creates only 9.8 N of force 0.36 m from the elbow. This is because the biceps inserts so close to the elbow.

Suppose one were to hold a 2 kg mass instead. It would generate 7.0 N·m of torque and the biceps would have to generate 88 N of force to create the same torque in the opposite direction. Obviously it takes more force to hold a heavy mass than a light one, but understanding the physics is essential for understanding the effect of arm position.

The Effect of Arm Position

To illustrate the effects of arm position on the force required to hold a mass, suppose that the forearm is extended rather than being partly flexed. The moment arm for the biceps to generate counterclockwise torque becomes much shorter (Figure 2, solid green line). If it is shortened to 0.03 m, the biceps must create 117 N of force to generate 3.5 N·m of torque. This explains why it is so uncomfortable to hold a heavy mass with the forearm fully extended. It takes a lot of force to generate even small amounts of torque when the moment arm is so short.

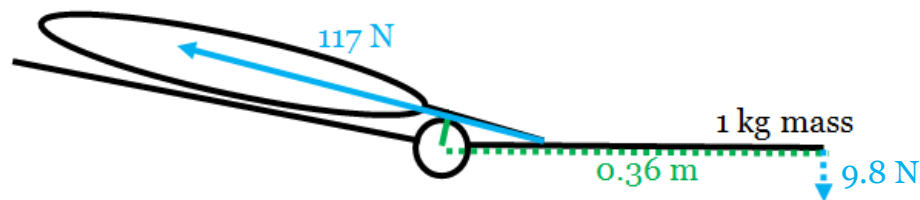


Figure 2. Holding a 1 kg mass with the forearm extended. The force generated by the biceps is represented by the solid blue line. The distance from the pivot point (elbow) to the solid blue line, i.e., the moment arm, is just 0.3 m (solid green line). Consequently, the biceps must generate 117 N of force to create the same torque, but opposite in direction, as the 1 kg mass held in the hand.

The Electromyogram

The electromyogram (EMG) is an extracellular recording of a muscle's electrical activity. Because the electrodes are outside of the cells, it is not possible to measure

membrane potential with an EMG. Action potentials, however, generate currents around cells that induce voltages in the EMG electrodes. Thus, the EMG shows electrical activity, but the recordings do not resemble action potentials as they often appear in textbooks. If surface electrodes are used, as in this exercise, the waveform of the EMG appears chaotic, but the amount of electrical activity can still be determined. Consider two recordings that show different amounts of electrical activity (Figure 3). More electrical activity is present in the bottom trace than in the top one. To quantify the amount of electrical activity, one cannot, however, simply take the average of all the y-values (amplitudes). That average would be close to 0 mV because the waveform goes below the baseline as well as above it. Two popular quantities can be calculated to get around this problem. One is average rectified value or mean absolute value, referred to here as mean deviation (Zar 1999, 34–35). Mean deviation is simply the average deviation from the baseline. It can be calculated by subtracting the baseline from every amplitude value (or the other way around), taking the absolute values of the deviations that result, and averaging those absolute values. One reason to use mean deviation in a teaching laboratory is that it is easy to explain. It tells you how much, on average, the trace deviates from the baseline.

