

# A novel approach to physiology education for biomedical engineering students

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Physiology education for biomedical engineers

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Abstract –

It is challenging for biomedical engineering programs to incorporate an in-depth 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 at the University of Rhode Island, this issue is addressed to some extent by implementing an experiential physiology laboratory which 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 eight hour lab 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. The 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 paper 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.

Keywords –

Biomedical engineering, engineering education, project-based learning

## Introduction –

Biomedical engineering education may come from within a traditional engineering curriculum. This is the case at the Department of Electrical, Computer, and Biomedical Engineering at the University of Rhode Island. The Biomedical Engineering Program focuses on electrical engineering as it pertains to biomedical applications. The core curriculum includes fundamental biology courses such as Mammalian Physiology (4 semester-based credits) and Human Anatomy (4 semester-based credits), yet the underlying physiological systems interdependence as well as the response to external stimuli, both introduced and studied by biomedical engineers, are somewhat obfuscated. Of critical concern is the inability of many of our engineering students to participate in high level physiology courses due to the necessity of lower level prerequisites. To compound matters, the national undergraduate curriculum in life sciences has witnessed a steady decrease in required human physiology instruction for the past several years (8). This two-semester project course elucidates higher level physiological relationships while providing laboratory skills in whole animal dissection, instrumentation and physiological measurements. Additionally, the course serves as an electrical engineering design elective by incorporating electrical engineering concepts and applications with biological science. Engineers are better prepared to solve problems when they have a first-hand understanding of what the problem is and its cause. To this end, we have developed this laboratory course to address these issues and give biomedical engineering students the insight and research skills necessary to understand and help solve biological and

physiological problems.

The course is taught jointly by a biomedical engineering professor and a biology professor. In addition, a professor of neurobiology from the University of Science in Okayama Japan visits once a year to sharpen skills in techniques required for microelectrode research with living tissue. This interdisciplinary approach makes the course beneficial to the engineering students, as they are presented the opportunity to apply their engineering skills to physiological systems.

#### 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, 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 which 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 one lists the animals and preparations currently investigated in the course. These animals are used each year and students are encouraged to learn each preparation, though most focus on one or two. Since the course can be taken more than once under a different course level listing, those who pursue this option learn all the preparations.

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

Table 1.

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. The 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 circuit design, and choose to model a biological system with diodes, transistors, and the like. It is in this way that the course attempts to integrate the project design based on the students' interests. Standard physiology courses are unable to offer this type of selective experimentation.

Each semester the students meet for a total of six 8-hour lab periods. We have found that the only day that this block of time is available given the additional academic demands of a senior engineering student is Sunday. The day starts at 9:00AM with an organizational meeting where each team of students, ranging from 2 to 4, discusses the outline of the protocol they expect to follow for the day. Professors, as well as other students, make comments and suggestions as to how a particular research project should proceed. In this way, the entire class is aware of the physiology research being conducted by each of the other researchers. Collectively, the class meets again at 4:30PM to discuss the results of

the day and to forecast the procedures for the next meeting period. The somewhat lengthy laboratory was adopted since not every dissection or preparation will yield results and a shorter interval may not leave enough time to prepare another animal or run the experiment. This was the issue that led to creating the course, as the 3 hour physiology lab we attempted to convert simply did not afford the time necessary to teach the dissection, setup and calibrate the equipment, and then run the experiment. To be sure, much of this can be done before the class starts; however, engineering students must be aware of these procedures if they are to make contributions to the process. We recognize that we are not physiologists, nor are we attempting to be physiologists. Our role as engineers is to figure out a better, perhaps easier, way of using instrumentation to conduct an experiment or to apply our understanding of electrical engineering principles to biology. In order to accomplish this, our students must be intimately familiar with the complete preparation and experiment, from start to finish. To this end, students are required to keep a composition style journal of their lab experiences.

Whenever possible, the class meets on consecutive Sundays in order 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 IEEE conference paper template and are then submitted to the Northeast Bioengineering Conference for consideration. Upon acceptance, the 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 minutes to deliver a podium presentation with 5 minutes for questions. Poster presentations require the preparation of several different verbal discussions ranging from a one-minute synopsis to a 5 minute in depth 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 4-6 hour 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 micro dissection. These difficulties can only be overcome by hands on, small class instruction. The 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 are developing 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).

The Preparations –

### *Electrophysiology*

By far, the workhorse in our lab 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 lab, 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 RPD-1 in the visceral ganglion, constructed microcontroller based artificial synapses to interface such analog circuits, and have 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 micro dissection techniques and using three-plane micromanipulators are well prepared to perform such a standard preparation. However, for engineering students with limited macro dissection 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 to 6 hours.

