A novel approach to physiology education for biomedical engineering students

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DiCecco J, Wu J, Kuwasawa K, Sun Y. A novel approach to physiology education for biomedical engineering students. Adv Physiol Educ 31: 45–50, 2007; doi:10.1152/advan.00054.2006.—It is challenging for biomedical engineering programs to incorporate an indepth study of the systemic interdependence of cells, tissues, and organs into the rigorous mathematical curriculum that is the cornerstone of engineering education. To be sure, many biomedical engineering programs require their students to enroll in anatomy and physiology courses. Often, however, these courses tend to provide bulk information with only a modicum of live tissue experimentation. In the Electrical, Computer, and Biomedical Engineering Department of the University of Rhode Island, this issue is addressed to some extent by implementing an experiential physiology laboratory that addresses research in electrophysiology and biomechanics. The two-semester project-based course exposes the students to laboratory skills in dissection, instrumentation, and physiological measurements. In a novel approach to laboratory intensive learning, the course meets on six Sundays throughout the semester for an 8-h laboratory period. At the end of the course, students are required to prepare a two-page conference paper and submit the results to the Northeast Bioengineering Conference (NEBC) for consideration. Students then travel to the conference location to present their work. Since the inception of the course in the fall of 2003, we have collectively submitted 22 papers to the NEBC. This article will discuss the nature of the experimentation, the types of experiments performed, the goals of the course, and the metrics used to determine the success of the students and the research.

COURSE STRUCTURE AND PREPARATIONS

Course Structure

Biomedical engineering students at the University of Rhode Island are required to fulfill 8 semester-based credits of engineering design electives, typically in the senior year, which are separate from an additional 12 required engineering design credits to be fulfilled in both the junior and senior years. The biomedical engineering curriculum currently includes 4 credits of human physiology and 4 credits of human anatomy, and each includes a laboratory section. There is some overlap of physiology and anatomy instruction in two biomedical engineering design electives but only as it relates to medical imaging and medical instrumentation. This course is designed to be supplementary to the formal physiology and anatomy education and is not intended to be a replacement for that education.

Experiments are based on standard preparations that have been well documented and provide extensive references. The most relevant of these references are distributed to students at the beginning of the course and are required reading for all students. Listings of the experiments are made available, and students are invited to choose which experiments they would like to research further. Table 1 shows the animals and preparations currently investigated in the course. These animals are used each year, and students are encouraged to learn each preparation, although most focus on one or two preparations. Since the course can be taken more than once under a different
course level listing, those who pursue this option learn all the preparations.

Students select the preparation that interests them, and their first task is to learn and duplicate the techniques required to prepare the animal for an experiment. Since the course is not limited to undergraduate students, graduate students, who often have more in-depth knowledge of biological systems, assist undergraduates with improving their laboratory and dissection skills. Experiments are determined by the field of study of the student. For instance, a student may choose an electrical engineering tract that focuses on signal processing. The student may then acquire a biological signal, slowly vary key parameters such as temperature, pH, or salinity, and observe the changes. Using signal processing techniques, the student may develop an algorithm to detect these changes before they are observable on a monitor or recording. Still another student may choose an engineering tract that is based on electrical circuitry, electrode design, and signal processing. Matlab are emphasized. Software tools such as LabView and MATLAB are emphasized.

Table 1. Currently investigated animals and preparations

<table>
<thead>
<tr>
<th>Animal</th>
<th>Preparation</th>
<th>Purpose</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Lymnaea stagnalis</td>
<td>Sharp microelectrode recording from the central nervous system</td>
<td>Dissection skills, general electrophysiology, time series analysis, instrumentation testing, and signal processing</td>
<td>Demonstrated live tissue experimentation laboratory techniques and application of engineering knowledge to physiological systems. General knowledge of invertebrate anatomy and physiology is gained.</td>
</tr>
<tr>
<td>Aplysia californica</td>
<td>Sharp microelectrode recording from the central nervous system</td>
<td>Dissection skills, general electrophysiology, time series analysis, instrumentation testing, and signal processing</td>
<td>Demonstrated live tissue experimentation laboratory techniques and how to apply engineering knowledge to physiological systems. General knowledge of invertebrate anatomy and physiology is gained.</td>
</tr>
<tr>
<td>Homarus americanus</td>
<td>Sharp microelectrode recording from the cardiac trunk</td>
<td>Dissection skills, general electrophysiology, and staining techniques</td>
<td>Exposed students to the need and use of biological staining. General knowledge of crustacean anatomy and physiology is gained.</td>
</tr>
<tr>
<td>Acheta domesticus</td>
<td>Electromyogram recording from the hind leg</td>
<td>Interface with digital and analog circuitry, electrode design, and signal processing</td>
<td>Demonstrated the difficulties acquiring of biological signals and the importance of proper electrodes when recording from live tissue. Circuit design is emphasized.</td>
</tr>
<tr>
<td>Mercencaria mercenaria</td>
<td>Muscle contractility of the heart</td>
<td>Biomechanics research, general muscle physiology, and data acquisition</td>
<td>Knowledge of muscle physiology is gained. Software tools such as LabView and MATLAB are emphasized.</td>
</tr>
</tbody>
</table>

