Paper ID #23255

Modeling and Design: a Hands-on Introduction to Biomedical Engineering

Dr. Eileen Haase PhD, Johns Hopkins University

Eileen Haase is the Director of Undergraduate Studies and a Senior Lecturer in Biomedical Engineering at Johns Hopkins University. She is also chair of the Johns Hopkins Applied Biomedical Engineering graduate program for Engineering Professionals. She received her BS in ESM from Virginia Tech, and her MS EE and PhD in Biomedical Engineering from Johns Hopkins.

Modeling and Design: A hands-on Introduction to Biomedical Engineering

Abstract

How can we impart the excitement of biomedical engineering to our freshmen from the moment they step on campus? We have found great success with "Modeling and Design" an innovative, required course which engages our students as biomedical engineers from their first day at Johns Hopkins. Small groups, guided by upperclassmen lab managers, teaching assistants, and faculty, work through five modules including modeling human efficiency, the arm, and the cardiovascular system, as well as a foam core design project. By the conclusion of the fifth module, an independent modeling project, 96% of the students appreciate the value of working in teams to tackle complex challenges. They have become adept at developing and testing their hypotheses, and presenting their results through written lab reports and oral presentations. By the end of the semester, 84% of freshmen "strongly agreed" or "agreed" that the course had met its goal of providing a solid introduction to modeling physiological systems, academic and career mentoring, exposure to research and design opportunities available at Johns Hopkins, and a concrete basis for a career choice in BME. More importantly, the course helps set up our students for long-term academic success, as indicated by a 94% freshmen/sophomore retention rate.

Developing a mathematical model to describe a physiological system is a new concept for freshmen. For each project, the freshmen are provided with a one page background summary with just enough information to get started. Experimental testing of the mathematical model is an essential component of the learning process, and allows the students to collect data and perform a statistical analysis of their model. At first, the process of making assumptions, writing equations, developing an experimental protocol to test the model, and analyzing the results is daunting. By the final independent project, 88% of students felt exploring their own topic was an "excellent" or "good" learning experience and valued presenting their results at a final poster session. Not only do the freshmen benefit from the course, but the upperclassmen lab managers believe they have gained valuable leadership and professional skills, such as providing constructive feedback and public speaking.

Introduction

Freshmen arrive on campus ready to become a part of the excitement of biomedical engineering. They are eager to work in a lab, "tinker" in the design studio, and "learn by doing" rather than just sit in a lecture hall. The required fall semester freshmen course, "Modeling and Design", focuses that freshmen enthusiasm into solving complex modeling and design problems through five modules [1]. The freshmen class of 115-140 students is divided into five-person teams. Students are challenged to develop, simulate, and test three physiological models; the arm, the cardiovascular system, and human efficiency. Students gain exposure to the design process through a foam core challenge. For their final project, students perform their own research, choose a project, and start from scratch developing and testing their model, often designing their own equipment in the process. The course does not have a formal lecture component. Instead, we ask the students a series of questions so that they can develop a unique model based on their own "conceptual representation" [2]. A summary of the five modules is listed in Table 1.

Table 1: Freshmen Modeling and Design Modules

Module	Objectives
Human Efficiency Model	Develop a simple model of human efficiency, design an experiment to test the model, obtain and analyze experimental data, and compare model predictions with experimental results in a written lab report.
Arm Model	Develop a free body diagram of the arm. Calculate the force generated in an arm muscle while holding a weight. Design an experiment to test the arm model, obtain and analyze experimental data, and compare model with experimental results in a written lab report.
Cardiovascular System Models	Derive the relationship for flow in a single tube using dimensional analysis and experimental data. Use an electrical model to calculate flow through a system of tubes in series and parallel. Estimate changes in heart rate due to activation of the baroreceptor reflex, a negative feedback control system. Discuss results in a written lab report.
Foam Core Design Project	Ideate, design, build, test, explain in an elevator-pitch, and demonstrate two simple machines which transport a ping-pong ball across a distance of 3 meters and back.
Independent Project	Build on previous experience and consultations with experts in the field to develop equations which model a physiologic system. Experimentally test the model, which might require creating a computer program, fabricating equipment using 3-D printing, constructing a circuit, working with faculty to use specialized apparatus, etc. Compare model predictions with experimental data and present results at a poster session.

During the course, freshmen progress through five modules of increasing complexity. The teams develop models, test their models with laboratory experiments, and validate their models with experimental data. At the conclusion of the course, freshmen gain an appreciation for the power of modeling physiological systems and can propose their own hypothesis, which they can then test in lab. With practice, freshmen become more comfortable with the modeling process [3]. They understand the value of solving challenging, open-ended problems with multiple potential solutions. Engineering students must learn to creatively ideate and assess numerous approaches, often with conflicting outcomes, starting their freshmen year. Modeling and design team-based projects engross students in learning beyond lectures and memorization. The iterative thinking process required to achieve even partial success in solving ambiguous problems not only actively engages students, but has also been shown to improve learning and retention [4].

Developing collaborative problem-solving skills, starting with the transformative freshmen year, provides students with the outlook and tools crucial for academic and professional success [5], [6]. Integrating design into the first semester exposes students to the complex process of creating, assessing, selecting, and realizing an initial prototype [7, 8]. By incorporating a fun foam core design project, students gain exposure to the design process such that many of them are comfortable designing their own equipment for their final project. More importantly, freshmen, many of whom have never “failed” before, learn to appreciate that failure is a crucial component of creativity and an essential part of solving challenging problems.

Previous researchers have shown the significant value of collaborative versus competitive learning [9]. The importance of developing teamwork skills in college is emphasized by ABET as one of the primary “a through k” objectives: an ability to function on a multi-disciplinary team. Both problem-based learning and cooperative learning provide the essential skills required for ABET accredited programs [10, 11]. A critical component of the Modeling and Design course success is the collegial atmosphere. Students from diverse backgrounds and educational experiences work in teams. The teams are encouraged to address any concerns in their graded lab reports and can re-submit their lab reports for a higher grade. The emphasis on working with peers to maximize learning, rather than simply striving for a grade, is an essential element in creating a positive environment where all students can thrive.

Upperclassmen lab managers mentor freshmen on the plethora of opportunities available outside the classroom, which are such an essential component of professional success. One of the requirements for the lab managers is to accompany the freshmen teams on three separate faculty lab visits to the Johns Hopkins Medical Institute. The opportunity for the freshman to meet the faculty as they are working in their labs often serves as a gateway to a research position, sometimes within weeks of the lab visit.

What is Modeling?

The complexity of the human body requires that biomedical engineers use models to develop their hypothesis. Many variables can only be estimated based on previously published data. While there are multiple definitions of a “model”, we use the Hestenes’ definition which states that a model is a “conceptual representation of the real thing” [2]. In essence, a model is a mathematical equation which provides a description of how a system works. In the human body, that description can be quite complex. Models allow us to use simplifying assumptions to understand multifaceted physiological processes.

Faculty introduce each model by asking questions about the system to determine the students’ baseline knowledge. The students summarize everything they know about that system, whether it is the definition of efficiency, a sketch of the muscles in the arm, or a drawing of the circulatory system. The arm model, for example, starts with too many muscles to solve an equation for force, resulting in an indeterminate system. At this point, students need to make some assumptions, carefully keeping track of how they simplified their equations. Each of the modeling exercises starts by justifying the model. We ask the students what insight they could gain by modeling this system. The goal of the course is for every student to understand why biomedical engineers use models by actually developing and testing their own models. The team lab reports utilize peer reviews for each of the modules to ensure that each team member is participating and learning.

The processes used to develop each of the three models are described in the following pages.

Module 1: Model of Human Efficiency

We first ask the students "What would a model of human efficiency tell us?" Calculating human energy needs is a common problem for dietitians working to determine army rations, space station food rations, or the requirements for a six-month underwater submarine mission. In addition to military applications, natural disasters, such as the devastation from a hurricane, requires an accurate estimate of the food allotment required for large populations.

A model of human efficiency would predict how much work a human could do with a given amount of energy. Conversely, such a model could also predict how much energy was needed to perform a given amount of work. Students are initially asked to predict the possible relationship between energy input and work output, as sketched in Figure 1 below.