Two other electrophysiology preparations are introduced by courtesy of Professor Kiyooki Kuwasawa: sharp microelectrode recording from the visceral ganglion of *Aplysia californica* and microelectrode recording from the cardiac trunk of *Homerus americanus*. The dissection of *A. californica* is demonstrated and the 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 in order 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 stains in physiological investigations (1).

Research Topic	Animal	Learning Points	Evaluation
<p>Experiential learning in neurophysiology for undergraduate biomedical engineering students</p> <p>Linear and nonlinear data analysis of neuronal action Potentials.</p> <p>Active analog circuit design for emulating neuronal action potential signals</p> <p>Analog circuit design for modeling a reciprocal inhibitory oscillator</p> <p>Physiological event detection using statistical nonstationarity in time series recordings of neuronal action potentials</p>	<i>Lymnaea stagnalis</i>	<p>Solution preparation</p> <p>Invertebrate anatomy</p> <p>Electrophysiology</p> <p>Microdissection and laboratory skills</p> <p>Electrical engineering</p> <p>Documentation and lab journal skills.</p> <p>Analog circuitry</p> <p>Linear and nonlinear signal processing</p> <p>Statistics and real-time data processing</p>	<p>Does the student understand chemistry and chemical properties?</p> <p>Can the student perform the animal dissection?</p> <p>Does the student follow standard lab practices, i.e. keeping records, cleaning equipment, and following disposal regulations?</p> <p>Can the student apply his/her knowledge of electrical engineering to biological systems?</p>
Design, construction and testing of a completely digital universal instrument for biological measurements, stimulation, clamping and processing	<i>Lymnaea stagnalis</i> <i>Aplysia californica</i> <i>Homerus americanus</i>	Same as above with the addition of digital signal processor (DSP) learning as well as systems integration.	Same as above with the addition of questioning if the student understands electrical engineering concepts such as systems design using DSPs.
Neuronal dose-response relationships using neurotransmitters.	<i>Aplysia californica</i>	Same as entry one with the addition of understanding neuronal responses to different neurotransmitters.	Same as entry one with the addition of questioning whether the the student understands neuronal dose responses to different neurotransmitters.
Muscle mechanics and physiology in stretch and release experiments using the bivalve heart.	<i>Mercenaria mercenaria</i>	<p>Solution preparation</p> <p>Invertebrate anatomy</p> <p>Dissection and laboratory skills</p> <p>Electrical engineering</p> <p>Documentation and lab journal skills.</p> <p>Systems integration using MATLAB® and LABVIEW®</p>	Same as entry one with the addition of questioning whether the student understands muscle physiology and has the ability to adapt software to control physiological measurement instrumentation.
Microprocessor based control of electromechanical devices using electromyogram signals from the hind legs of the common house cricket.	<i>Acheta domesticus</i>	<p>Electrophysiology</p> <p>Laboratory skills</p> <p>Electrical engineering</p> <p>Documentation and lab journal skills.</p> <p>System design using analog circuitry and microprocessors</p> <p>Linear and nonlinear processing</p> <p>Electrode design for interfacing with biological tissue</p>	Same as entry one with the addition of questioning if the student understands electrical engineering concepts such as systems design using microcontrollers.

Table 2.

It is important to mention that many of the sharp electrode experiments performed in our lab utilize a device that was designed and built here at the University of Rhode Island by Dr. Jiang 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 publications demonstrate (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 domestica*, 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 PIC 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 when teaching.

Several experiments are conducted on the clam heart including stretch-activation and shortening deactivation. Shorting-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 with such movements. In addition, the experiments utilize a dual mode lever system (Model 300B, Aurora Instruments) controlled by LabView® software. The experiments require the 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 Northeast Bioengineering Conference. 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, the 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 lab journal and choice of reference material are considered in determining grades.

In the three years since the course was first offered, it has generated 22 accepted student conference papers. Of these 22, 14 were requested to be presented in podium presentation form and 8 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 in the first year, to 11 in the second, and 14 in the third. To date, there have been 7 different graduate students, 18 undergraduates, 4 professors, and one 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: year one there were 4 A's, 1 A-, and 1 B+, year two there were 7 A's, and 4 A-'s, and year three there were 9 A's and 5 A-'s.

Not every student has submitted conference papers as first authors. Some are 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 which 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 are listed as authors but do not present at the conference are 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 to 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 8 hour classes, to eight 6 hour classes. Still, the 6 hour block of time is formidable.

A pressing concern from an educational stand point 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 lab journal and choice of references. Instructors consider the abilities of the students to perform dissections as well as their overall lab skills. This is an observed metric and is somewhat subjective. Going forward, the course will require more written examples of 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 which 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 the Conceive, Design, Implement, Operate initiative, or 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, while 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.

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