Whenever possible, the class meets on consecutive Sundays to maintain the momentum of the research. In the second semester, the focus shifts from research to documenting the results in a conference paper format. The results are documented according to the two-column Institute of Electrical and Electronics Engineers (IEEE) conference paper template and are then submitted to the Northeast Bioengineering Conference (NBEC) for consideration. Upon acceptance, students prepare either a poster presentation or podium presentation, depending on the will of the conference selection committee. The Sunday before the conference is to be held, a mini-conference is held, where the students deliver their results to the rest of the class in a structured conference forum. They are given 15 min to deliver a podium presentation with 5 min for questions. Poster presentations require the preparation of several different verbal discussions ranging from a 1-min synopsis to a 5-min indepth explanation. Using educational grant monies, every student travels to the location of the conference. The attendance at this conference is compulsory and serves as one metric for evaluating a student’s performance in the course.

We are aware that a Sunday laboratory may be difficult for many institutions to implement. A possible solution would be to hold the laboratory over a 4- to 6-h period during the academic week where several classes are devoted strictly to...
students becoming familiar with dissection techniques. This is a critical phase and cannot be compromised. Many of the frustrations and difficulties engineering students have with these particular biological preparations stem from the fact that they simply don’t have the training to perform what, in many instances, amounts to microdissection. These difficulties can only be overcome by hands-on, small-class instruction. Students must be guided through the dissection techniques and then be afforded the opportunity to practice before any experiments can take place. This serves two purposes. First, students develop laboratory skills that can easily be applied to preparations not covered in this course, and, second, the ability to successfully execute any of these preparations, particularly those involving sharp microelectrode recording from neurons, builds confidence while providing critical hands-on, investigation-based learning. The need for such learning has been emphasized by the National Academy of Science, the National Academy of Engineering, and the Institute for Medicine and continues to play a vital role in educating scientists who are capable of developing experiments to solve currently unsolved problems. This course addresses these issues in the spirit of the National Science Education Standards set forth by the National Research Council relating to teaching sciences through discovery (7).

Preparations

Electrophysiology. By far, the workhorse in our laboratory is the pond snail Lymnaea stagnalis. Previous research involving this animal provides the course with a stable of experiments that students can repeat and adapt to their own engineering background (6). In our laboratory, research on this animal is based on sharp microelectrode recording from the central nervous system. To date, students have created analog circuits that emulate the waveform generated by the neuron RPD-1 in the visceral ganglion of Lymnaea stagnalis, constructed microcontroller-based artificial synapses to interface such analog circuits, and performed nonlinear dynamics analysis to investigate biological event detection (Table 2). While the preparation requires discipline to learn and master, it provides students access to higher-level research activity. Intracellular recording of neuronal action potentials is a well-established, and well-documented, procedure (2). Students who conduct research using this preparation are required to demonstrate their ability to perform not only the dissection but the microelectrode recording as well. To be sure, biology students who spend time learning and practicing microdissection techniques and using three-plane micromanipulators are well prepared to perform such a standard preparation. However, for engineering students with limited macrodissection experience, this technique can require an intensive commitment of time to learn. In our experience, this is the single most significant obstacle in shortening this course to 4–6 h.

