

AC 2010-603: INCORPORATING THE IMPORTANCE OF INTERDISCIPLINARY UNDERSTANDING IN K-12 ENGINEERING OUTREACH PROGRAMS USING A BIOMIMETIC DEVICE

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Incorporating the Importance of Interdisciplinary Understanding in K-12 Engineering Outreach Programs using a Biomimetic Device

Abstract

The project presented in this paper is designed to motivate interest in the engineering field for K-12 students, especially those who have previously viewed engineering as disconnected from biological sciences or the medical field. This idea is supported by recent trends in biomedical engineering, namely that the number of biomedical engineering bachelor's and master's degrees awarded throughout the United States has more than doubled since 2000, and that the demand for biomedical engineers will increase through 2010. However, to stimulate early interest in the biomedical engineering field, there is an apparent need for simple projects that clearly convey the relevance of engineering to biomedical contexts.

This paper describes a novel educational program that seeks to achieve this connection at the K-12 understanding level using a build-and-test experimental device that incorporates physics, biology, teamwork, engineering analysis, and cutting edge technology into a single, integrative project. The build-and-test device used in this program is an actuator that simulates the action of sarcomeres (individual contractile units of muscle fibers) during muscle contraction, which demonstrates how creativity in engineering design may be inspired by a phenomenon found in nature. To build the device, a group of three or four students are assigned individual tasks that combine to produce a working device. The diversity of these specific tasks also allows students to identify areas of engineering that may pique their interest. Furthermore, the project implements new technology in the form of electroactive polymer (EAP), which produces a motion when subject to a voltage difference. After assembling the device and running the experiment, each student group gathers data from their test and determines basic engineering parameters (i.e., force, amount of work done) associated with the results of their experiment. Finally, the students are also given "challenge questions" to stimulate critical thinking skills by applying the same lessons used to complete their initial analysis in other contexts.

We assess the quality of the program based on students' performance in building and testing the device within a given time frame, their answers to challenge questions and basic biological questions that form the basis of this project, and their feedback on the overall program. The authors finally suggest further improvements to the current project based on these assessments.

1. Introduction

The Office of Recruitment and K-12 Engineering Education Outreach at Michigan State designed to attract prospective engineering students from middle and secondary schools through a plethora of visiting opportunities and workshops, some of which include: Design Day, Grandparents University, Wireless Integrated Microsystems (WIMS) Pre-College Enrichment Programs, which includes WIMS for Teens and WIMS for Women in Engineering^[1]. At such venues, the visitors are exposed to actual research and are invited to engage in hands-on projects designed to show them how an engineer may solve a given problem. Additionally, the variety of engineering disciplines shown to these visitors allows them to observe the career possibilities within the engineering field.

One of more recent career possibilities in the engineering field is biomedical engineering, which has proven to be a rapidly growing trend within the United States, according to recent increases in the number of master and doctoral degrees awarded in this field^[2]. Consistent with this trend, we may expect future increases in the number of biomedical engineering programs offered by universities around the country, particularly at the undergraduate level. Therefore, it may be beneficial for prospective K-12 engineering students to have preliminary exposure to this field and determine their level of interest in biomedical engineering. Based on these ideas, we sought to design a relatively simple project that would clearly demonstrate not only the connection between biology and engineering, but also expose the students to the engineering analysis and critical thinking skills necessary to be successful in the biomedical engineering field. Such multidisciplinary projects have been recommended by National Research Council, which claims that biology curriculums should contain emphasis on math, statistics, and should be interdisciplinary^[3].

2. Objectives of Project

According to recent studies, there appears to be a gap forming between the number of engineering graduates from the United States to those from foreign countries such as China and India^[4]. According to the U.S. Department of Labor biomedical engineering jobs are projected to grow the fastest among all occupations through 2010, and to supplement this increase in demand, universities throughout the country have begun incorporating biomedical programs into their undergraduate curriculum^[5]. Papers written on the subject of K-12 recruitment into the engineering and technological fields are beginning to reach a consensus that crucial decisions regarding pursuing an engineering career may be made between the sixth and eighth grades^[4]. Currently in the United States, pre-engineering programs are not common or required in primary schools. Thus, it is apparent that outreach programs promoting pre-engineering projects that will expose students to engineering and motivate interest within the field may be an effective method for the United States to close the gap with other developed countries.

An additional desired outcome of the project is to increase the involvement of underrepresented groups in engineering, particularly women. According to current

reports, male undergraduate engineering students outnumber females nearly 4 to 1 ^[6]. Conversely, female enrollment in biological sciences is three times greater than female enrollment in engineering programs ^[6]. As such, a strategy to include more females in engineering may be to introduce engineering from a biological perspective, providing them with a clear connection between the two fields. Previous studies on integrating biological and engineering concepts into integrated lessons have proven successful ^[7].

Finally, teachers may benefit from this project as well. The supplementary lecture providing the necessary background to understand both the biomimetic device and physiological background may be incorporated into a K-12 curriculum. Thus, after covering the background material in a previous lecture, the teacher could set aside an after-school activity to engage the students in the hands-on portion of the project. In this project, teachers would also be able to gauge their students' ability to incorporate real world engineering skills into their curriculum, which include, but are not limited to: planning, building, testing, analysis, problem-solving, and teamwork. Thus, the teacher is able to create an "active learning environment" with such projects ^[8].

To summarize the objectives of this project, we have sought to:

- *Promote the growth of engineering studies within the United States, and more specifically, provide a means to include historically underrepresented students into our project and encourage their involvement in biomedical engineering.*
- *Encourage visiting students and teachers to fully connect concepts from engineering to biology using simple engineering analysis at the K-12 understanding level.*
- *Provide students with an opportunity to obtain hands-on engineering experience that emphasizes building, testing, and teamwork.*

Based on our objectives, our project also addresses multiple STL (Standards for Technological Literacy) standards ^[9], in particular:

- *Standard 1. Students will develop an understanding of the characteristics and scope of technology.*
- *Standard 3. Students will develop an understanding of the relationships among technologies and the connections between technology and other fields of study.*
- *Standard 12. Students will develop the abilities to use and maintain technological products and systems.*

For this K-12 program, educational kits of an EAP-based actuator that mimics the basic contractile mechanism of a muscle cell have been developed. Using these kits, 15-20 minute hands-on sessions for 3~4 student groups were offered as a part of Cardiovascular and Tissue Mechanics Laboratory experience for the participants of WIMS for Teens and Women in Engineering, both of which emphasize participation of groups underrepresented in STEM areas.

3. Biomimetic Device

The biomimetic device was based on the function of the sarcomere, the basic contractile unit of a muscle cell. In the following sections, we first provide the biological and engineering theory behind the biomimetic device, and then present features of the device. Taken together, both the background information and the device provide a clear demonstration of how an engineer might develop a device to achieve a desired motion.

Biological Background

In the human body, a skeletal muscle cell shortens or lengthens using a sarcomere. On a simplistic basis, the sarcomere is comprised of four main components: the actin filament, and the myosin filament, the myosin head, and the Z-line^[10]. A schematic of these basic units and how contraction is completed can be seen on Figure 1.

