Incorporating Interdisciplinary Understanding for K-12 Students using a Biomimetic Device

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Abstract

Biomedical engineering is a rapidly growing discipline. One way to attract new students to this discipline may be to provide greater emphasis of the way in which biomedical engineering connects engineering to biomedical sciences. Because crucial decisions regarding whether or not to pursue an engineering career are often made prior to college entry, we devised a simple project for junior and senior high school students that clearly conveys the relevance of engineering to biomedical contexts. The experimental device we designed incorporates principles from physics, biology, engineering analysis and cutting-edge technology into a single, integrative project. More specifically, we designed a build-and-test device that 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 natural phenomena. We used this device during summer programs for junior and senior high school students and found that junior high school students had more difficulty completing the assembly of the device in the allotted time. Although high school level students were able to complete assembly on time, they were not able to complete all of the challenge questions that tested comprehension of the fundamental biological and engineering principles involved in the allotted time. Further, relatively few participants indicated that this program was their favorite activity in the lab experience. Based on these observations, we have recommended changes to the program.

Introduction

One rapidly growing field of engineering within the United States is biomedical engineering (1). 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 engineering programs into their undergraduate curriculum (2).

Research on K-12 recruitment into engineering and technological fields is beginning to reach a consensus that crucial decisions about pursuing an engineering career are often made between the sixth and eighth grades (3). Thus, we hypothesized that outreach programs promoting pre-engineering projects will expose students to engineering concepts and motivate interest in engineering fields.

Based on these ideas, we designed a relatively simple project that would expose 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 the National Research Council, whose members have emphasized incorporation of math and statistics into interdisciplinary biology curriculums (4).

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 female undergraduate engineering students nearly four to one (5). Conversely, female student enrollment in biological science programs is three times greater than in engineering programs (5). As such, a strategy to include more women in engineering may be to introduce engineering concepts from a biological perspective, providing students with a clearer connection between the two fields. Previous studies on integrating biological and engineering concepts into lessons have proven successful (6).

In order to begin to test these hypotheses, we developed a biomimetic device that was used to supplement lecture material that illustrated the connections between biological and engineering concepts in a program developed for junior and senior high school students. The biomimetic device was based on the function of the sarcomere, the basic contractile unit of a muscle cell in the human body.

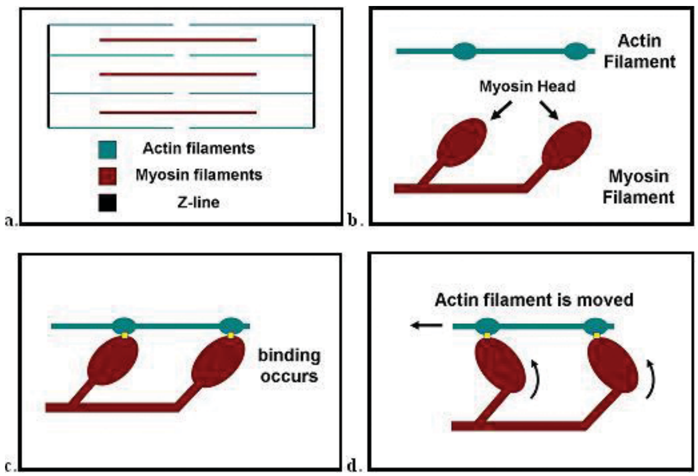

Figure 1 (a) Large-scale, simplified view of a sarcomere. The actin filaments are attached to the Z-line and are moved by myosin heads on the myosin filament. (b) Close-up of the configuration of actin and myosin filaments before activation. (c) Binding of actin and myosin filaments before the myosin 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.

On a simplistic basis, the sarcomere is comprised of four main components: the actin filament, the myosin filament, the myosin head and the Z-line (reviewed in Ref. 7, Fig. 1). Several steps are required to generate sarcomere lengthening or shortening (7).

Action potentials generated in the brain travel down nerve fibers and trigger release of the neurotransmitter acetylcholine (ACh) at a particular skeletal muscle group. ACh stimulates the release of calcium within the intracellular space of skeletal muscle cells. 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 rotates and binds 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.

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, a muscle fiber may contain anywhere between 5 and 10,000 myofibrils, and an average adult human may contain approximately 250 million muscle fibers (8). Using this information, we may calculate a rough average of 5.625 quadrillion (that is, 5.625×10^{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 (8).

Biomimetic Properties of Electroactive Polymers

Electroactive Polymers (EAP) have been coined "artificial muscle" due to their relatively quick response, which has been employed for biomimetic applications (9). Ionic EAP function via the movement of ions throughout an electrolyte sandwiched between two conducting layers on either side. Therefore, EAP must be submerged in water to allow the movement of ions, making it a perfect candidate to simulate myosin head movement within an intercellular space (10). These properties of EAP made it an ideal candidate for our device that simulated a sarcomere.