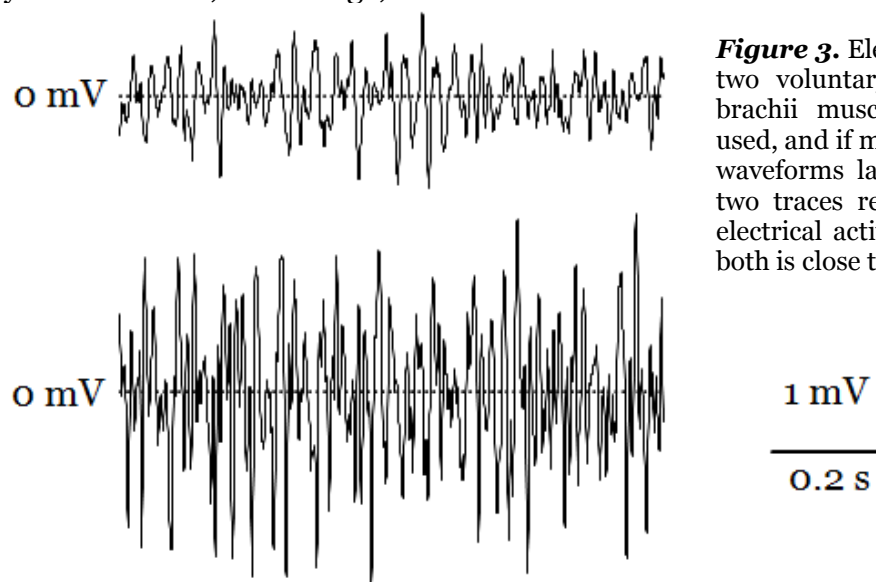


Figure 3. Electromyogram recordings from two voluntary contractions of the biceps brachii muscle. If surface electrodes are used, and if many motor units are active, the waveforms lack any pattern. Although the two traces represent different amounts of electrical activity, the average amplitude of both is close to 0 mV. Subject: F. Corotto.

Another popular quantity is root mean square (RMS), which is the same as standard deviation. Root mean square is obtained by subtracting the baseline from every amplitude value (or the other way around), squaring the resulting deviations to make them positive, averaging the squared deviations, and taking the square root of that average (Urone 2001, 489). This is cumbersome to explain; RMS is the square root of the average squared deviation from the mean. Why is such an awkward quantity popular when mean deviation is comparatively simple? To understand the common use of root mean square, consider an alternating current passing through a resistor. The average amount of power consumed is equal to the RMS of the current multiplied by the RMS of the voltage (Urone 2001, 489). Therefore, RMS provides an indication of signal power. The validity of RMS as a measurement, however, has been questioned when it comes to EMGs; mean deviation appears to be a superior indicator of electrical activity (Clancy and Hogan 1997). Regardless, I prefer mean deviation simply because it is easy to explain and understand. The procedure I provide lets students obtain that quantity. If you prefer root mean square, both LabChart and LabScribe can calculate it.

What Does the Amount of Electrical Activity Reflect?

The amount of electrical activity reflects the number of myofibers firing action potentials and the frequency of firing of those cells. The number of cells firing depends on the number of motor units firing and the number of myofibers within them. The more motor units, the larger the motor units, and the higher the spike frequency in those motor units, the greater the electrical activity observed in the EMG, and the greater the force generated. While an increase in electrical activity typically means a greater force is generated, the relation between force and EMG activity is complex. One cannot be equated with the other (De Luca 1997). It is important to emphasize to students that they will measure electrical activity in this exercise, not force itself.

OBJECTIVES

The learning objectives are as follows:

1. To understand that the force generated by the biceps brachii muscle reflects the following:
 - a. The number of motor units recruited.
 - b. The size of the motor units that are recruited.
 - c. The action potential frequency within those motor units.
2. To understand that the same three things that influence force also govern the amount of electrical activity generated by the muscle.
3. To understand that, in spite of 1 and 2 above, force and electrical activity are different quantities. Students do not measure force in this exercise. They measure electrical activity.
4. To understand that the greater the mass that is held, the greater the force that is required. To generate more force, more motor units must be recruited, the newly-recruited motor units are larger than the ones initially recruited, and all the activated motor units must fire at a higher frequency.
5. To understand the relation between force, torque, and the moment (lever) arm as they pertain to arm mechanics.
6. (Optional) To understand the nature of digital sampling, and to appreciate how digitized physiological recordings can be manipulated and analyzed in a spreadsheet.

METHODS AND RESULTS

The instructor need only set up workstations for recording small biological signals. iWorx provides a variety of products for recording electromyograms. With products from ADInstruments, recording leads are plugged into the Bio Amp input of the Powerlab unit. Beyond that, all that is needed is skin electrodes, a meter stick or tape measure so students can measure their forearms, and 1.14, 2.28, and 4.55 kg masses (e.g., 2.5, 5, and 10 lb barbell weights). For best results, students should use the 2.28 and 4.55 kg masses, but some are more comfortable with 1.14 and 2.28 kg masses. If electrodes tend to peel off, then tape for the electrodes is also helpful.

A student begins with two EMG surface electrodes on the biceps brachii and a third ground electrode on the triceps. The student squats by a lab bench with his or her arm outstretched upon it (Figure 4A). The student elevates the forearm slightly while a lab partner records a 1 s EMG trace. It is essential to record the EMG when the forearm is held steady and elevated, not when it is being raised or lowered. This is repeated but with

the student holding a 2.28 kg mass and then a 4.55 kg mass. Next, the student is repositioned so that the forearm is partly flexed (Figure 4B) and the process is repeated with no mass, then 2.28 kg, then 4.55 kg. The result is six traces that show the muscle's electrical activity with each mass and arm position (Figure 5). Clearly, both arm position and the amount of mass held influence the amount of electrical activity generated in the biceps.