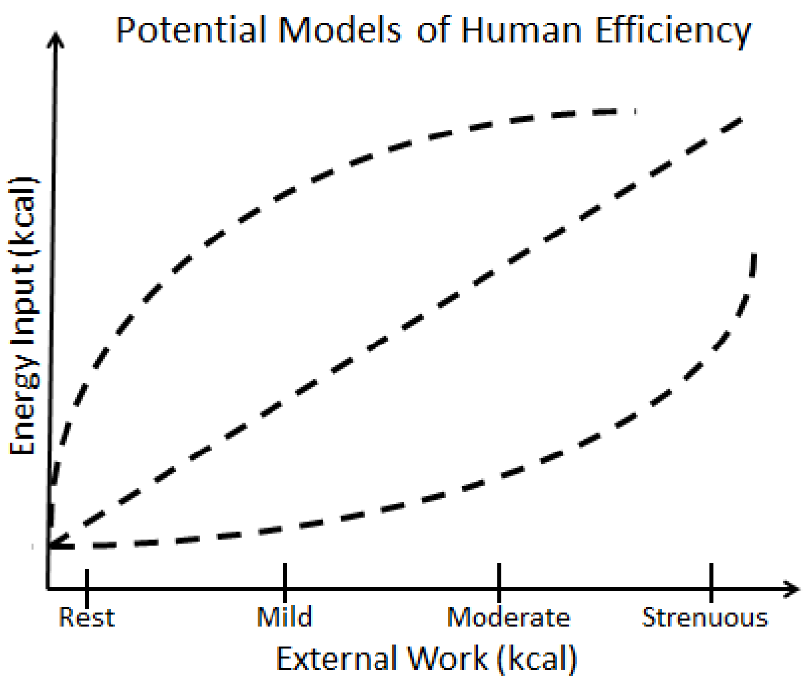

Figure 1: Possible models of human efficiency. Students initially "guess" that energy input increases with work, in either a linear or non-linear relationship. They then design an experiment to test their model.

The simplest relationship is the linear one: as external work increases, the energy required (oxygen) increases proportionally. Is this correct? Students develop a model through a three-step process:

1. Simplify a human system and make some basic assumptions.
2. Develop a mathematical model which is the basis of the hypothesis. This mathematical model is used to predict their experimental results.
3. Design an experiment to test the model in lab, comparing the experimental results with the model predictions.

We start by asking the definition of efficiency:

(Eq 1) $$Efficiency = \frac{output}{input}$$

The equation for efficiency has two parts, which can be calculated separately:

- The numerator (output) - the amount of obvious external work observed by the outside world
- The denominator (input) - the amount of energy a human needs to do this amount of work

Thus, human efficiency is simply output divided by input, leaving the students to define what exactly is meant by “human output” and “human input”. The teams easily grasp the idea of “human output” as work, or exercise, and can quickly come up with equations and experiments to calculate work.

One simple form of work is the movement of the body up a step of height, Δh. Mathematically,

(Eq 2) $$Work = (bodymass)(gravity)(n)(\Delta h) = (weight)(n)(\Delta h)$$

Work can be increased by

- increasing the height of the step (Δh)
- increasing the number of times the student goes up the step (n)
- increasing weight by having the student hold weights as they step

The teams are encouraged to calculate work using other approaches, such as the work performed with a push up, pull-up, jump, or another method.

“Human input” is a more complex concept to define and model. Most freshmen initially equate “input” with food. Over the long term, food intake is the source of all of our body’s energy since we would starve to death without it. However, upon questioning the students realize that they can exercise even if they have not eaten within the previous 24 hours. At this point we encourage everyone to stand up and do vigorous jumping jacks for one minute and observe any physiological changes, such as an increase in heart rate and ventilation. We ask the students how they get the energy from food to do work, what is meant by “cellular respiration”, and what is the relationship between ventilation and cellular respiration. Humans require oxygen to liberate the energy from food. During exercise, our body needs more of the energy from our food stores, and we must take in more oxygen to release this energy. Thus, the “energy in”, over the short term, is proportional to the amount of oxygen consumed, not the amount of food consumed. For someone who has a normal diet (a mix of carbohydrates, proteins and fats), 1 liter of oxygen yields approximately 5 kcal of energy from food. The energy from food can be used to make cellular energy (ATP) through cellular respiration as evident by the equation for metabolism:

(Eq 3) $$Food + O_2 \rightarrow CO_2 + H_2O + Energy\ (ATP)$$

The Biopac Data Acquisition system can measure total ventilation, $\dot{V}_{\text{total}}$ [12]. Oxygen use can be estimated by assuming the inhaled volume of air is 21% oxygen, while the exhaled volume is 14% to 16% oxygen. The amount of oxygen used is calculated through a mass balance equation (Eq 4 and Fig 2):

(Eq 4) $$\dot{V}_{total} = \frac{breaths}{minute}\ x\ \frac{liters}{breath} = \frac{liters\ of\ air}{minute} = total\ ventilation$$

Amount of oxygen used (energy input) = Total ventilation x (21%-15%)

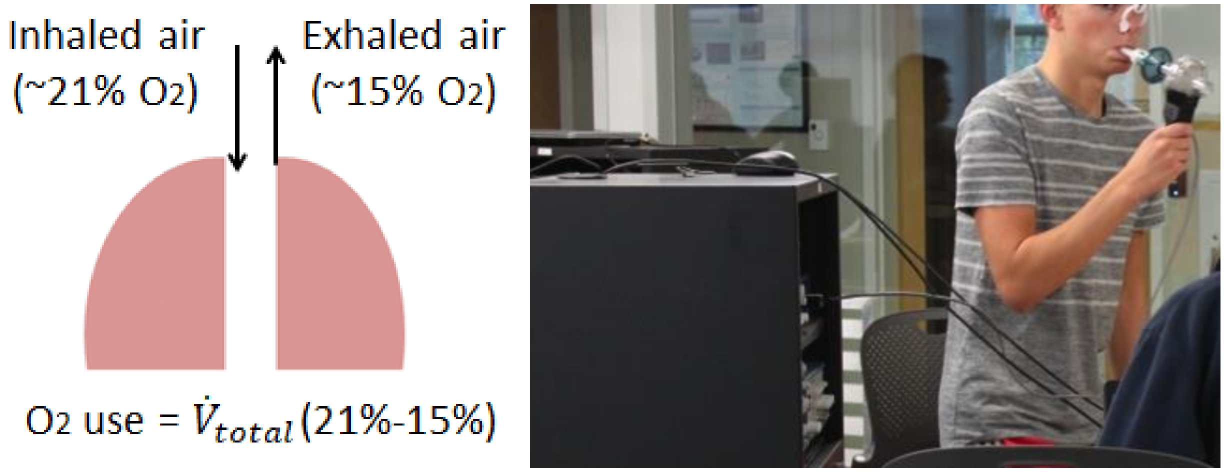

Figure 2: A simple model for the calculation of oxygen use (left). A student recording his total ventilation in lab using the Biopac Data Acquisition System (right).

The model can be expanded to be used beyond the lab to calculate oxygen use during work. Simultaneously measuring heart rate and ventilation during different levels of exercise, provides the data needed to build a model which can be used to predict either oxygen use or external work based on heart rate. The students are essentially reproducing the results from Guyton et al, who showed a linear relationship between heart rate, oxygen use, and exercise [13]. Most teams end up with a "Final Model of Human Efficiency" which is fairly linear, as illustrated in Figure 3. The slopes of the lines vary with each student, depending on their fitness level. Athletic students use less oxygen for a given amount of work, which has been demonstrated previously [14].