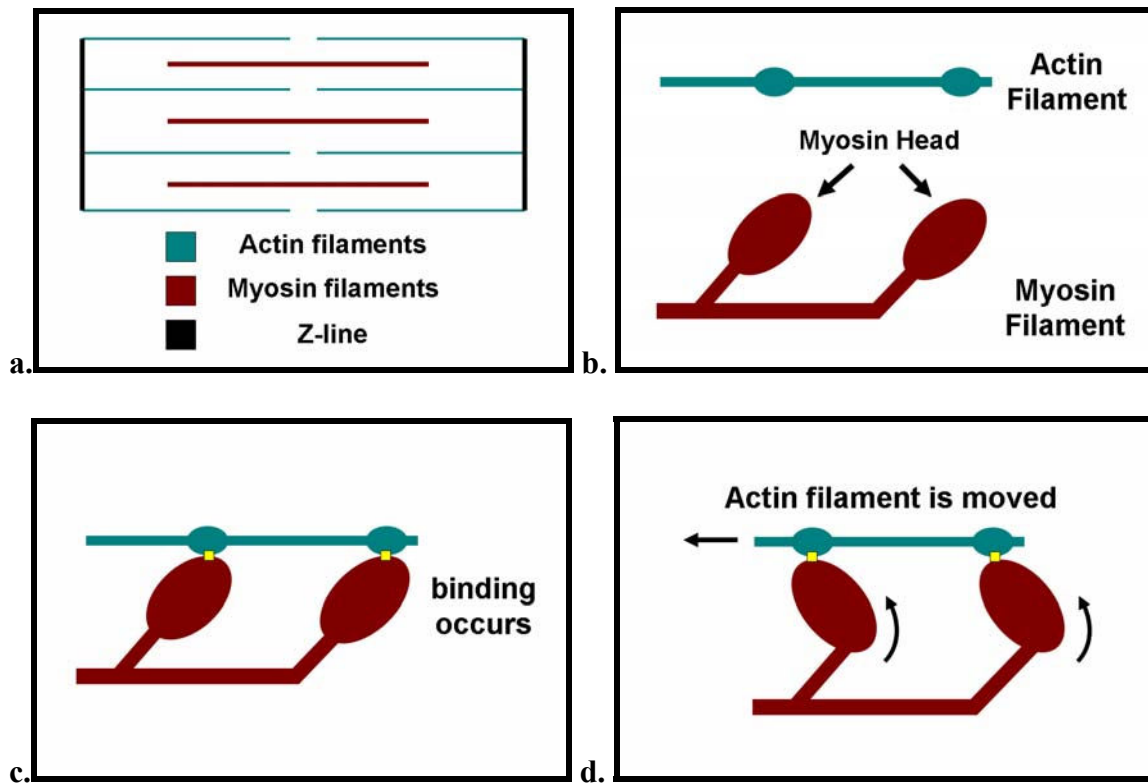


Figure 1. (a) Large-scale, simplified view of a sarcomere. The actin filaments are attached to the Z-line, and are moved by myosin heads on the myosin filament. (b) Close-up of the configuration of actin and myosin filaments before activation. (c) Binding of actin and myosin filaments before the myosin head power stroke. (d) Configuration of actin and myosin filaments after myosin head power stroke. The myosin head moves the actin filament while the position of the myosin filament remains fixed.

To briefly summarize the physiological series of events to generate sarcomere lengthening or shortening, action potentials generated in the brain travel down nerve fibers and are released as the neurotransmitter acetylcholine (ACh) at a particular skeletal muscle group. ACh stimulates the release of calcium within the intracellular space of skeletal muscle cell. The binding of calcium to a component located on the actin filament (known as Troponin C) releases the chemical bond holding a myosin head. Then, via ATP hydrolysis, the myosin head able to rotate and bind to another site on the actin filament in an event known as the power stroke of the myosin head. Finally, multiple power strokes are completed until the sarcomere reaches the desired contraction state ^[10]. The scale of sarcomere contraction is very small, and therefore large numbers of sarcomeres are required to work in unison to produce a noticeable movement. For example, a typical myofibril may contain 4500 sarcomeres ^[11], a muscle fiber may contain anywhere between 5 and 10,000 myofibrils, and an average adult human may contain approximately 250 million muscle fibers. Using this information, we may calculate a rough average of 5.625 quadrillion (that is, $5.625 \cdot 10^{15}$) sarcomeres in an adult human. The body is innervated such that in an individual muscle, all of its muscle fibers are stimulated simultaneously. Therefore, all sarcomeres in a particular muscle group act in unison to produce a desired contraction, and it is the summation of small forces from each sarcomere that is responsible for noticeable body limb movements ^[11].

Engineering Background

Ionic EAP functions via the movement of ions in throughout an electrolyte sandwiched between two conducting layers on either side. Therefore, it must be submerged in water to allow the movement of ions, making it a perfect candidate to simulate myosin head movement within an intracellular space ^[12]. In this project, we use a class of EAPs called ionic polymer-metal composites (IPMCs) as actuators. Figure 2 briefly illustrates the behavior of an IPMC actuator.

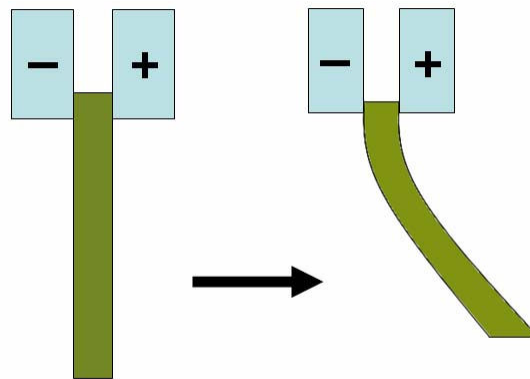


Figure 2. Illustration of an IPMC actuator. With the application of voltage through two electrodes, the EAP deflects opposite to the direction of applied current.

EAP has been coined “artificial muscle” due to its relatively quick response, which has been employed for biomimetic applications ^[13]. In our project, we use the deflection of

EAP to push an intermediate strip and reader to a measurable distance. Then, we determine the amount of work done on the system based on the measured weight of the intermediate strip, and the amount of distance pushed.

We may determine the amount of work done on the system (i.e. the work done by the EAP on the intermediate strip and reader) using the simplified work integral $W = F \cdot d$, where W is work, F is force, and d is distance moved. Additionally, the students would need to determine the force F , which can be calculated using Newton's 2nd Law of Motion, or in the simplified case: $F = m \cdot a$, where m is the mass of the intermediate strip and reader, and a is the gravitational constant of 9.8 m/s^2 [14]. Finally, we are able to relate the work and force calculated when testing the biomimetic device to the amount of work and force necessary to produce muscle contraction in the human body.

Description of Device

A visual description of this biomimetic device is shown in Figure 3.