Two other electrophysiology preparations are introduced by courtesy of K. Kuwasawa: sharp microelectrode recording from the visceral ganglion of Aplysia californica and microelectrode recording from the cardiac trunk of Homarus americanus. The dissection of A. californica is demonstrated, and students are then directed to perform the dissection on their own. This trial-by-fire methodology is critical to the immersion-based learning that is the hallmark of the course. For instance, failure to recognize the branchial nerve and sever it quickly results in an ink-based lesson in mechanical nerve stimulation that students are not likely to forget. The preparation of H. americanus is not quite as treacherous but has its own lessons to offer. The identification of neurons in the cardiac trunk of H. americanus is difficult due to the opacity of the neurons and the ease with which they blend into the myocardium of the heart. It is therefore helpful, if not necessary, to stain the preparation with methylene blue to differentiate the neurons and neural tissue from the surrounding musculature. In this way, students are exposed to the techniques, as well as the importance, of using temporary vital stains in physiological investigations (1).

It is important to mention that many of the sharp electrode experiments performed in our laboratory use a device that was designed and built here at the University of Rhode Island by J. Wu. The Universal Clamp (a patent-pending electrophysiology instrument) performs voltage, current, and dynamic clamping. The onboard digital signal processor allows for analog-to-digital conversion, data acquisition, and recording. This all-in-one design allows us to investigate, among other topics, coupling properties and network connections. Such research is contemporary and relevant, as recent articles have demonstrated (4). In addition, the development of this device, in parallel with the course, serves as a motivational tool for students as well as providing feedback about the performance of the device. This, in turn, aids in its advancement as a useful physiological tool.

One of the more popular research topics from both the student’s and the University’s perspective is the project we’ve dubbed the “Cricket Car.” Simply put, the Cricket Car is a remote control car that uses electromyography (EMG) signals to “drive” a remote-controlled car. That is, electrodes are inserted into the legs of the common house cricket, Acheta domesticus, and the EMG signal is amplified. This amplified signal is then sampled by the PIC16F88 (Microchip) processor. Using threshold detection and conditional logic algorithms, the PIC16F88 processor sends command signals to the printed circuit board of the remote-controlled car. Features such as ultrasound object/collision detection, cricket stimulus, and additional signal-processing algorithms have been added to help “teach” the cricket how to drive. Although this idea is not novel (5), our research is focused on adapting this technology to assist people with disabilities in controlling their environment.

Biomechanics. A benefit of attending a university along the North American shore line is the access to marine animals. In Rhode Island, no single marine animal is more ubiquitous, either in ecology or culture, than the quahog, Mercenaria mercenaria. The animal has an easily dissectible heart that is long lived once removed from the animal—a trait that has tremendous advantages for use in teaching.

Several experiments are conducted on the clam heart, including stretch-activation and shortening-deactivation. Shortening-deactivation refers to a quick release of a muscle specimen, the whole clam heart in this case, resulting in a sudden decrease of the afterload during contraction. Deactivation is defined as the fraction of maximum force lost during a contraction when a muscle is shortened rapidly to a known length relative to a control isometric contraction. These experiments help elucidate muscle mechanics and the physiology associated
### Table 2. Research topics and preparations