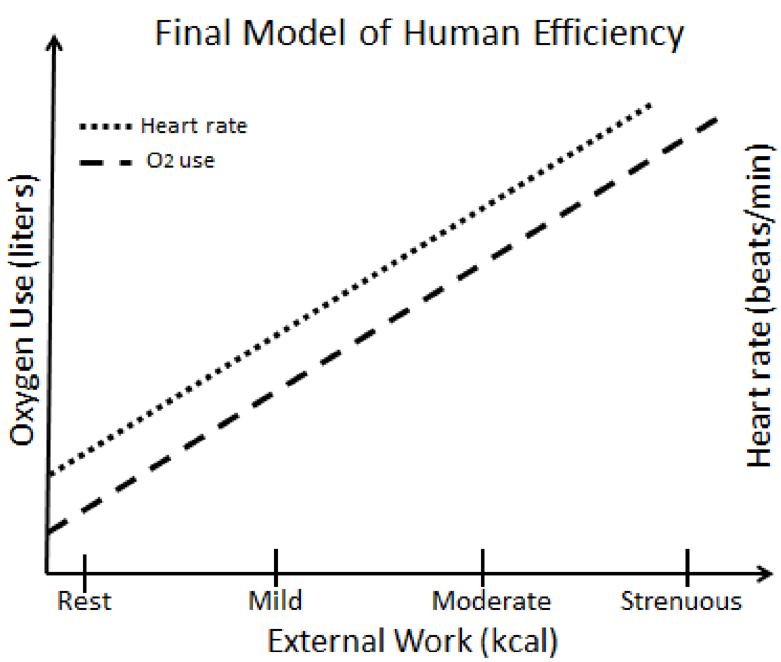

Figure 3: A typical student model of human efficiency relating oxygen use and external work, expanded to include heart rate. Students measure their heart rate and calculate oxygen used for varying levels of exercise. These results are similar to the linear relationship shown by Guyton [13].

The Human Efficiency model can be used to answer the following questions:

- What is the relationship between heart rate, oxygen use and external work? This relationship can be depicted graphically, or as an equation:
  Work = f(heart rate, oxygen use, etc.)
- How efficient is a human "machine" at doing work?
- Are humans more efficient during rest or exercise?
- What happens to our efficiency when we double the external work load?
- What happens to human efficiency if the size of the person doing the work doubles?
- Can your model use heart rate to predict the amount of oxygen required?
- Can your model use heart rate to predict the amount of work done?

Teams are encouraged to add their own questions and explore additional relationships between external work, oxygen use, and heart rate in understanding human efficiency. Since the human efficiency module is first, we asked the students how comfortable they felt obtaining and analyzing respiratory data using the Biopac Data Acquisition System. Some of the student comments are in Table 2.

Table 2: Student comments on Human Efficiency Model and using Biopac

The human efficiency model is a great start to get used to lab equipment as well as data analysis.
I am now fairly comfortable using the BioPac system. My group actually used this system later on for our final project and found it very useful.
As it was my first time reading such data it was confusing at first, but thanks to my lab manager she instructed us on how to read and process the data. Having an actual BME lab manager was very helpful throughout the course.
Yes, I felt comfortable using this system, and it was a cool module that introduced me to new technology.
I feel comfortable using the system to analyze data but I would probably need some help setting the instrument up. I think the lab managers should ensure that everyone in the group has an understanding of how the biopac works, not just the people using it.
This was an interesting experiment in that we were able to observe our breathing patterns in a graphical model. It was a comfortable lab experiment to conduct and write about.
Using the Biopac system was a fun experience and a great way to start off the year!
Yes I felt like it was a good model. Everything that was hard/uncomfortable with this model stemmed from it being the first model and kind of being thrown into it and not actually from any serious difficulties with equipment or topics.
This data acquisition was more difficult but once we figured it out it seemed intuitive.
It was a very comfortable system to use for data analysis and acquisition.
It was confusing at first, but I thought it was a good learning experience as well as a good chance to get familiar with this course in general. I think it was a good intro to begin with.
I did not have any problems with the Biopac. I thought it was pretty easy to use, data collection was successful, and TAs were there to help if we had any questions.

Module 2: Model of the Arm

Students start this module by discussing why it might be useful to model the arm, such as designing prosthetics, assist devices, or even robots. The goal of this module is to calculate the force needed to hold the arm itself and a reasonable weight. A natural place to begin is with a sketch of the arm, such as the one in Figure 4.

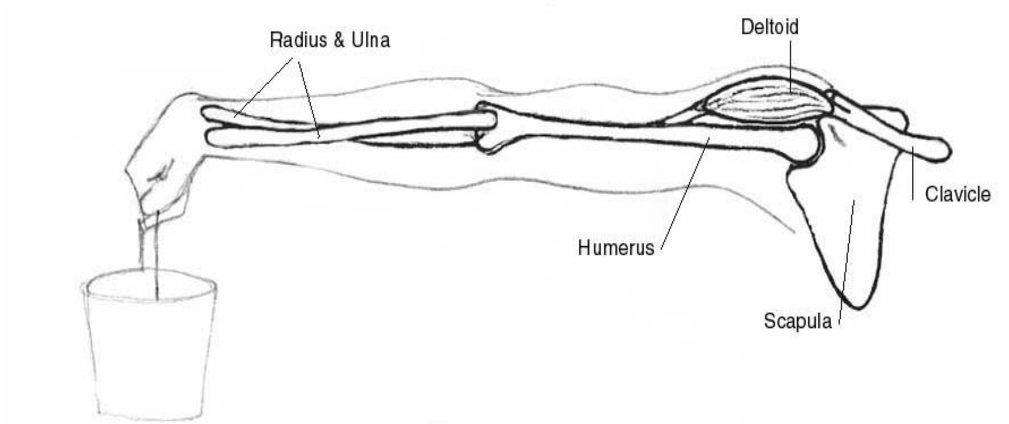

Figure 4: The first step in developing a free body diagram of the arm involves a simple sketch.

The sketch is used to develop a simple free-body diagram. Often students will have multiple muscles in their original sketch, which would make the system indeterminate. One of the main assumptions in this model is that most of the force required to hold up the arm is in the deltoid muscle. Students need to decide on the shape, length, and density of the arm in order to pinpoint the location of the forces on the free-body diagram. The initial free-body diagram for a simple cylindrical arm model is shown in Figure 5. Many students use a conical-shaped arm, or two cylinders of different diameter.

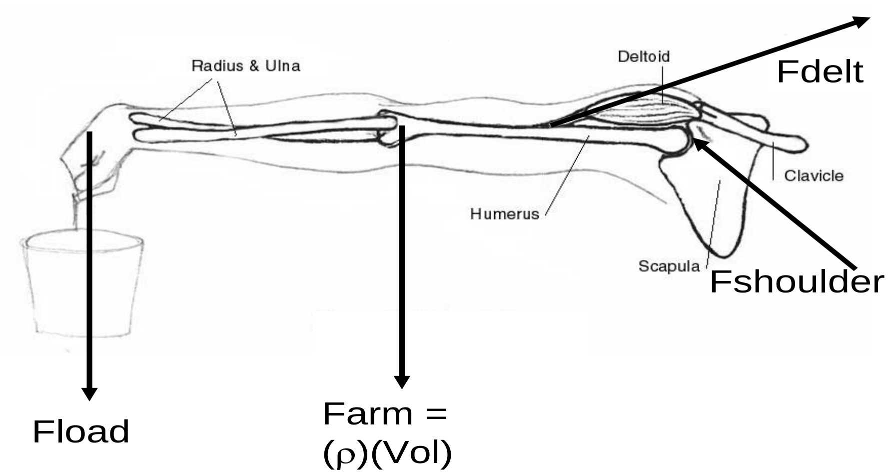

Figure 5: The initial sketch is supplemented to include forces from the deltoid muscle (Fdelt), the shoulder (Fshoulder), the weight of the arm (Farm) and the load which is carried by the arm (Fload). The magnitude and location of Farm depends on the arm's shape, length, and density.

At this point the students are ready to finalize their free-body diagram and solve for the force in the deltoid, as shown in Figure 6.