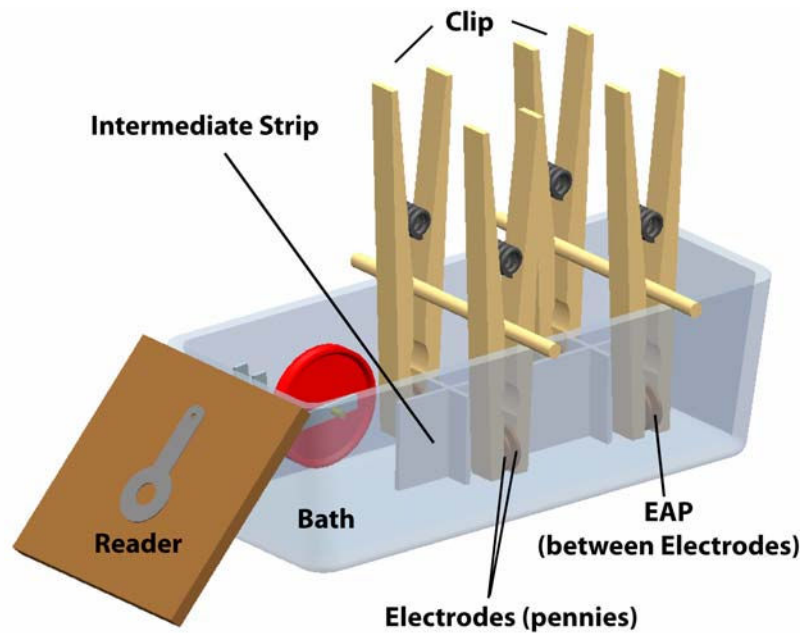


Figure 3. CAD assembly of biomimetic device. Wiring is not shown.

In its broadest sense, the device in Figure 3 uses electrical input to produce a deflection in multiple pieces of EAP, the motions of which are combined in parallel to produce a linear displacement of an intermediate strip. Table 1 summarizes the relationship between major design features in the biomimetic device and their corresponding biological components.

Table 1. Analogy table showing the relationship between major engineering design features of the biomimetic device to biological components in the human body.

Engineering Design Feature	Biological Analog
Wiring	Muscle Innervation
Reader	Body Limb
Clip / EAP	Myosin Filament / Myosin Head
Water (Bath)	Intracellular Space
Electrical Input	Action Potential
Intermediate Strip	Actin Filament
Electrodes (Pennies)	Proteins to conduct Chemical Signals
Power Source/Voltage Regulator	Brain

Using the relationships listed in Table 1, we seek to bring the information from both the engineering and biology backgrounds full-circle, and give the student a clear sense of the possible topics and applications within the biomedical engineering field.

Building Components

When designing this device, the following decision matrix was employed considerations were deemed most important:

Table 2. Decision matrix used to guide the design of the biomimetic device. Weights: 1 \equiv low importance, 2 \equiv moderate importance, 3 \equiv high importance.

Major Category	Design Consideration	Weight
Biomimetic Design	Minimizing number of components	3
	Team-based construction	3
	Ease of construction	3
	Availability of building materials	2
	Construction costs	2
	Construction time	1
Lecture Material	Interdisciplinary project	3
	Use of mathematics & physics	2
	Physiological accuracy	2

Assuming that a student group consists of three or four students, the construction of the device alone was initially projected to require 30 minutes. Detailed instructions on how to construct the biomimetic device seen in Figure 3 may be found in the Appendix at the end of this paper.

4. Assessment of Program Quality

The assessments for this program were designed to measure both how effectively the biological and engineering lessons were presented and the students' overall enjoyment while working through the project. Assessments in previous interdisciplinary bioengineering projects included exams administered before and after the project was completed, a comparison of the results, and a feedback ranking scale based on a five-level agreement survey ^[7]. Following these methods, we designed questions to determine both the amount of knowledge gained by the students during the project and their overall enjoyment while completing the project. After completing the project, the students were assessed according to the criteria found in Table 3.

Table 3. Assessment criterion for program objectives. Possible outcomes for the tasks were “Yes,” “No,” or “Did not Respond (or Did not Complete)”. In Enjoyment, ‘No’ means that the participant chose another activity as his/her favorite in the Cardiovascular and Tissue Mechanics Laboratory Experience.

Assessment	Task
Retention	Were the physiology questions answered correctly?
Construction	Was the device built within the time limit?
Calculations*	Were calculations answered correctly?
Critical Thinking*	Were challenge questions answered correctly?
Enjoyment	Was this the favorite activity of the visit?

An asterisk in Table 3 indicates that the assessment of objectives for the project was varied with respect to the age group of participants. Thus, participants within the 12-14 year old range were asked to simply construct and test the device, answer basic physiological questions, and provide enjoyment feedback, whereas 15-17 year old participants were also asked to perform engineering analysis and answer challenge questions within the allotted time period.

5. Results

The project was first piloted as part of engineering visitations for WIMS for Teens and WIMS for Women in Engineering, specifically as part of the Cardiovascular and Tissue Mechanics Laboratory Experience at Michigan State University. Although the exact demographics of the participants were not measured, the success of WIMS programs have been characterized by their strong diversity, namely in “phenomenal participation count and percentages by female and minority students” (over 50 percent) ^[1]. In addition, applicants for both programs met the following prerequisites:

- GPA \geq 3.2 Preferred
- Satisfactory completion of Essay, Math/Science requirements

- Teacher-Recommended

For both WIMS for Teens and WIMS for Women in Engineering, the Cardiovascular and Tissue Mechanics Laboratory Experience consisted of one hour with multiple stations (microscopy of arterial tissues, mechanical test of arteries, medical image segmentation, and computational simulation of a vascular disease, and biomimetic device construction). Thus, to allow full participation in each station, the participants constructing the biomimetic device were allotted roughly 20 minutes to complete the project. Thus, we pre-assembled certain components of the device to hasten the construction process.

WIMS for Teens visit

For the WIMS visit on July 2, 2009, a total of 17 visiting students between the ages of 12-14 years and between the 7th and 9th grades were asked to construct the bath, the intermediate strip, and then assemble the device. However, we observed that many students had difficulty constructing the intermediate strip and consequently in the first trial, no groups were able to completely finish the building and testing of the device within the allotted 20 minute period.

In the second and third WIMS trials, the intermediate strip was also pre-assembled so that students needed only to finish constructing and wiring the device. In these trials, all students were able to fully assemble and test the device. Figure 4 summarizes the results from this visit.