Methods

Office of K-12 Outreach in Engineering Education

One goal of the Office of K-12 Outreach in Engineering Education at MSU is to attract prospective engineering students from schools throughout the area. One way that the office meets this goal is to provide opportunities for students to visit MSU and learn more about ongoing research in engineering. Visiting students have the opportunity to engage in hands-on projects designed to show how an engineer could solve a given problem. Additionally, visiting students interact with people from a variety of engineering disciplines, which allows them to observe the career possibilities within engineering fields.

Two specific summer programs offered to students by the Office of K-12 Outreach in Engineering Education at MSU are Wireless Integrated Microsystems (WIMS) and Women in Engineering (WIE). WIMS is a five day residential experience for seventh and eighth grade students with a B+ or better average in math or science courses, who are interested in becoming engineers and have been recommended by their math or science teacher for participation. WIE is a five day residential experience for tenth, eleventh and twelfth grade women with a 3.0 or better GPA (or top 15% cohort ranking), who are interested in becoming engineers and have been recommended by their math or science teacher for participation. More information about both programs is available at egr.msu.edu/future-engineer/programs/summer.

Biomimetic Device Desing

We used a class of EAPs called ionic polymer-metal composites (IPMCs) as actuators in our biomimetic device. We used the deflection of EAP to push an intermediate strip and reader to a measurable distance. Then, we determined the amount of work done on the system based on the measured weight of the intermediate strip and the amount of distance pushed. A schematic of this device is shown in Figure 2.

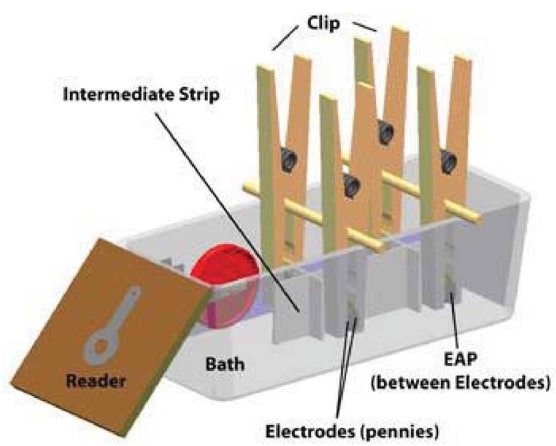

Figure 2 Schematic representation of biomimetic device.

In its broadest sense, the device in Figure 2 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. The following list summarizes the relationship between major design features in the biomimetic device and their corresponding biological components:

1. Wiring: Muscle Innervation
2. Reader: Body Limb
3. Clip / EAP: Myosin Filament / Myosin Head
4. Water (Bath): Intercellular Space
5. Electrical Input: Action Potential
6. Intermediate Strip: Actin Filament
7. Electrodes (Pennies): Proteins to conduct Chemical Signals
8. Power Source / Voltage Regulator: Brain

Assessment of Program Quality

We designed assessments to measure 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 and a feedback ranking scale based on a five-level agreement survey (6). 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 below.

1. Retention: Were the physiology questions answered correctly?
2. Construction: Was the device built within the time limit?
3. Calculations: Were calculation questions answered correctly?
4. Critical Thinking: Were challenge questions answered correctly?
5. Enjoyment: Was this the favorite activity of the visit?

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.

An asterisk indicates that the assessment of objectives for the project was varied with respect to the age group of participants. Thus, participants in WIMS were asked to simply construct and test the device, answer basic physiological questions, and provide enjoyment feedback, whereas WIE participants were also asked to perform engineering analysis and answer challenge questions within the allotted time period. For the challenge questions, one had to synthesize the knowledge based on the given equations for analysis to determine a single characteristic of the system, and then use that characteristic to design a solution for a problem of a much larger magnitude. The first challenge question asks the student to observe the system and determine how much work must be done by a single strip of EAP. The next question then involves using that characteristic number to then determine the number of sarcomeres necessary to generate movement within a physiologically relevant weight. This problem therefore provides a means to understand the magnitude of sarcomere function (e.g., the sarcomere alone provides a very small force, but given enough of them, they generate enough force to move a body limb).

Test populations and conditions

The project was first piloted as part of student visits for Wireless Integrated Microsystems (WIMS) on July 2, 2009, specifically as part of the Cardiovascular and Tissue Mechanics Laboratory experience. A total of 17 visiting students (12-14 years, approximately 80% male) were asked to construct the bath, the intermediate strip and then assemble the device. 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.

The second project was piloted for Women in Engineering (WIE) on July 9, 2009, which consisted of 21 participants (15-17 year old, 100% female), who completed this project as part of the Cardiovascular and Tissue Mechanics Laboratory Experience. 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 calculations and challenge questions.