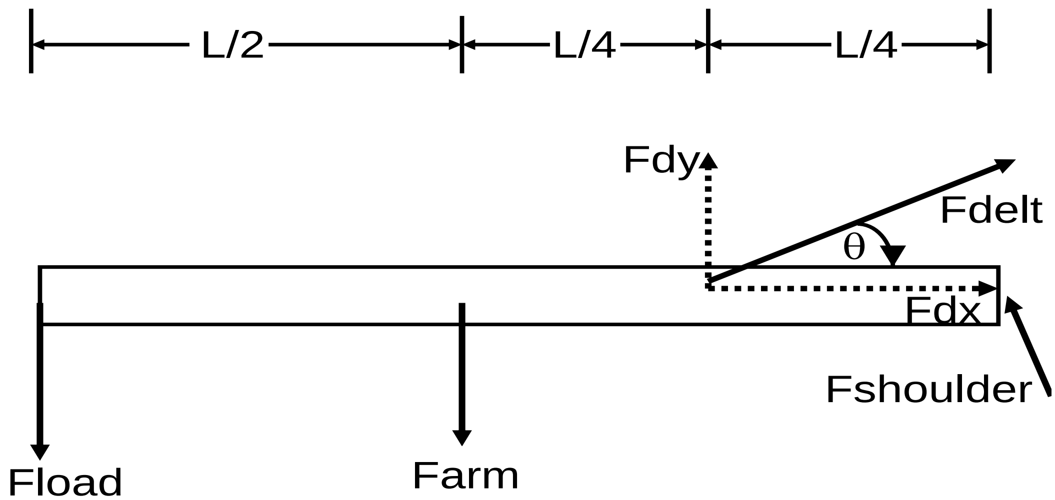

Figure 6: Final free body diagram for the static arm. L is the length of the arm, Farm is the weight of the arm, Fload is the weight held in the hand, and Fdelt is the force of the deltoid muscle required to balance the arm and load. The angle of attachment, θ, of the deltoid muscle and the location of the insertion of the deltoid muscle, L/4, are two of the assumptions of the model. In this example, the arm is modeled as a cylinder with its center of mass at L/2.

Since this is a static arm, the sum of the torque around the shoulder adds to zero as shown in Eq 5. The deltoid force can be divided into two components, Fdy and Fdx, using trigonometry.

(Eq 5) $$\sum \tau_{shoulder} = 0 = -F_{arm}\left(\frac{L}{2}\right) - F_{load}(L) + \left(\frac{L}{4}\right)F_{deltoid}\sin\theta$$

For a simple, cylindrical arm model, the force in the deltoid muscle, $F_{deltoid}$, can be calculated as shown in Eq 6. Other models of the arm, such as a truncated cone instead of a cylinder, will have slightly different equations.

(Eq 6) $$F_{deltoid} = \frac{2F_{arm} + 4F_{load}}{\sin\theta}$$

The freshmen can experimentally test their model in lab by lifting different weights (F_{load}) and comparing the calculated deltoid force, $F_{deltoid}$, with an estimate based on the cross-sectional area of their deltoid muscle. Although there is some variation in published values, a reasonable value of maximum muscle force per unit area is 30-40N/cm^2. A cross-sectional picture of the arm through the deltoid, something many of the students get to see in an imaging lab, can provide an estimate of the cross-sectional area of the deltoid, and consequently maximum deltoid force [15].

The arm model demonstrates that based on the free-body diagram, the deltoid muscle force is significantly greater than the load that can be lifted. For a cylindrical model of the arm, the force in the deltoid is approximately fifteen times the lifted load, assuming an angle, θ, of approximately 15°. In other words, lifting a ten pound weight requires 150 pounds of force to be generated by the deltoid muscle. One of the main points that students learn with their arm model is that not all variables are equally important. Students can demonstrate this mathematically by plotting the change in force that would need to be generated by the deltoid muscle in response to changes in arm length, shape, angle of insertion of the deltoid muscle, and point of insertion of the deltoid muscle. Males have a mechanical advantage due to the fact that their deltoid muscle is inserted closer to the elbow than for females. Even with the same cross-sectional area, and consequently the same maximum force in the deltoid, a male student can lift more weight simply due to physics, as demonstrated by the free-body diagram.

After the development and testing of the model of the arm, the teams should be able to answer the following questions:

- What design criteria have you established for a prosthetic? This is best answered using a sketch with the approximate length, weight, and shape as well as muscle attachment points.
- How well did your experimental data correspond to your model? Were you able to predict the amount of weight you could lift based on your model?
- Some of the variables in the arm model include length, weight, shape, points of muscle attachment, etc. Which variables are the most important (i.e. how does the force on the deltoid change if you change a variable such as arm length versus arm weight by 10%)?
- What happens if you double the weight held by the arm, change the shape of the arm, etc.?
- What additional design criteria do you need to include motion in your prosthetic? Specifically, does the arm need to be stronger to throw a ball than it does to hold the ball?
- How can a model help with the design of an experiment?

The comments in Table 3 reflect whether the arm model prepared students to develop their own model.

Table 3: Student Comments on the Arm Model

Developing a model of an arm demonstrated, somewhat convincingly, that biological systems can be modeled with math and physics. I will never doubt the importance of a basic physics course again.
This course introduces the basic aspects of modeling and design. Through all of the experiments, we have step by step learned how to develop our ideas, build our own mathematical model and assumptions, design our experiment and test, and analyze and interpret data.
This was actually very cool. After the calculations and being able to test it out (and seeing it was accurate!!) was awesome. I recommend doing this again. I would definitely need help modeling other physiological systems, but am definitely more confident after the module.
I could design a very rudimentary mathematical model for a basic system, however I don't think I have enough experience for anything advanced. My group learned to develop models by talking through project backgrounds with my TA. He always had us interact in his lesson, asking us leading questions to get us to the models.
The arm model lecture was certainly very helpful and it's where our group learned mostly how to develop our own model for our independent project. I feel somewhat comfortable starting a model of any physiological system.
this model allowed me to realize that we have developed the skills to approach almost any model.
Steps: Make a bunch of assumptions Make your model Test your model Revise your model

Table 3 continued: Student Comments on the Arm Model

I definitely feel more confident starting a model of physiological systems, but would still not be perfectly comfortable doing it.
I think that we are somewhat ready to start a model of a physiological system, but I feel that doing the project independently will be different than doing it with my teammates.
I think this was a good exercise in learning to model complex systems like an arm. We started off with fairly simple assumptions and added in more details later on.

Many of the freshmen build on the concepts learned in developing an arm model in their final project. Individually analyzing each of the variables within the free body diagram helps students to understand the power of using a computer model to determine which variables have the largest impact.

Module 3: Model of the Cardiovascular System

Cardiovascular disease is responsible for one in four deaths in the United States [16]. Symptoms of cardiovascular disease include hypertension, narrowing of the blood vessels due to atherosclerosis, and electrical and mechanical problems with the heart itself. Modeling the flow of blood through the body allows clinicians to study the impact of individual factors, such as a blocked blood vessel, on total peripheral resistance and consequently blood pressure.

This module is designed to model the cardiovascular system in multiple ways:

1. Electrically: a circuit models total peripheral resistance and the effect of a change in resistance to flow through series and parallel paths

2. Mathematically: dimensional analysis is used to determine the relationship between flow and tube radius, length, viscosity, and pressure gradient in a single blood vessel.

3. Control Theory: a negative feedback control loop is used to model the blood pressure control system by activating the baroreceptor reflex and measuring the resulting change in heart rate at an amusement park

The cardiovascular module begins by having the freshmen sketch the flow of a red blood cell through the circulatory system, starting at the left ventricle. The sketch should include pathways to different organs (skeletal muscle, brain, intestines, and heart) on the journey back to the heart. The key point is for the students to realize that the circulatory system has many parallel pathways, and that the flow through these pathways can vary depending upon the resistance. Asking whether there are other circuits with flow through parallel pathways quickly leads students to the idea of an electrical circuit. The beauty of using an electrical model of the circulatory system is that there are already equations for electrical circuits, specifically Ohm's law and Kirchoff's law. Modeling the circulatory system as a circuit allows us to use these same equations to analyze blood flow in series and in parallel. This model can predict increases in total peripheral resistance (R_{total}) due to removal of a kidney, and decreases in R_{total} due to the vasodilation which occurs during exercise.

Figure 7 summarizes the steps involved in developing an electrical model of the circulatory system. In this model, the pulmonary system is neglected and only the systemic circulation is shown.