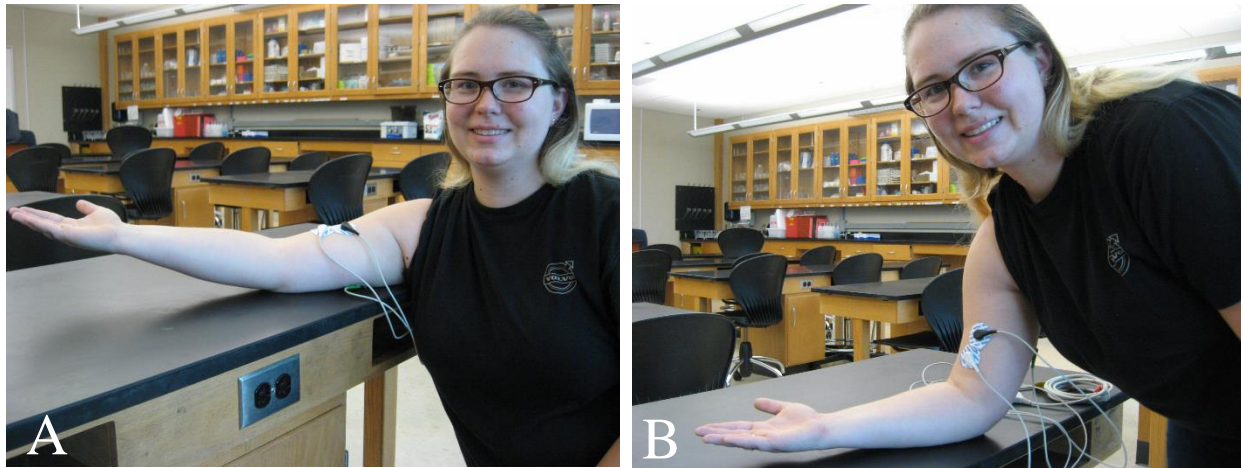


Figure 4. Recording the electrical activity of the biceps brachii muscle at two arm positions. A. The forearm is extended but must not rest on the tabletop during the recording. B. The forearm is flexed. Again, it must not rest on the tabletop. Recording electrodes are placed about 20 mm apart on the belly of the biceps brachii, though the adhesive discs may overlap. The ground electrode is on the triceps brachii. Electrode position follows the recommendations of the SENIAM project, seniam.org/bicepsbrachii.html. Model: Bailey Hallock.

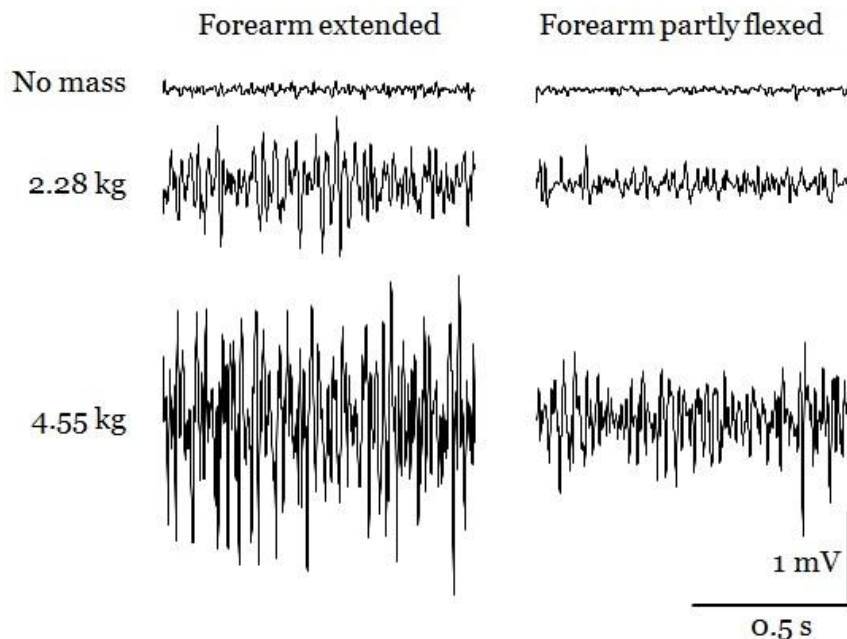


Figure 5. Representative EMG recordings obtained from the biceps brachii muscle while the subject holds different masses at two arm positions. Subject: F. Corotto.