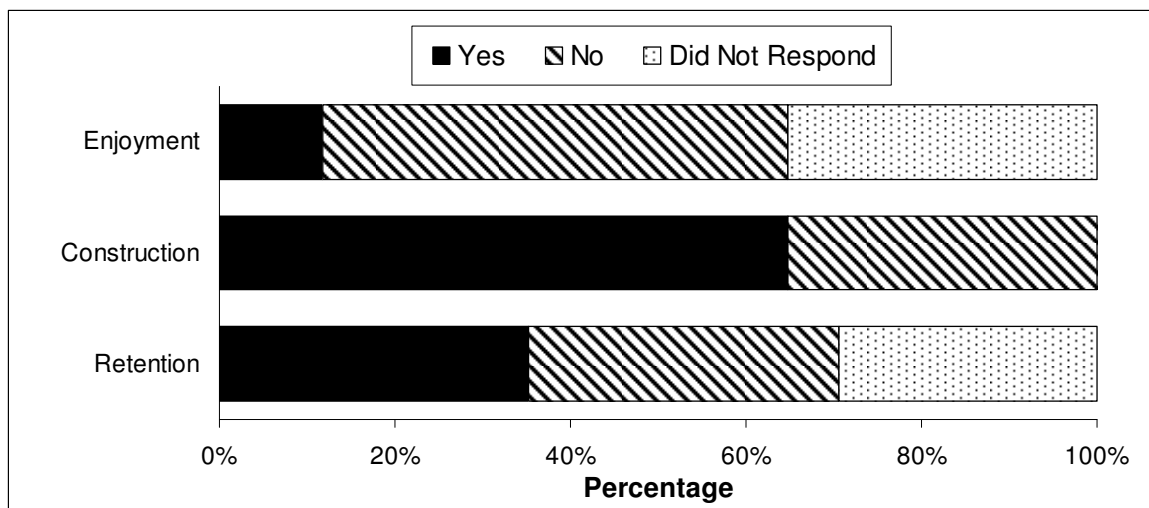


Figure 4. Assessment results for WIMS visitors.

WIMS for Women in Engineering visit

The device was next piloted at WIMS for Women in Engineering on July 9, 2009, which consisted of 21 participants. Participants of this all-female group were in between the 10th and 12th grades, and fell within the 15-17 year-old age range. These students were not

only asked to build the device (which was again partially pre-assembled) within the 20-minute time period, but were also asked to complete the calculations and challenge questions. The results from this visit can be seen in Figure 5.

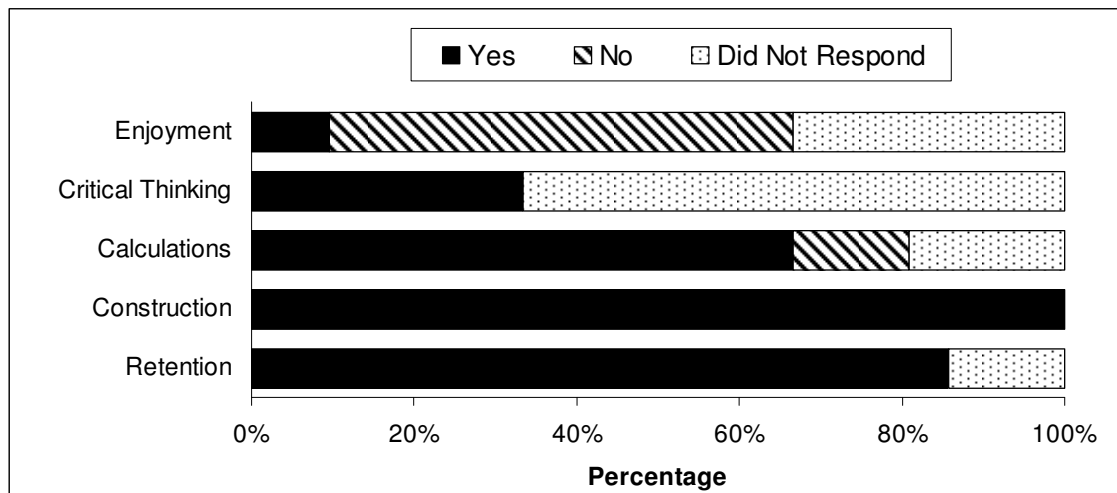


Figure 5. Assessment results for Women in Engineering.

Based on Figure 5, all groups from Women in Engineering were able to completely construct the device within the 20 minute time period, and most successfully completed the calculations section. However, only about 30 percent were able to correctly answer the challenge questions, the remainder of which did not respond. These results prove that 20 minutes was insufficient for fully completing the project. Also, similar to the WIMS visitors, the majority of respondents did not list the experience as their favorite activity, claiming that the computer simulations were most interesting.

6. Discussion & Recommendations

The hands-on section presented within this paper demonstrates a novel educational program that incorporates a multidisciplinary awareness within K-12 students who are considering a career in the engineering field, and moreover provide a means to include underrepresented students that may have not previously considered pursuing engineering. Also, this multidisciplinary project allows students to identify which aspects of engineering they find most interesting. Our project allows an “active learning environment,” which thrives not only on the interactions between students and teachers, but also helps in forming successful group learning sessions ^[8]. However, there are areas for improvement, which will be addressed in the following sections.

Construction

For our previous trials, time constraints limited the amount of time set aside for completing the project, and may have limited the quality of the experience. Upon realizing this need, we pre-assembled parts of the kit to speed up building times, although the device is designed to be constructed independently. Therefore, we recommend that this project may be expanded over the course of two individual time periods, one time

period would be used for the lecture material, and the second time period would encompass the building session and worksheet questions. Previous multidisciplinary, collaborative projects completed over a four-week period have shown success ^[15]. However, we believe that our biomimetic device program can produce a comparable experience in a shorter period of time, that is, over two lecture periods.

Even with enough time to construct the device, there may also be technical shortcomings when testing the device. When the EAP was activated, we observed degradation of the penny electrodes resulting from the addition of electrical current. Thus, the increase in electrical resistance between the electrodes and the EAP resulting from degradation of the penny may contribute to a decrease in the observed deflection. However, this shortcoming may actually serve as yet another connection between disciplines, namely physics and chemistry. Thus, for yet another interdisciplinary project, an instructor may adapt the lecture to address such troubleshooting issues.

Retention

Based on the results from Figures 4 and 5, we noticed that given the same amount of time, the participants from WIMS (the older age category) were able to more effectively answer the retention questions, which indicates that the assessment questions may need to be modified in order to suit the understanding level of a given audience.

Enjoyment

Also based on the feedback from Figures 4 and 5, we also observed that the vast majority of students visiting the Cardiovascular and Tissue Mechanics Laboratory seemed to be more impressed with computer simulations and patient-specific imaging techniques than the biomimetic device. This result may be attributed to the lack of a pronounced visual indication for success when completing the project, namely that the deflection of the lug reaches a maximum of 3 mm for successful trials. Because such deflections may be difficult to recognize with the naked eye, the meaning of the experiment may be difficult to convey in the absence of the supplementary lecture. Therefore, a computational simulation of the expected behavior for the device may be an effective method to not only convey the synthesis of the background information, but also act as a visual guide when constructing the device. Moreover, the success of using computer simulations to aid in learning has been documented in previous studies ^[16].

Lecture Material

There is overt simplification of physiological concepts in order to achieve simplicity and functionality of the device. As an example, the titin molecule returns the actin filaments within a sarcomere to their original resting length after contraction is complete ^[10]. One method to simulate this effect in the biomimetic device would be to attach a springs to the intermediate strip. However, the addition of springs would counteract the force produced from the bending of the EAP, resulting in essentially no movement of the intermediate strip or reader. We plan to further investigate solutions to increase the physiological

accuracy of the project while not drastically affecting building time or technical complexity.

Assessments

Based on the results of Figures 4 and 5, we would like to assess the outcomes of the project without the influence of other presentations. In this way, we plan to implement a full start-to-finish trial of the project, and determine if there are other areas of either construction or presentation that may be improved. Also to obtain a more clear understanding of students' enjoyment while completing this project, we also plan to use the five-level agreement survey method.