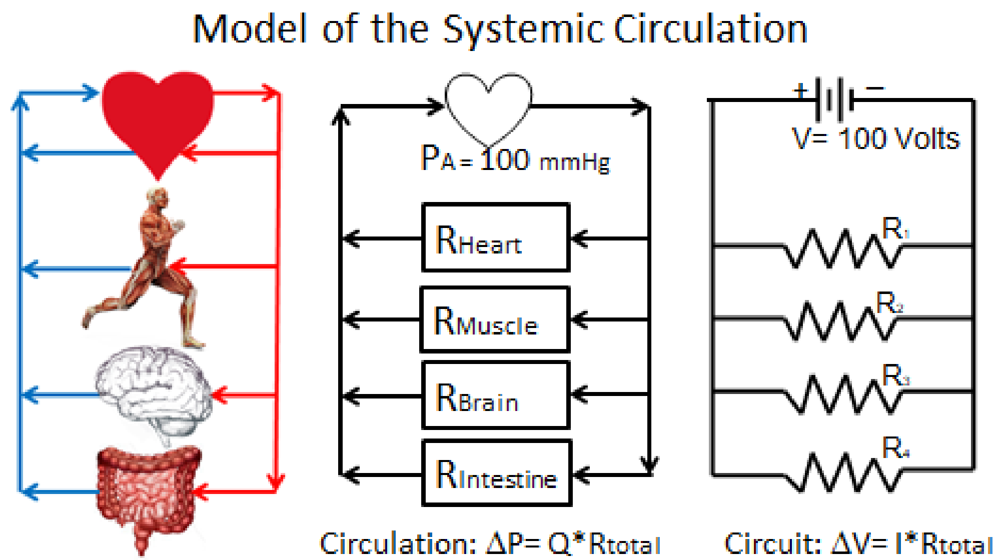

Figure 7: Three models of the systemic circulation depicting the steps in using an electrical model to quantify blood flow through four parallel beds, the heart, skeletal muscle, brain, and intestines, with varying resistances, R_1, R_2, R_3, and R_4.

Mathematically, when resistors are added in parallel, the total resistance decreases as shown by Equation 7:

(Eq 7) $$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}$$

One of the results from the model is that students realize that the total resistance of the circuit is less than the resistance through any single pathway. In other words, $R_{total} < R_1$, and $R_{total} < R_2$, etc. Replacing the general resistances with blood flow through a specific organ, Equation 7 can be re-written as Equation 8 below, which calculates the total peripheral resistance (TPR) assuming only four parallel pathways (gut, brain, skeletal muscle and heart):

(Eq 8) $$\frac{1}{TPR} = \frac{1}{Rgut} + \frac{1}{Rbrain} + \frac{1}{Rskeletal\_muscle} + \frac{1}{Rheart}$$

Using their earlier analysis, the students can calculate that the resistance to blood flow through the brain, R_{brain}, is greater than the total peripheral resistance: $R_{brain} > TPR$. The blood flow through different organ beds can be modeled by using an electrical circuit and applying the analysis above. A short video (less than five minutes) posted on Blackboard provides hands-on examples of how to build a circuit, connect it to the power supply, and measure voltages with a multimeter as shown in Figure 8.

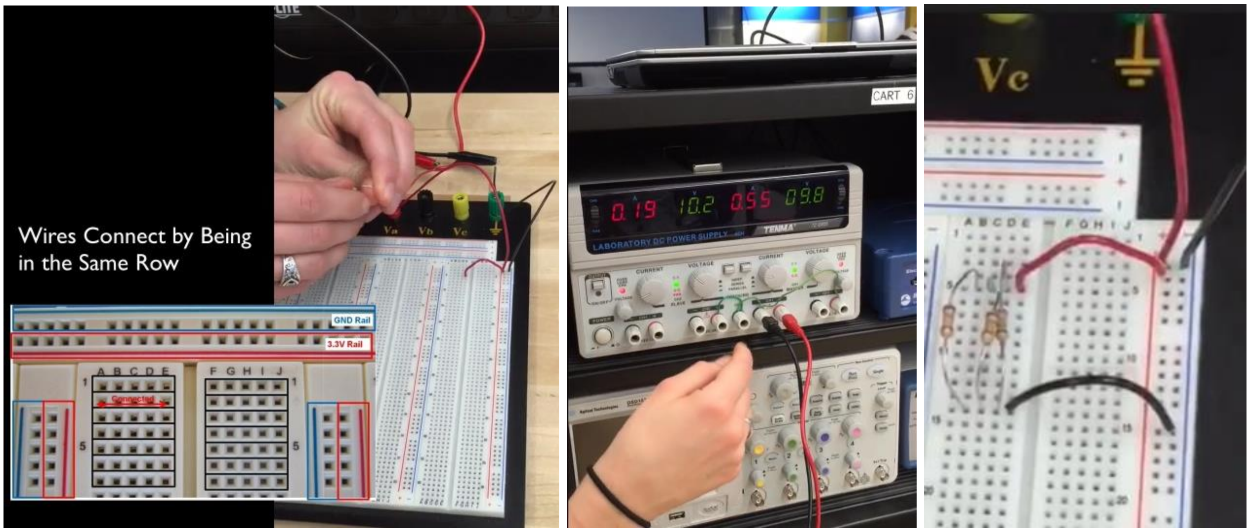

Figure 8: Short videos posted on Blackboard guide students through the process of building a circuit, using a power supply and multimeter, and adding resistors in series and parallel to model flow through the circulatory system.

While the electrical circuit model provides a realistic tool for studying the entire circulation, it does not give information on the factors which cause a change in resistance within a single blood vessel. One way to determine the physiological mechanisms which change resistance within a single vessel is by using dimensional analysis. Dimensional analysis involves listing all possible variables (with their units) to determine the relationships between the variables. The coefficients of the known and unknown variables are compared. The variables involved in flow and their units are listed in Table 4. The coefficients have been assigned as depicted in Equation 9.

Table 4: Using Dimensional Analysis to model flow through a single vessel

VARIABLE	UNITS	COEFFICIENT
	(m=mass, l=length, t=time)	
flow	$l^3\ t^{-1}$	
pressure	$ml^{-1}t^{-2}$	A
length	l	B
radius	l	C
viscosity	$ml^{-1}t^{-1}$	D

Students start by guessing which variables might affect blood flow, such as tube radius, tube length, fluid viscosity, and the pressure gradient. They might also include variables which do not factor into Poiseuille's Law, such as temperature. In this way, they learn that any extra variables should drop out of the equation at the end.

The exact relationship is unknown, so coefficients are used for the exponents as shown in Equation 9.

(Eq 9) $\text{FLOW}\ (l^3\ t^{-1}) = f\,(\text{pressure}^A, \text{length}^B, \text{radius}^C, \text{viscosity}^D) = (ml^{-1}t^{-2})^A\ (l)^B\ (l)^C\ (ml^{-1}t^{-1})^D$

Exponents can be equated for each of the three basic units (mass, time, and length):

1. mass: $0 = A + D$ therefore $A = -D$
2. time: $-1 = -2A - D$ therefore $A = 1, D = -1$
3. length: $3 = -A + B + C - D$ therefore $B + C = 3$

Dimensional analysis produces the three equations above for the coefficients of mass, length, and time with four unknown coefficients (A, B, C, and D). Solving equations 1 and 2 yields that flow is directly proportional to pressure (A = 1), and inversely proportional to viscosity (D = -1). Equation 3 provides a relationship for the sum of the coefficients of length and radius together (coefficient for length + coefficient for radius = B + C = 3). Students can experimentally determine the actual coefficients (B = -1 and C = 4). Before performing any experiments, students predict whether flow should increase or decrease as the tubing *length* increases and whether flow should increase or decrease as the *radius* increases. Predicting the sign of the coefficients, B and C, requires using intuition and experience, core components of modeling.

In summary, dimensional analysis yields the following relationships:

(Eq 10) Flow α Pressure (A = 1) Flow α 1/viscosity (D = -1)

The lab has a constant pressure reservoir and PE tubing of different lengths and diameters as shown in Figure 9. Students design experiments to determine the correlation between flow and length, and between flow and diameter. Plotting the relationship between flow versus radius, and flow versus length, provides the data needed to determine the coefficients for radius and length, namely "4" and "-1", respectively. The combination of dimensional analysis and experimental results yields Equation 11, which is Poiseuille's law for flow, where:
μ = viscosity, r = radius, l = length, and ΔP = pressure gradient.

(Eq 11) $$Flow = \frac{\pi \Delta P r^4}{8\mu l}$$

Often the most surprising result for the students is the powerful relationship between flow and radius. Their data show that doubling the radius increases flow sixteen-fold. When we ask the students which of the variables in the relationship for flow can be changed during exercise, they realize that the pressure gradient changes very little, and the length of our blood vessels and viscosity of our blood cannot change at all. The only variable that can be changed during exercise is blood vessel radius. However, just a small change in radius causes a tremendous change in blood flow to an organ.