<table>
<thead>
<tr>
<th>Research Topic</th>
<th>Animal</th>
<th>Learning Points</th>
<th>Evaluation</th>
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<tbody>
<tr>
<td>Experiential learning in neurophysiology for undergraduate biomedical students</td>
<td><em>Lymnaea stagnalis</em></td>
<td>Solution preparation, invertebrate anatomy, electrophysiology, microdissection and laboratory skills, electrical engineering, documentation and laboratory journal skills, analog circuitry, linear and nonlinear signal processing, and statistics and real-time data processing</td>
<td>Does the student understand chemistry and chemical properties? Can the student perform the animal dissection? Does the student follow standard laboratory practices, i.e., keeping records, cleaning equipment, and following disposal regulations? Can the student apply his or her knowledge of electrical engineering to biological systems?</td>
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<tr>
<td>Linear and nonlinear data analysis of neuronal action potentials</td>
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<tr>
<td>Active analog circuit design for emulating neuronal action potential signals</td>
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<tr>
<td>Analog circuit design for modeling a reciprocal inhibitory oscillator</td>
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<tr>
<td>Physiological event detection using statistical nonstationarity in time series</td>
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<tr>
<td>recordings of neuronal action potentials</td>
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<tr>
<td>Design, construction, and testing of a completely digital universal instrument for biological measurements, stimulation, clamping, and processing</td>
<td><em>Lymnaea stagnalis, Aplysia californica, and Homarus americanus</em></td>
<td>Solution preparation, invertebrate anatomy, electrophysiology, microdissection and laboratory skills, electrical engineering, documentation and laboratory journal skills, analog circuitry, linear and nonlinear signal processing, statistics and real-time data processing, digital signal processing learning, and systems integration</td>
<td>Does the student understand chemistry and chemical properties? Can the student perform the animal dissection? Does the student follow standard laboratory practices, i.e., keeping records, cleaning equipment, and following disposal regulations? Can the student apply his or her knowledge of electrical engineering to biological systems? Does the student understand electrical engineering concepts such as systems design using digital signal processing?</td>
</tr>
<tr>
<td>Neuronal dose-response relationships using neurotransmitters</td>
<td><em>Aplysia californica</em></td>
<td>Solution preparation, invertebrate anatomy, electrophysiology, microdissection and laboratory skills, electrical engineering, documentation and laboratory journal skills, analog circuitry, linear and nonlinear signal processing, statistics and real-time data processing, and understanding neuronal responses to different neurotransmitters</td>
<td>Does the student understand chemistry and chemical properties? Can the student perform the animal dissection? Does the student follow standard laboratory practices, i.e., keeping records, cleaning equipment, and following disposal regulations? Can the student apply his or her knowledge of electrical engineering to biological systems? Does the student understand neuronal dose responses to different neurotransmitters?</td>
</tr>
<tr>
<td>Muscle mechanics and physiology in stretch and release experiments using the bivalve heart</td>
<td><em>Mercenaria mercenaria</em></td>
<td>Solution preparation, invertebrate anatomy, dissection and laboratory skills, electrical engineering, documentation and laboratory journal skills, systems integration using MATLAB and LabView</td>
<td>Does the student understand chemistry and chemical properties? Can the student perform the animal dissection? Does the student follow standard laboratory practices, i.e., keeping records, cleaning equipment, and following disposal regulations? Can the student apply his or her knowledge of electrical engineering to biological systems? Does the student understand muscle physiology? Can the student adapt software to control physiological measurement instrumentation? Does the student understand electrical engineering concepts such as systems design using microcontrollers?</td>
</tr>
<tr>
<td>Microprocessor-based control of electromechanical devices using electromyogram signals from the hind legs of the common house cricket</td>
<td><em>Acheta domesticus</em></td>
<td>Electrophysiology, laboratory skills, electrical engineering, documentation and laboratory journal skills, systems design using analog circuitry and microprocessors, linear and nonlinear processing, and electrode design for interfacing with biological tissue</td>
<td>Does the student understand chemistry and chemical properties? Can the student perform the animal dissection? Does the student follow standard laboratory practices, i.e., keeping records, cleaning equipment, and following disposal regulations? Does the student understand electrical engineering concepts such as systems design using microcontrollers?</td>
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with such movements. In addition, the experiments use a dual-mode lever system (model 300B, Aurora Instruments) controlled by LabView software. The experiments require students to understand systems integration involving both hardware and software. Signal analysis and conditioning (filtering) is performed using MATLAB, which provides real world applications to the theoretical work that most engineering students perform using this software.

RESULTS

As previously mentioned, one metric used in evaluating students is the quality of the presentation at the NBEC. Since this course is designed to encourage original research and novel applications of existing research, other metrics dealing specifically with evaluating the effectiveness of the applications are needed. To that end, students are required to determine a research topic or application and perform original research with respect to that topic for the first semester. Often, this involves continuing research performed by students in previous years. The animals and preparations used in this course have been used extensively in electrophysiology and biomechanics research. However, there are always applications that have not been considered with regard to this research. Fundamental questions, such as “Can the student correctly evaluate previous research and either expand or find novel applications for the results of the research?” and “Does the student comprehend the needs and benefits of previous research?,” are asked. The academic merits of the research as well as the scope of the application of the research to science and society are key components of the evaluation and, ultimately, the grading scheme. Additionally, the thoroughness of the laboratory journal and choice of reference material are considered in determining student grades.