Acknowledgements

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Appendix

Instructions for Building the EAP-driven Sarcomere Biomimetic Device

Table of Contents

Materials	15
Building Instructions.....	15
Bath	15
Plastic Strip Reader.....	17
Wiring	18
Removing the Rubber	18
Removing the Zinc.....	19
After Removing the Insulation.....	20
Assembly Instructions.....	20
Running the Experiment	23
After the Experiment.....	24
Taking Measurements.....	24
Calculations.....	24
Calculating the Weight of the reader	24
Calculating the amount of Work done	24
Summarizing the Results	24
Challenge Questions	25
Discussion	25

Materials

- 4' red hook-up wire
- 4' black hook-up wire
- 5" string
- (1) 3" by 3" cardboard square
- (1) 2.5" by 3" by 6" plastic dish
- (8) copper pennies
- (1) 1" diameter plastic pulley
- (1) 1/8" diameter bolt, with nut
- (2) wooden bar stock pieces, 1/8" diameter, 4" length
- (4) wooden clothespins
- (1) power source with voltage and current control
- (4) strips electroactive polymer (EAP), each with dimensions of 1 cm by 3 cm
- (1) 1" by 5" rectangle of sheet plastic
- (1) solder lug, weighing about 0.25 g
- (1) marker pen
- scissors
- duct tape
- wire strippers
- small file

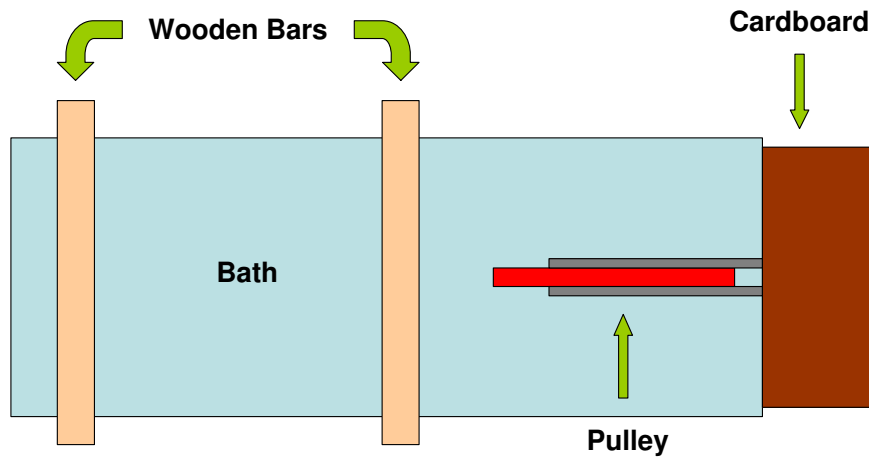
Building Instructions

Bath

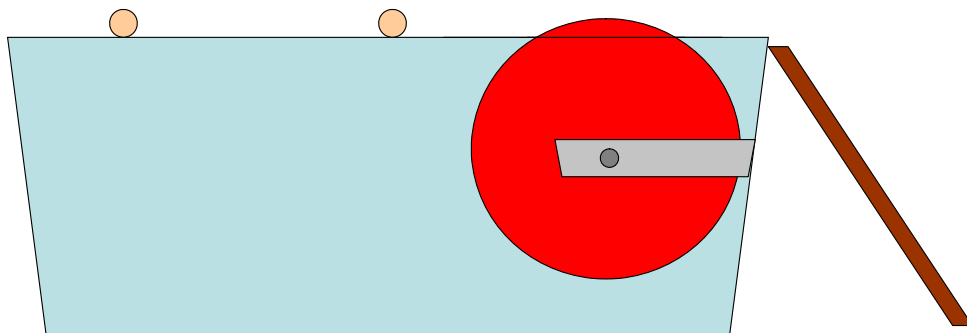
1. To attach the pulley, drill a 1/4" hole that is centered on one of the short faces of the plastic dish, about 1/4" away from the top. This step should be completed by the instructor to avoid safety concerns.
2. Now, take the supporting end of the pulley and bend it so that it lies tangent to the bath, with both holes coincident.
3. Next, put the bolt through both holes and use the nut to secure the attachment.
4. Attach duct tape to the cardboard square and position it so that it lies 45 degrees (or diagonal) to both the bath and the ground.
5. Attach the pieces of wooden bar stock to the bath. Ensure that they are about 1.5" apart and are at least 1" away from the end of the bath.

After finishing all of these steps, make sure your figure looks like the setup in the following figures:

Top View



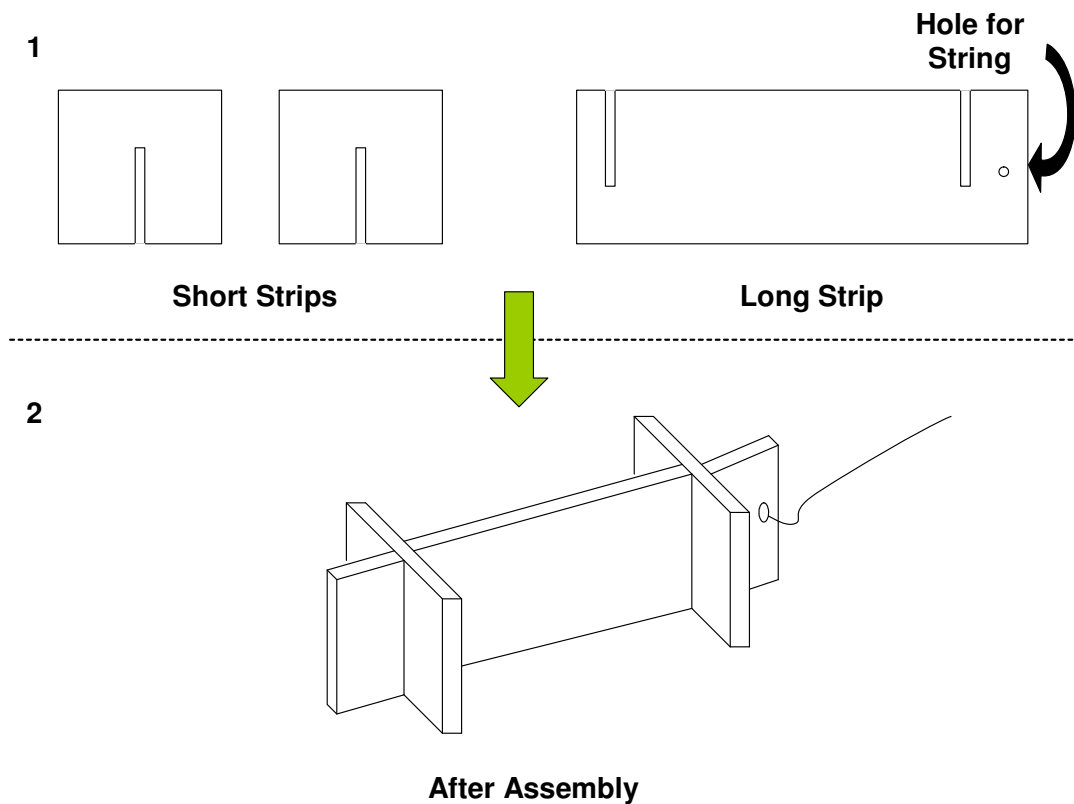
Side View



Plastic Strip Reader

1. Cut the sheet plastic into strips of the following sizes:
 - a. (1) 1" by 3" strip
 - b. (2) 1" by 1" strips
2. In strip (a), cut two $\frac{3}{4}$ " slits that are separated by the same distance as was put between of the wooden bars when making the bath.
3. Cut a $\frac{3}{4}$ " slit in the middle both of strips cut in step (b).
4. Match the slits in the (b) strips with the slits (a) strip so that they line up perpendicular to each other.
5. At one of the longitudinal ends of strip (a), use a hole puncher to create a hole.
6. Now, insert the string through the hole created in the previous step and tie a secure knot.