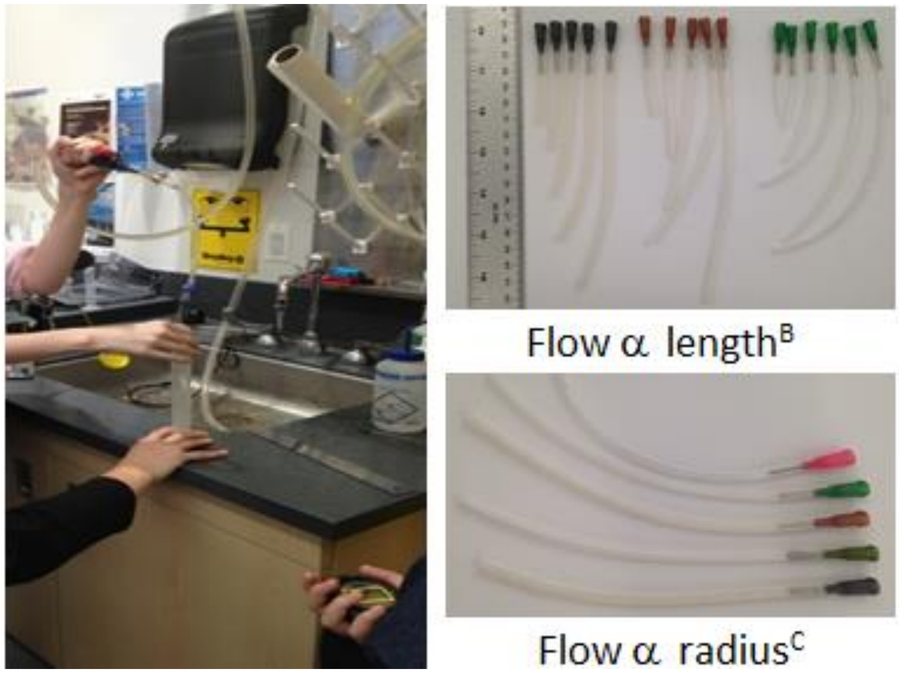

Figure 9: Set-up to measure flow through tubing. Flow is measured using a constant pressure reservoir at a height of 1.25 meters (left), through tubes of different lengths (top right) and diameters (bottom right) to experimentally determine the exponents in Poiseuille's Law.

The final component of the Cardiovascular Module is a fun, team building field-trip to Six Flags Amusement Park in Largo, Maryland, about an hour drive from the Johns Hopkins campus. Students receive a lecture, and demonstration, on the baroreceptor reflex and its role in the control of blood pressure. During the demonstration, students measure their heart rate in both a standing and head down position. Figure 10 illustrates the negative feedback control of blood pressure due to the baroreceptor reflex. When students are in the head down position, the pressure sensed by the baroreceptors is increased, causing a signal to be sent to the brainstem indicating that blood pressure is too high. The cardiovascular system compensates by lowering the heart rate. As the head is raised, heart rate goes back up to normal.

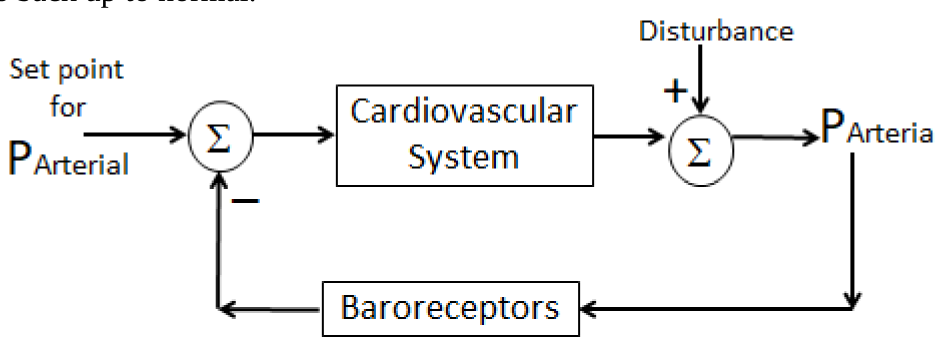

Figure 10: Negative feedback control loop for the baroreceptor reflex control of arterial blood pressure. The set point for arterial pressure is ~ 100 mmHg. If the pressure sensed by the baroreceptors is too high ($P_{Arterial}$ >100 mmHg), the cardiovascular system will decrease heart rate and total peripheral resistance to decrease $P_{Arterial}$.

Students test this reflex on multiple rides, including a 140 foot straight descent known as the "VooDoo Drop" as shown in Figure 11. The Johns Hopkins University Design Teams built equipment specifically for these experiments. Known as SHARDs (**S**imultaneous **H**eartrate and **A**cceleration **R**ecording **D**evices), these devices store the students' heart rate and the ride acceleration in an easily analyzed file [17]. The freshmen complete an online course on "Human Subjects Research" to become familiar with the Internal Review Board (IRB) so that they can determine whether or not they wish to record their own heart rate data. The experimental protocol for this field trip has received IRB approval for over fifteen years.

Figure 11: Six Flags trip: Students test their baroreceptor reflex at Six Flags Amusement Park by simultaneously measuring heart rate and acceleration. The SHARDs (Simultaneous Heartrate and Acceleration Recording Device) are indicated with the red box on the Superman roller coaster (left) and 140 ft free fall on VooDoo Drop (center). The fourth generation SHARD is shown at right.

Upon completion of the three modeling exercises, students should be able to answer the following questions about the cardiovascular system:

- What factors are involved in the control of blood flow?
- What is the relationship between flow and tube radius? Between flow and tube length?
- What happens to flow if you add tubes in parallel? Tubes in series?
- Draw an electrical model of the circulation. How would your model account for an increase in radius? Length? Blood vessels in parallel? Blood vessels in series?
- How does heart rate, resistance, and blood pressure change when we exercise?
- How does the baroreceptor reflex control blood pressure at rest, during exercise, and on an amusement park roller coaster?

In the end-of-semester anonymous survey, students were reminded that the cardiovascular system was modeled in three ways:

1. Electrically to demonstrate the shift in blood flow from one organ to another
2. Mathematically using dimensional analysis and tubing experiments to predict flow through a single tube
3. Using negative feedback to model baroreceptor control of blood pressure

The students were asked whether using three very different models helped their understanding of the cardiovascular system.

Table 5- Student Comments on Cardiovascular System Models

Like any other human physiological system, the cardiovascular system is complex, with an intricate control and regulatory system. By modeling the system three different ways, we were able to see the regulatory system at three different levels: local (individual vessel); regional (organ network); and global (human body). Doing so provided a more comprehensive overview of the system.
Looking at the cardiovascular system through the three different models was definitely useful in terms of understanding the underlying concepts behind how the cardiovascular system works.
It demonstrated the pros and cons of using different systems to model the same behavior. I would improve this project by emphasizing the circuitry portion, as it was the part that was least understood by most students initially.
The cardiovascular system project was very useful, and I found it fun. We were able to simplify the cardiovascular system in different ways and experimented based on the models. The six flags trip was extremely fun, as well as educational.
I thought it was very interesting at the end when we were able to combine and integrate the data and conclusions we were able to draw from all three experiments to model the cardiovascular system. It taught me that to understand something completely I not only have to look at it based on the individual components, but I also have to look at how these individual parts are related to and work with each other.
Honestly, the flow system probably allowed me to understand it best, though I can see why some people learn different ways and prefer different methods. I do wish that the Matlab was a bit more comprehensive for people like me who had no coding experience prior.
Looking at the cardiovascular system in three separate ways helped my understanding by greatly simplifying the complex system and allowing me to look at how the individual components work before putting them together. For example, it was helpful to model the blood vessels themselves using Poiseuille's Law and then determine the relationship between the acceleration and heart rate, and finally put it all together with the concept of the baroreflex. This project could be improved by possibly giving us more instruction on how to use the power source for the circuit section because we spent a large amount of time trying to get it to work
Yes, I think the cardiovascular model was one of the most coherent and complete projects of the entire course. The three parts illustrated how many ways one complex system could be modeled to learn different information

The model of the cardiovascular system is the third of the three physiological models. At this point in the semester the freshmen have become more comfortable with developing models and designing experiments to test them. Just prior to their field trip to Six Flags we ask the teams to submit their final projects proposals for review.