In the 3 years since the course was first offered, it has generated 22 accepted student conference papers. Of these 22 papers, 14 papers were requested to be presented in podium presentation form and 8 papers have been poster presentations. While the bulk numbers are impressive, the course has submitted award-winning presentations in each of the three conferences attended, as determined by the appointed selection committee. The success of several of the research topics presented have given rise to further research that has been presented at professional conferences including the Biomedical Engineering Society, the Whitaker Foundation Summit on Biomedical Engineering Education, and the Society for Neuroscience. The course has also generated a provisional patent and has aided in the development of a patent-pending device. Enrollment in the course has increased from 6 students in the first year, to 11 students in the second year, and 14 students in the third year. To date, there have been 7 different graduate students, 18 undergraduate students, 4 professors, and 1 high school student who have participated in this course. It is this diversity that drives the course, pitting undergraduates with graduate students and professors with the goal of fostering a commitment to novel research. The grade distribution is as follows: in the first year, there were 4 A’s, 1 A−, and 1 B+; in the second year, there were 7 A’s and 4 A−’s; and in the third year, there were 9 A’s and 5 A−’s.

Not every student submitted conference papers as first authors. Some were listed as second or third authors, depending on the degree to which they contributed to the research. To date, only two students have had no affiliation with a research paper. This was due to research that did not produce results in time for the journal paper to be submitted to the NEBC. Those students were still required to submit a paper to the instructor but received a lower grade for the course. Students who were listed as authors but did not present at the conference were not penalized as only one student is chosen to present, usually the first author.

Limitations

There are, of course, some difficulties with running a course such as this. First and foremost, it is difficult to entice an engineering student who already has a course load of 16–18 credits to come back to the university on a Sunday. In addition to the obvious time commitment, there is the issue of Sunday being a religious day of worship. This means that the course is constrained by the fact that it cannot be a curriculum requirement and so it must remain an elective course. The pool of potential students is reduced considerably. A possible remedy to this is to attempt to reformat the course from six 6-h classes to eight 6-h classes. Still, the 6-h block of time is formidable.

A pressing concern from an educational standpoint is the development of a meaningful system of metrics. Since the course is relatively small, the instructors have intimate knowledge of the students and the research they perform. While the conference paper provides a tangible example of work that the student, or team, has performed, ultimately grading is reduced to the instructor’s impression of the student and his or her work ethic. This is based on tangible items such as the laboratory journal and choice of references. Instructors consider the abilities of the students to perform dissections as well as their overall laboratory skills. This is an observed metric and is somewhat subjective. Going forward, the course will require more written examples of the work product, such as project proposals and a research paper separate from the IEEE two-column format. Additionally, future courses will require an evaluation of the course by students that will include directions to indicate how much has been learned, the strengths and weaknesses of the course, and general suggestions on improving the course. These metrics for evaluation are consistent with those adopted by CDIO Initiative (3).

DISCUSSION

The biomedical engineering program at the University of Rhode Island has developed what we believe to be a novel approach to experiential undergraduate research. The Sunday Lab, as it is affectionately known, has grown in popularity and is becoming a sought-after engineering design elective by biomedical engineering students and electrical engineering students alike. Additionally, the course has generated a renewed interest from the Biology Department by resurrecting previously underutilized research and special topics courses. The steady increase in enrollment has highlighted the need for a more rigid evaluation process, whether in the form of testing or formal report writing. Still, this need is tempered somewhat by the need to provide valuable whole animal experiential training with applications that are contemporary and relevant but, most importantly, physiologically based. Despite the specificity of the experiments, they exemplify advanced research in
electrophysiology and biomechanics. Some of these experiments are technically challenging to motivate those students with a firm understanding of biology and physiological processes, whereas others are more accessible. As a result, the course is able to generate a synergy not attainable in the standard “canned-laboratory” setting. More importantly, the course introduces biomedical engineering students to the field of physiology with meaningful engineering applications.

ACKNOWLEDGMENTS

The authors thank Dr. Robert Hill, research professor at the University of Rhode Island, for initiating the course and establishing the network of researchers for us to draw on. Without this generous support, both in laboratory equipment and teaching, the successes of this course would be few to be sure. We also thank Dr. Ken Lukowiak of the University of Calgary for providing the initial colony of *Lymnaea stagnalis* and Dr. Bob Yantorno from Temple University (Philadelphia, PA) for insightful comments and suggestions in review of this manuscript.

REFERENCES