After all these steps have been completed, the device should look similar to the reader in step 2 of the following figure:



Wiring

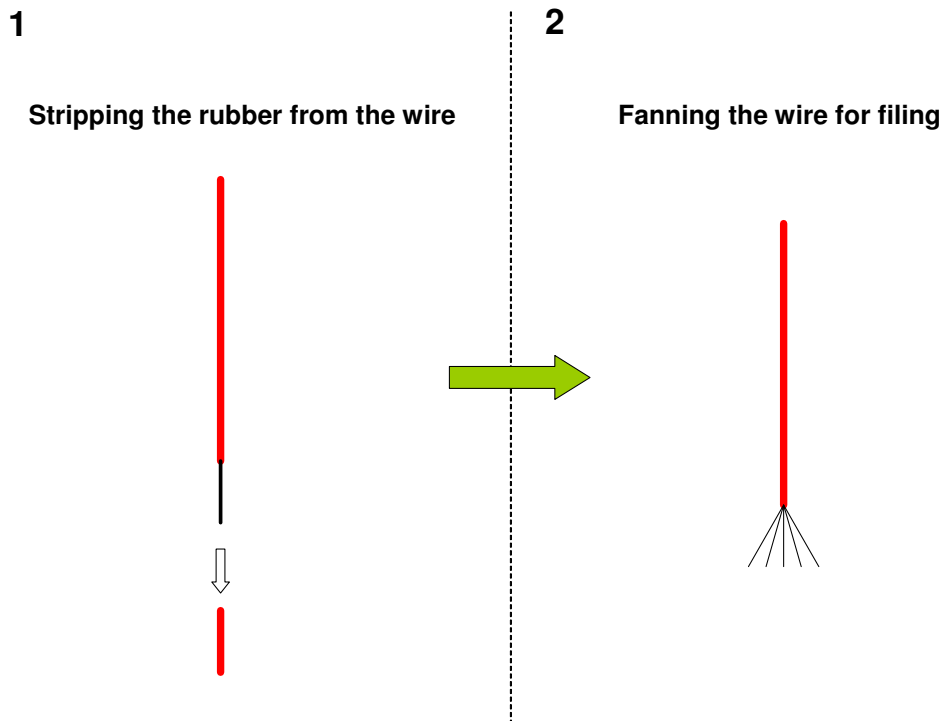
1. Take both pieces of red and black hook-up wire and cut them into four 1' lengths.

***Note: ALL OF THE INSTRUCTIONS FOUND BETWEEN THE DOTTED LINES MUST BE REPEATED 4 TIMES!!**

2. Strip both red and black wires about ½" the ends. To strip a wire, you must do the following:

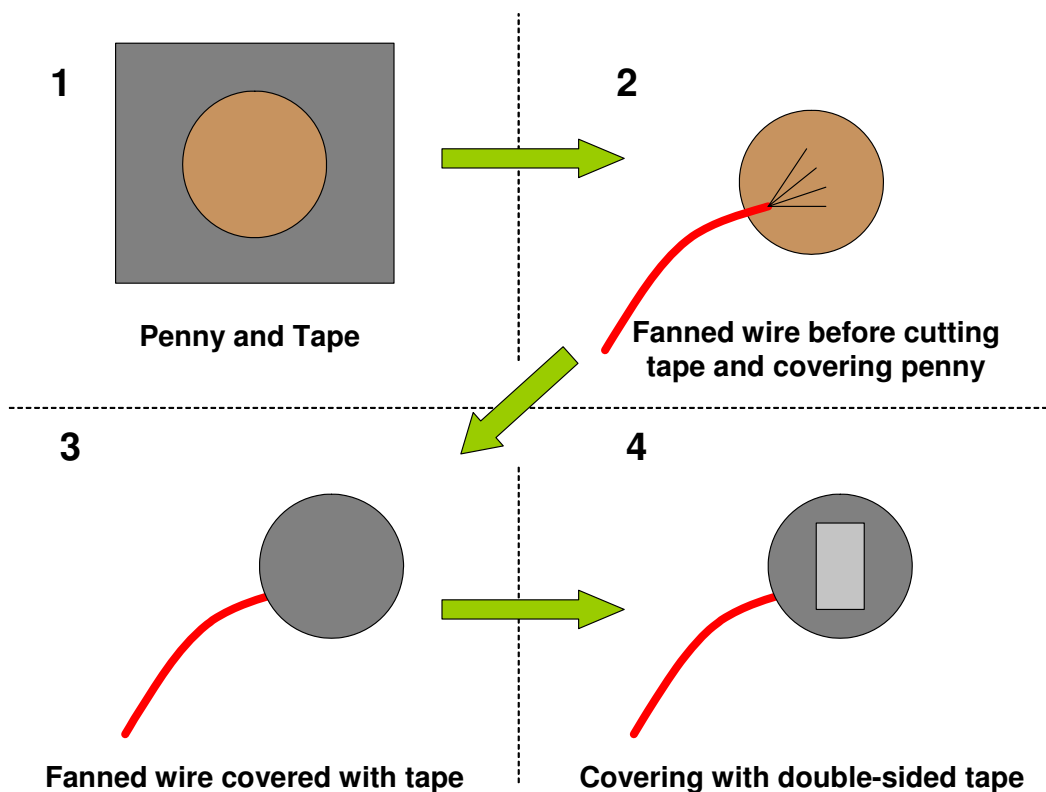
Removing the Rubber

3. Take the wire stripper and locate the third-closest hole from the inner hole. Look at the following picture to ensure you have the correct hole:
4. At this point, you have to unsheathe the rubber coating from the wire. To do so, clamp down on the wire about ½" away from either end. Now, after making sure that the rubber has been fully broken, pull outward along the length of the wire.
 - a. Hint: To ensure that you do not accidentally cut and pull off some wires in the unsheathing process, make sure that you lock one arm and move the other.