Module 4: Foam Core Design Project

Interspersed between the first two models is a fun team-based design project. After an introductory lecture on the design process, students are ready to brainstorm on ways to move a ping-pong ball in the most exciting, yet automated, mechanisms possible. Each team constructs two different devices to transport a ping-pong ball three meters along a horizontal surface. In this project, students learn the value of testing their ideas. Inevitably, the teams that do the best in the actual competition are the ones which allowed time to trouble-shoot and even re-design if necessary. Since a substantial portion of the grade is for creativity, students need to weigh the advantages of moving the ping-pong ball simply, such as down a ramp, against potential failure of a more complicated device.

Grading has three components, each worth a third of the final project grade:

1. Each team gives a two-minute “elevator pitch” describing their devices, the physics used to move the ping-pong ball, and how long it should take the ping-pong ball, theoretically, to travel the six meters.
2. Each team demonstrates their project during an outside (weather permitting) competition. Teams receive extra points for spirit, including costumes and music. Audience participation is strongly encouraged.
3. Each team keeps a detailed lab notebook, which is graded based on demonstration of multiple ideas with sketches and physics calculations, as well as prediction of ball speed using the final designs.

Success requires a combination of creativity, presentation skills, modeling prowess, the ability to predict results, and, of course, device triumph. Most student teams pick a theme for their designs, such as super heroes, Star Wars, the jungle, an amusement park, pin-ball machine, or a ski slope, just to name a few. The project rules and materials are listed in Table 6, and illustrated in Figure 11.

Table 6- Foam Core Design Project Rules and Supplies

Foam Core Rules
Students have a strict limit of six hours in lab to build their designs.
The device must be able to be reused, it cannot be destroyed while transporting the ball.
Team member's hands may never touch the ball (points off if the ball needs some “taps”)
At least one, and potentially both, devices must “roll”.
The device must be self-propelled.
The time it takes to move 3 meters twice must be under three minutes.
Supporting team members may only cheer or otherwise urge on their teammates.
Every team member must make sure that this project is FUN! Don’t take yourselves too seriously.
Foam Core materials
Foamcore, 5 mm thick, 30” by 40” per sheet; two sheets per team.
Rubber bands, 5 per device, ten per team, (no more than 2 extra large).
Construction Paper, as desired, for color. Paper may not be used for support.
Wooden dowel, < 8 mm diameter, 91.4 cm length, two per team.
White or hot melt glue, used as an adhesive only.
Rulers, protractors, scissors, exacto knives, as needed

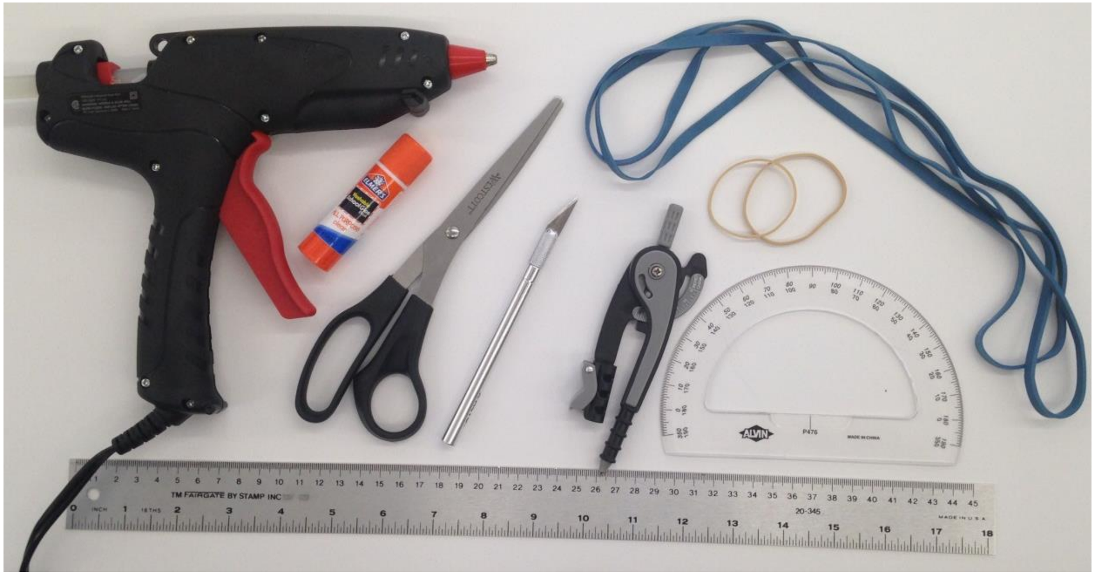

Figure 11a – Supplies available to the students for the foam core project include glue guns and glue sticks, Exacto knives and scissors, measurement tools (ruler, protractors), large and small rubber bands, two wooden dowels and two large pieces of foam core.

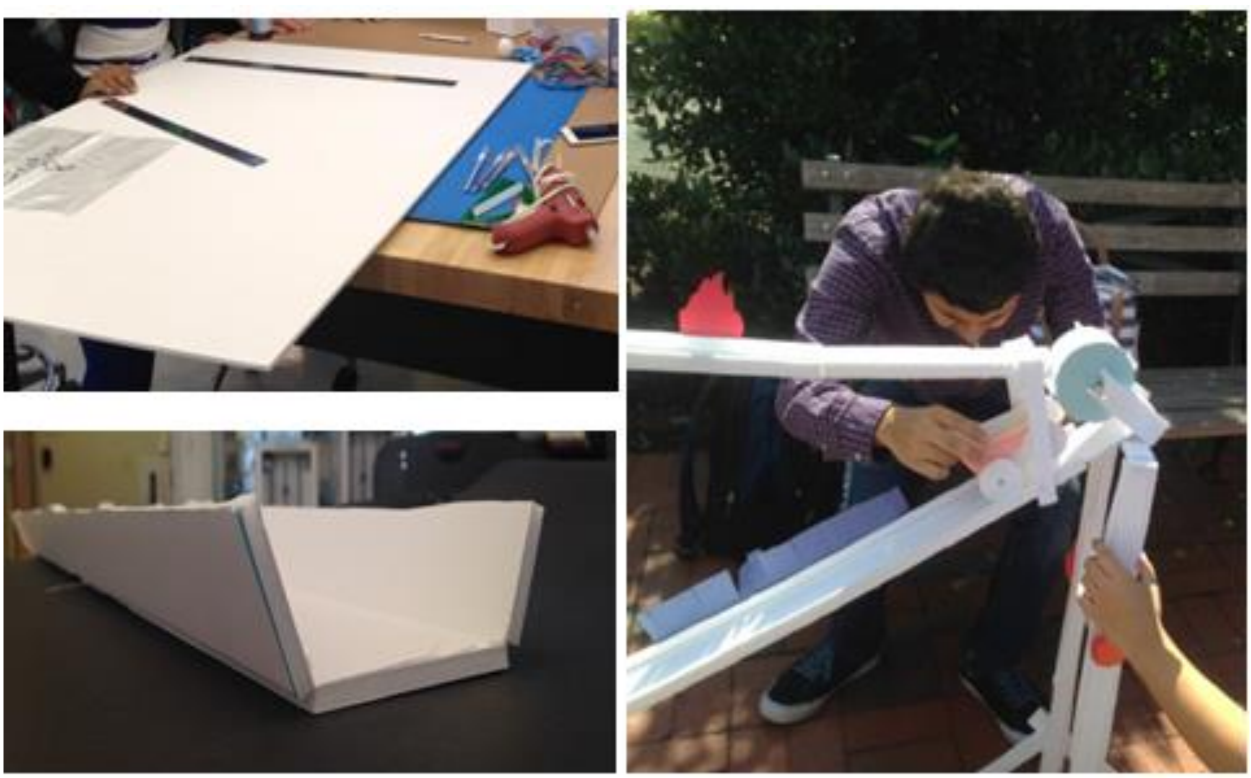

Figure 11b –Students start assembling their foam core devices in the design studio (top and bottom left), and finish with the final touches outside (right)

Figure 11c –One of the design constraints is portability. Students need to move their foam core devices from the design studio (left), down a flight of stairs, and outside (right).

One of the most important rules of the foam core project listed in Table 6 is the strict time limit. There is simply not enough time to make a perfect device, which teaches the value of allotting testing time into the schedule. Table 7 lists some of the students' comments regarding the learning objectives for the foam core project including; team-building skills, improvising, prototyping, testing, time-management, and the realization that prototypes do not work as planned.