Results

Wireless Integrated Microsystems (WIMS) visit

For the WIMS visit on July 2, 2009, 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 3 summarizes the results from this visit.

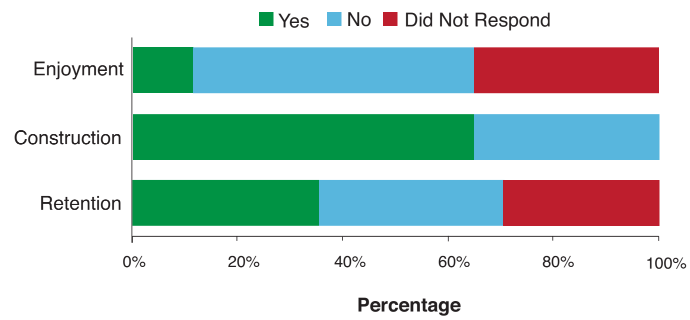

Figure 3 Assessment results for WIMS students

For the WIE visit on July 9, 2009, we observed that all groups were able to completely construct the device within the 20 minute time period, and most successfully completed the calculations. However, only about 30 percent were able to correctly answer the challenge questions, the remainder of which did not respond. The results from this visit can be seen in Figure 4. These results demonstrate that 20 minutes is insufficient for fully completing the project. Also, like the WIMS visitors, the majority of respondents did not list the experience as their favorite activity, claiming that the computer simulations were most interesting.

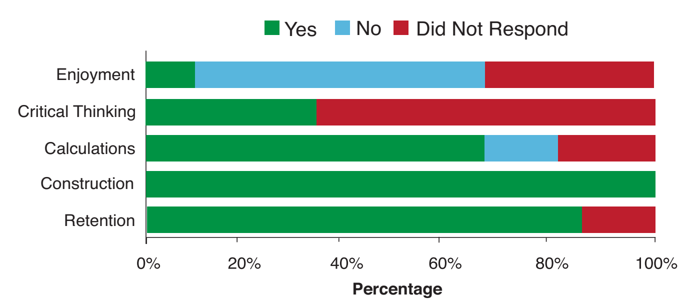

Figure 4 Assessment results for WIE students

Discussion

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 (11). 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 (12). However, we anticipate that our biomimetic device program can produce a comparable experience in a shorter period of time, that is, over two lecture periods, and plan to test this in future studies.

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 reaction resulting from the addition of electrical current. Degradation generally occurred gradually after the sixth use of the electrodes. Further investigations will be necessary to determine when the penny electrode becomes completely ineffective. 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 issues.

Knowledge Retention

Based on the results from Figures 3 and 4, we observed that given the same amount of time, the participants from the WIE group were able to more effectively answer the retention questions. Based on these results, we conclude that the students in the WIE group are better prepared to answer these questions. These differences in performance may be due to several differences between the groups, including age (15-17 year old students in WIE compared to 13-14 year old students in WIMS), gender (100% women in WIE compared to approximately 20% women in WIMS) or other differences in preparation or interests between the two groups. Once these differences are better understood, we can develop assessment questions that are modified in order to suit the understanding level of a given audience.

Enjoyment

Based on the feedback from students shown in Figures 3 and 4, we 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 reader 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 (13).

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Highlights from the National Press

Several Honors College Students were published by United Press International (UPI). Their work is summarized by Managing Editor Katelin McArdle.

Technology's Impact on Mecca Pilgramige

Daniel Redford's article describes the emergence of cell phone and other electronic device usage during the Mecca pilgrimage in Saudi Arabia. Some followers of Islam are concerned that this threatens the sanctity of the pilgrimage, while others celebrate technology's ability to realize the sharing of faith with others.

upi.com/Features/Culture_Society/1969/12/31/Cell-phones-Internet-interrupt-Mecca-pilgrimage-traditions/12628860435441/

Religious Tolerance Studied in Africa

Thomas Morrisey's article explains MSU professor David Robinson's ongoing grant project to document in print, video and audio the Muslim people of Ghana and Senegal. The research aims to illustrate and discover the peacefulness and coexistence of various religious groups in the region.

upi.com/Features/Culture_Society/1969/12/31/Professor-collects-tales-of-religious-tolerance-in-Africa/12590830815019/

Technological Innovations and Religion

Jeremy Blaney's article describes the ways in which technology is changing our interactions with religion. New innovations, such as an iPod App for the Qur'an, are changing the ways in which people integrate their faith into everyday life. However, others feel trepidation or dislike for this new way of spirituality.

upi.com/Features/Culture_Society/2009/11/11/Youre-a-Muslim-Theres-an-app-for-that/12579646575612/