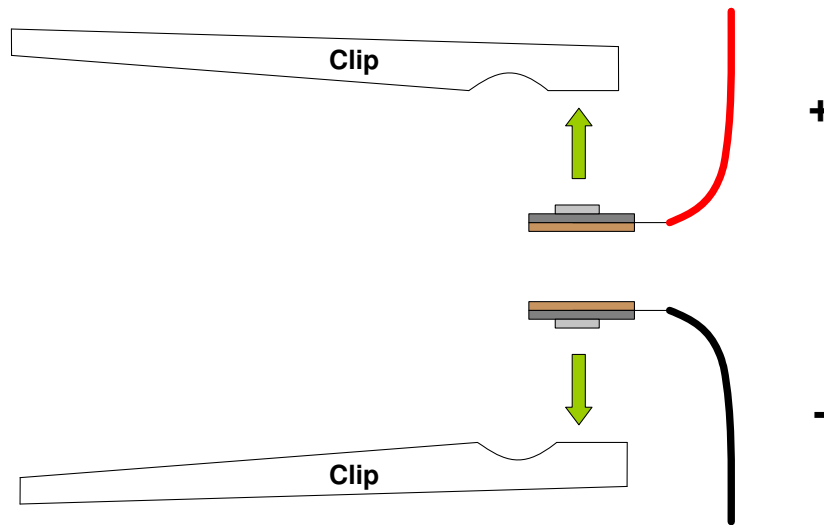
Removing the Zinc

5. Hook-up wire comes with a zinc (silver-looking) coating, which acts as another insulator. This must also be removed so that we get to the bare copper wire.
6. Take the file and file the exposed zinc wire threads until they attain a copper appearance. You do not need to press the file particularly hard against the bare wires to achieve this look:
 - a. Hint: you should ensure that every side of the wire is filed, so an easy way to do this is to fan out the individual wire threads, file them until they are copper, and then turn the setup over, and repeat.
7. Now, take a piece of duct tape and cut it so that is roughly the shape of a penny. Also cut another strip that is about ½" by 1/8".
8. After the wire has been stripped, make sure it is fanned out and place it upon the penny. Take the penny-shaped piece of tape and attach the bare wire to the copper penny. Also, take the other strip of duct tape and loop it so the adhesive lies on the outside. Attach this at the center of the penny, on the taped side.



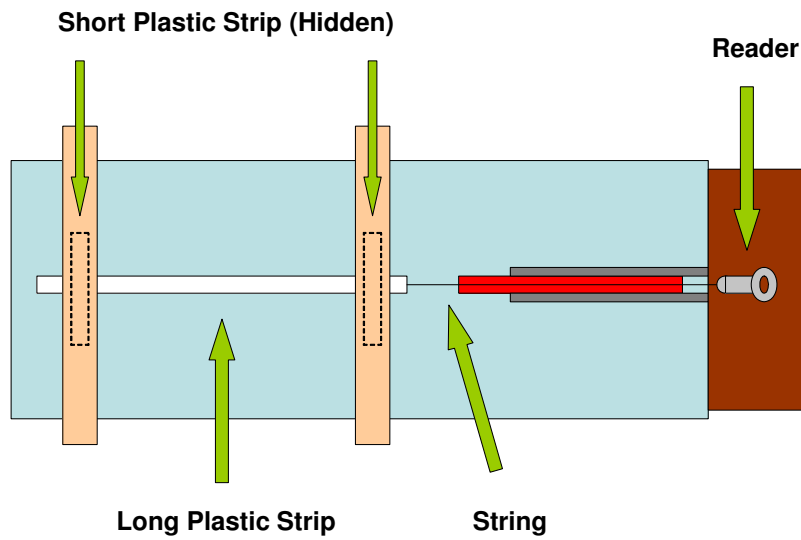
After Removing the Insulation

9. Repeat steps 3 and 4 for the other wire.
10. Take both completed wires and attach the other end of the double-sided strip to the end of the clothespin. Make sure that the untaped sides of the two pennies touch each other without any interference. It should look like this:

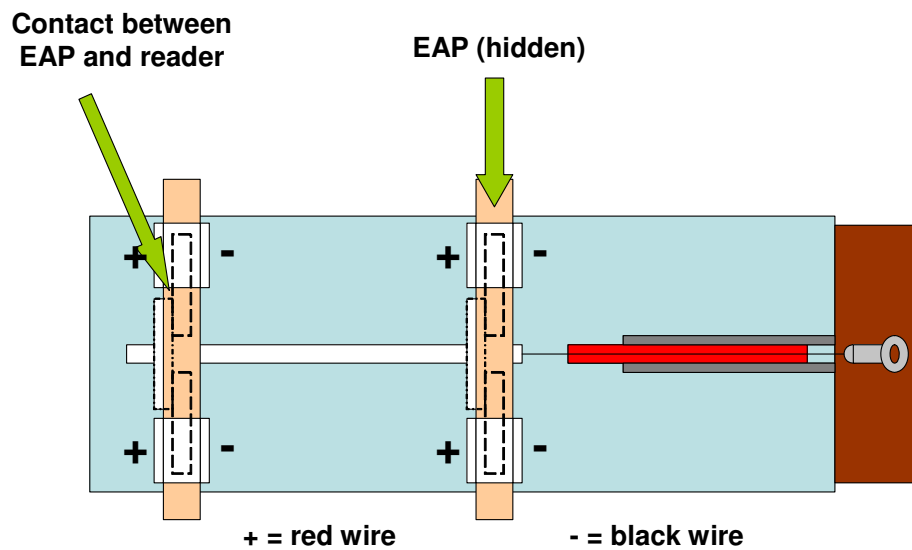


Assembly Instructions

1. Fill the bath about $\frac{3}{4}$ full with water. Keep a beaker of extra water in case you need to add more.
2. Take the plastic strip and insert it into the bath. Align it parallel to the pulley.
3. Thread the free end of the string on the plastic strip through the pulley. Lay it on the cardboard.
4. Use another knot to attach the eye hook to the free end of the string. It should look like the following figure:

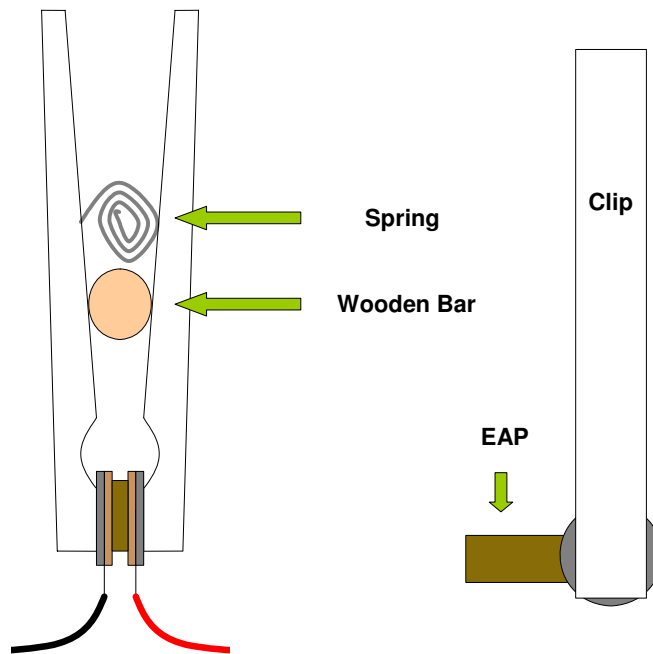


5. Open the clamps on all wired clothespins and fit them over the two pieces of wooden bar stock. To produce the correct deflection, make sure the negative (black) terminals are closest to the pulley. It should look like this:

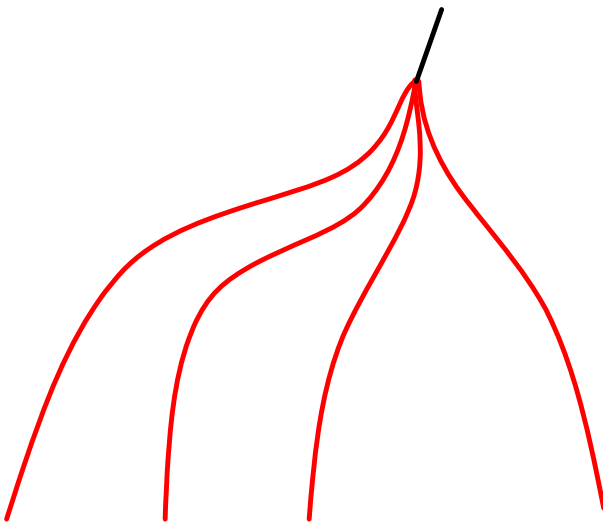


REMEMBER: All clips must be wired in the SAME orientation!

6. Now, insert the EAP into each of the clamps. The free ends of the EAP strip should come into contact with the perpendicular sections of the reader. Also, the reader strips should be on the positive (+) side of the EAP.
- a. Hint: To more easily insert the EAP, you can rotate a wired clothespin around the wooden bar.



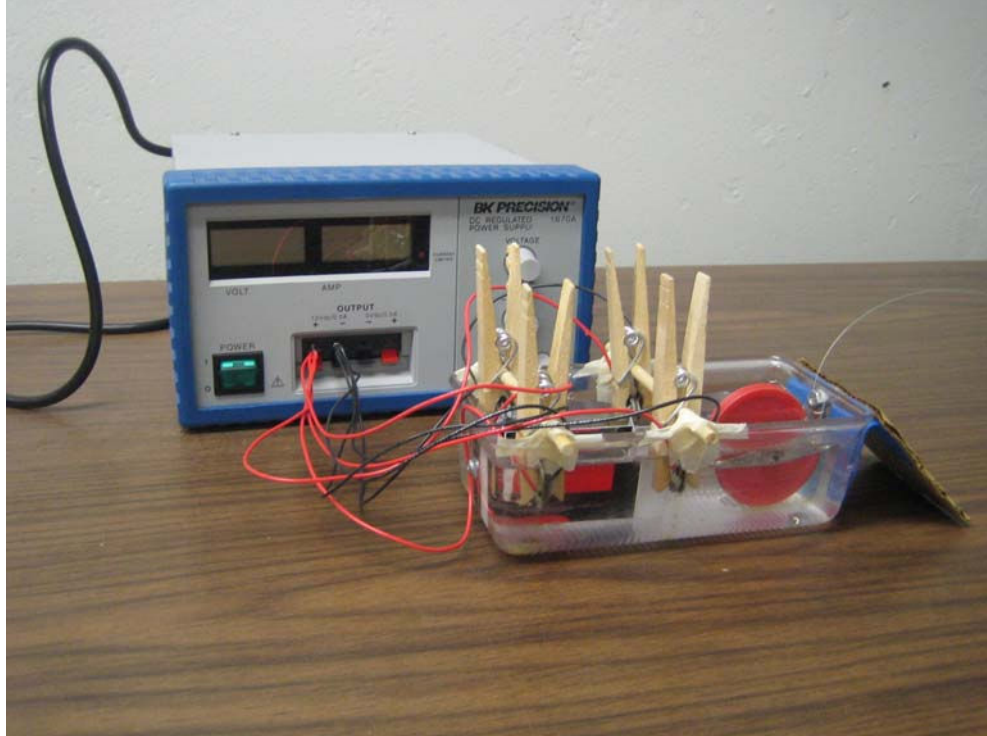
7. Now, gather all of the free ends of the red wire and twist them into a thicker wire. It should look like this:



8. Repeat step 7 for the black wire.

Running the Experiment

1. Insert the free twisted end of the red wire bunch into the red terminal.
2. Insert the free twisted end of the black wire bunch into the black terminal.
3. Inspect the completed setup and make sure it looks like the following picture:



4. BEFORE you turn on the power, take the marker and place a dot at the center of the lug.
5. DO NOT adjust the voltage and current settings on the voltage regulator! These will have already been preset for you by the instructor. Note: ionic EAP used in this device degrades at voltages of greater than 3.0 Volts.
6. TURN ON the power. If you have done everything correctly, the ends of the EAP will all deflect in the same direction.
7. At this point, you will see that the lug has been moved. NOW, take the marker and place another dot at its new position.
8. After the mark has been made, TURN OFF the power.

After the Experiment

Taking Measurements

1. Take the marker and use a straight line (use a ruler) to connect the two dots on the cardboard strip. Measure the length of the mark to the nearest tenth of a millimeter (i.e. 0.0001 m).
2. Mass the reader to the nearest tenth of a gram (i.e. 0.1 g). Be sure to include the strip, the eye hook, and all of the string when massing the reader.
 - a. Hint: water also carries a significant amount of weight, so make sure that you dry off the reader as much as possible.

Calculations

Calculating the Weight of the reader

In order to move the plastic reader strip, the EAP had to exert a force strong enough to move the marker. To calculate force, we use Newton's 2nd law:

$$F = m \cdot g$$

where F is the amount of weight force (in Newtons), m is the amount of mass (which you got from measurement 2), and g is the gravitational constant for Earth, which is 9.8 kg/m·s².

Calculating the amount of Work done

The amount of work done is defined as the force exerted over a distance. Therefore, the equation for work is:

$$W = F \cdot d$$

where W is the amount of work done (in Joules), F is the weight force of the reader strip, and d is the distance over which the force was applied (which you got from measurement 1).

Summarizing the Results

Now, input all of your results into the following table. The number for gravity is already given:

g (m/s ²)	m (g)	F (N)	d (mm)	W (J)
9.8				

Challenge Questions

- 1) We found the amount of total work done by four pieces of EAP. Assuming that each piece of EAP contributed equally to moving the reader strip, what was the work done by a single piece of EAP?

Answer: _____

- 2) Now, assuming that the number found in the previous question represented the maximum amount of work possible for a single strip of EAP, how many strips of EAP would be needed to move a 10 kg (remember: 1 kg = 1000 g) weight?

Answer: _____

Discussion

This design demonstrates the action of individual sarcomeres in the event of a muscle contraction. Even though you found a very small number for the amount of work done by four strips of EAP working in parallel, keep in mind that an individual sarcomere exerts a very small amount of force. So, then, given that the forces we generate from these sarcomeres are so small, how are we able to move our arms, legs, head, neck, etc? It is because many sarcomeres are recruited in parallel to produce one contraction.

In fact, a human muscle contains about 4500 sarcomeres per myofibril, an average of 5000 (anywhere from 5 to 10,000) myofibrils in a muscle fiber, and about 2000 muscle fibers for large muscles like the gastrocnemius (calf muscle). That's a total of about 45 billion sarcomeres working in parallel just to get you on your tiptoes!