Students often expect large signals from large, muscular persons. What they observe is the opposite. Slender students generate more electrical activity than more muscular ones. This is presumably because if a muscle is small, a large percentage of the motor units must be activated to generate a certain amount of force and all those motor units will be close to the electrodes. With a larger muscle, a smaller fraction of the motor units will be activated and many will be buried deep in the muscle away from the recording sites. Students often show interest in this matter.

Data Analysis

The next step is quantification. Students calculate mean deviation for each of the six traces. The result is a single number representing the amount of electrical activity in each recording. Students can then graph those values of mean deviation as a function of arm position and mass held. Although results vary, most students find that when arm position is held constant, the greater the mass, the greater the electrical activity (Figure 6). Most also find that, when mass is held constant, there is more electrical activity in the biceps when the forearm is extended than when it is flexed. I find it helpful to emphasize the fact that those two trends are present in nearly every student's results, especially because no two graphs will look identical, and some students become concerned by trivial differences among their graphs.

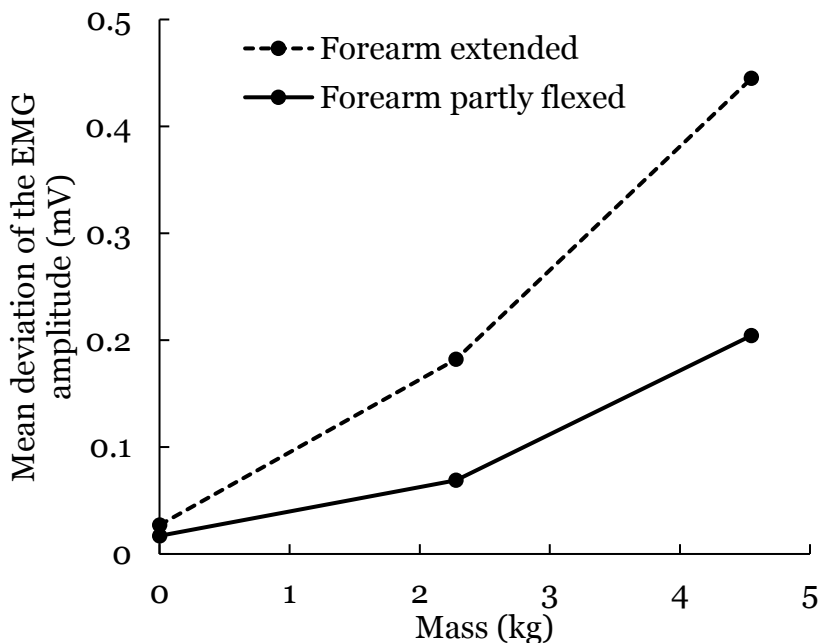


Figure 6. Data from Figure 5 plotted as might be done by students. Because the x-axis represents a numerical continuum, students should not make a bar graph.

USE OF A SPREADSHEET TO CALCULATE MEAN DEVIATION

While LabScribe and LabChart both make it easy to obtain mean deviation, I prefer for students to export their digitized recordings into Microsoft Excel where they can calculate mean deviation manually. This forces the students to obtain mean deviation themselves, so they are more likely to understand the calculation and its necessity. It also lets me emphasize the nature of digital sampling. Since each recording lasts 1 s, and since they sample at 2 kHz, each recording is converted into 2000 x-y pairs. Each pair takes up one row in Excel, with time values in column A and amplitudes in column B. Since there are six recordings at 2 kHz, and since they are arranged contiguously in those two columns, the resulting spreadsheet contains 12,000 rows. With the spreadsheet in front of them, students see digitized data, and can relate what they see to the original recordings. Next, they calculate mean deviation and graph their results. Whether or not your students use Microsoft Excel to calculate mean deviation, if they use Excel to graph their results, please encourage them to make a professional looking figure with large print, properly labeled axes, and a caption (Figure 6) rather than relying on Excel's default settings.

TECHNICAL MATTERS

Noise can be a problem with any electrophysiological recording. Most noise arises from electromagnetic interference, so it takes the form of a 60 Hz cycle waveform. Because noise moves the trace away from the baseline, it contributes to the calculated value of mean deviation. Provided that the amount of noise remains the same for all six recordings, this is not a problem. Noise simply shifts the data to higher values. Imagine the data in Figure 6 being shifted upwards a little. A student's understanding of the graph would not be affected. If, however, the amount of noise differs among the recordings, then not all data will be shifted to the same degree, and the outcome can be inexplicable. To ensure that the amount of noise goes unchanged, electrodes must be firmly attached to the skin and, for some brands, adding extra gel helps ensure good electrical contact. Tape the electrodes down if you choose a brand that tends to peel off. While it is common to lightly abrade the skin with sandpaper prior to placing the electrodes, I have never found it necessary to do so.

Noise can be an especially serious problem if leads are poorly shielded. In that case, the 60 cycle pattern can mask the EMG. To use such leads, stretch out the cable so that it is not coiled at all, and tape it down so it does not move. If that does not work, try different cable positions until you find one at which noise is minimized. Then, fix the cable in place. When troubleshooting noise, the electrodes must be connected to someone. Unconnected electrodes will act like an antenna and pick up huge amounts of interference. With good electrodes and leads, nearly noise-free recordings can be obtained easily, e.g., the top traces in Figure 5. Even poorly shielded leads and cables can perform well if they are stretched out fully and fixed in place.

A few things can go wrong if students use Excel to calculate mean deviation rather than having students use LabScribe or LabChart to do it. The procedure entails students setting up a table in which the calculated values of mean deviation are placed into six cells, one for each recording (Figure 7, blue cells).

| row | D | E | F | G |
|-----|------------------|-----------------------|------------------------|-------------------------|
| 1 | mass lifted (kg) | 0 | 2.28 | 4.55 |
| 2 | elbow at 180° | =average(C1:C2000) | =average(C2001:C4000) | =average(C4001:C6000) |
| 3 | elbow at 90° | =average(C6001:C8000) | =average(C8001:C10000) | =average(C10001:C12000) |

Figure 7. The table that students create in Excel to generate their graph, provided that Excel is being used to calculate mean deviation. Each of the six blue cells contains the formula to calculate mean deviation for one of the six recordings.

For the addresses in those cells to be correct, students must do the following:

1. perform the procedure in the correct sequence,
2. delete any recordings in which something went wrong,
3. ensure that no more than one student's results are in each text file that is imported into Excel,
4. ensure that no extraneous information is included in the text files.

An example of extraneous information is as follows. In the process of creating the text file in LabChart, students are asked to uncheck all boxes except for those for *Time* and *Always seconds*. If they do not remove the check from the box for *Block header* (and many will not) then six rows of descriptive information will be added to each recording.

Fixing all of these problems is easy. If students perform the exercise in the wrong sequence, the formulas in Excel (Figure 7, blue cells) can be rearranged accordingly. If there are extra recordings, then they can be deleted in LabScribe or LabChart, and new text files can be exported. The creation of new text files can also solve any problems with the export itself, such as the inclusion of unnecessary descriptive information.

CONCEPTUAL PITFALLS

There are several concepts that students often fail to understand. They often think that they are recording force when they are actually recording electrical activity. It is important to emphasize the distinction. They may also quickly grasp the concept of motor unit recruitment while neglecting the equally important issue of action potential frequency, i.e., summation and tetanus. Finally, the best students may try to explain their results by considering the effect of limb position on muscle length and then consider the familiar length-tension relationship of skeletal muscle. This phenomenon, however, has historically been studied in isolated muscles, which can be stretched or contracted to great degrees. In situ, muscles are limited by their attachments. The biceps is only lengthened by about 20% when fully extending the forearm from a partial flexion (Robinson and Snyder-Macker 2008, 90). So, when it comes to explaining the effect of limb position, it is mostly a matter of force, the moment arm, and torque. The familiar length-tension relationship of skeletal muscle is less important.

CONCLUSIONS

As college biology curricula move toward greater integration of mathematics and all the natural sciences, there will be a greater need for interdisciplinary laboratory exercises. The procedure I describe here has only a few pitfalls, described above, and they

are easily resolved. The exercise is easy to set up, typically goes smoothly, and provides an excellent combination of biology, physics, and simple mathematics.

ACKNOWLEDGEMENTS

The wording of the cover page footnote was taken from publications by the Association for Biology Laboratory Education.

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