Table 7- What Did Students Learn about the Design Process from the Foam Core Project?

This was a difficult but overall fun assignment. Prototyping and building does not always end up as expected and change is necessary.
I learned the most about the importance of testing your prototype. Although it seemed our design would work based on math, we were forced to go back and add supports because our calculations included assumptions and did not account for friction which was significant when working with foam core boards.
I learned more about physics than anything else for the foam core design competition
This was my favorite as I had never before brainstormed and then built something. I learned how to evaluate the pros and cons of several possible designs.
I learned that things often times don't work out, and you have to be able to adapt and change rapidly.
Presentation was good for skill... It taught us teamwork... Unfortunately our cycle failed somewhat but that's part of the process as well
We learned a lot about brainstorming, but did not really get a chance to prototype and learn from our mistakes through repetition.
I had so much fun and learned so much from foam core. Going into this process I knew that it was essential to plan out our build time, and even with all the planning we did, we still basically ran out of time, which was definitely important.
I learned that a lot of testing and improving is really necessary for success.
The foam core project was valuable because there were many curveballs. These unexpected challenges made me more flexible and taught me how to overcome adversity when working on a project.
It was fun, but it presented challenges with working together with a team

Table 7 continued - What Did Students Learn from the Foam Core Project?

I think it would have been better to emphasize the use of the design process when presenting students with the foam core project, so they understand that the most important part of the project is the method of tackling the problem rather than the foam core project itself.
It was difficult to turn an idea into reality. There were a lot of things that needed to be considered.
i loved the foam core! i learned that your ideas don't always work so improvising is really important, and being ok with changing ideas is really good.
This was a great module to learn the design process, and we went through all the steps. However, I wish we had more time to test and prototype. The time crunch meant glossing over those two key steps, which resulted in a lot of failures on final presentation day
I think the foam core project is what really helped me develop my team working skills for BME. It taught me how to be accommodating and encouraging of other people's ideas, and also how to speak up when I had ideas.

Most importantly, the introduction to the design process proved crucial for the final projects. Many of the students designed equipment using the 3-D printers, built circuits, or developed computer programs, all of which require time for testing and trouble-shooting. Working through the design process using foam core provided the freshmen with enough of the fundamental design concepts needed for success on their more complex final projects.

Module 5: Final Independent Project

Based on the end-of-semester surveys, the highlight of the semester is the final independent project. Draft project proposals are submitted early in the semester for review and include background information, the hypothesis/model, a free body-diagram if appropriate, possible experiments to test the model, and a list of equipment needs. The proposals are discussed by faculty, teaching assistants, and lab managers, and we provide guidance to the students on which ideas we think are feasible with finite amounts of time and resources. The final project may be a completely new idea, or it can be an extension of a previous project.

The complexity of the final projects demonstrates the value of working through the previous four modules. Students not only develop a model, they often consult with faculty experts throughout the university, write their own computer programs, and build their own experimental testing equipment. Table 8 lists the projects from the fall 2017 freshmen (n=116 students, 23 teams).

Table 8 - Final Projects for Freshmen Modeling and Design (Fall 2017)

Modeling Hypercholesterolemia
Osteoporosis in bones: Using deer legs to estimate Young's modulus
The effect of knee angle on leg lifting and curling strength in adolescent women
Neck Strains for Study Gains? Analyzing the Ergonomics of Chairs On Campus
A Comprehensive Review of Grip Strength: the Influence of Hand Span, Height, Weight, Gender, Hand Dominance and Strength Training on Grip Strength
Analysis of Systematic Weight Distribution at Varied Crutch Stride Distances
Rod and Cones and Headlights, Oh my! Study to determine the color/wavelength of light that would best prevent the drivers of oncoming vehicles from being blinded by high-beam headlights
Impact of high heels on ankle force
Computing and Modeling the Optical Refraction of light through the human lens
Eye love you – modeling the ability of peripheral vision to detect stationary and moving stimuli
Quantifying the Immersiveness of Virtual Reality through changes in heart rate
Ice Skating for all – designing, building, and testing a prototype for wheelchair-dependent people that can be used on the ice in a fun and safe way
Visual and Auditory Stimuli: Reaction Time and Distraction in Two Pathways
Model of Finger Movement
Reducing Finger Injury of Goalkeepers with 3-D Printed Finger Spines - modeling the force of a soccer ball kick on a goalkeeper's hands
Shouldering Through: Work, Force, and the Push-Up
Phonation and Vital Capacity
Over the Top: The Physics of Arm Wrestling
A "Hands-On" Approach: Modeling Strain and Stress in the Wrist
Working Hard or Hardly Working? How accurately does EMG reflect the body's work output?
Dizzy and Confused – a sound localization investigation (How accurately can human ears determine the origin of a sound?)
You might want to sit down: determining the relationship between relative elevation, heart rate and blood pressure

Once the proposals have been thoroughly vetted and approved, the students have three weeks to complete their final projects. The projects are presented at a poster session, with refreshments, and the event is open to faculty, friends, and family. Guidelines and videos on preparing and presenting a poster are posted on Blackboard, as shown in Figure 12.

Figure 12: Freshmen preparing their poster (top left).”Create a Poster” guidelines posted on Blackboard (top right) Short videos posted on Blackboard guide students through the poster presentation process (bottom). During the events, students present their results and answer questions from faculty, teaching assistants, upperclassmen lab managers, peers and invited friends and family.

By the end of the semester, the freshmen have worked together through enough projects so that they know each team member’s strengths and can divide the work successfully. Upperclassmen lab managers and teaching assistants are a crucial component in ensuring that every team gets the individualized help they need to succeed. The depth of insight the students displayed in their mathematical modeling, experimental design, statistical analysis, and final poster presentations demonstrate the tremendous learning which took place throughout the semester.

The end-of-semester survey asked about the most difficult and fulfilling aspects of the final project. The comments in Table 9 indicate that by the time they had completed the final project, students appreciated the value of working in teams on open-ended questions.

Table 9 - Student Comments on Final Projects

The independent project was my absolute favorite part of this course. It was most challenging figuring out how to quantitatively analyze our data. This project was most fulfilling because my team came up with a topic that we were all excited about that we were really proud of.
The most difficult part was learning enough MATLAB to run the simulation but this was also the most fulfilling as it allowed us to learn how to code much better and apply the math we know to real-world systems!
The most fulfilling aspect of the project was having statistically significant results that matched our hypothesis and the resulting potential for us to develop our design further.
Determining the actual project that we could do in the beginning was the hardest. The most fulfilling aspect was analyzing the data collected and seeing that our idea worked and was statistically significant.
The most difficult part of our final project was designing our device. The most fulfilling aspect was seeing our design work and seeing our hard work pay off.
The most difficult part of our project was thinking of an idea. The most fulfilling part was seeing the final poster presentation. Although our project wasn't groundbreaking, this was my first academic poster. I sent it to my family group chat and was so proud of what I accomplished
The most difficult part was modeling our project without the usual given background information from the lab. It was most fulfilling to see our data follow our hypothesis even though the project was relatively new and had no obvious answers.
This was the best part because we were able to model whatever we wanted. The most fulfilling aspect is looking back and knowing that we were able to model something that was daunting at the beginning.
The most difficult part of this final project was 3D printing the segmented finger spines. We had a lot of failed prototypes and not a whole lot of experience with 3D printing. Overall, it was pretty successful. The most fulfilling aspect was definitely taking advantage of all the resources in the design studio to fulfill both the modeling and design aspects of this course in our final project.
The most difficult part was conducting the experiment and then analyzing the data. The most fulfilling aspect of the final project was finishing and doing the presentation and being proud about the work the group completed.
Modeling the push up and coming up with an equation to fit that model. It was quite fulfilling to present all of our hard work even if it was a bit nerve wracking.
The most difficult part was designing a model and experiment that accurately reflected what our project focused on. The most fulfilling aspect was presenting our model and experiment that we worked so hard on to an audience.
The most difficult part of our final project is to make appropriate assumptions in order to design a suitable measuring method. The most fulfilling aspect is to be able to create our own experiment and evaluate our own ideas and methods.
The hardest part of the final project was figuring out the experiment design and actually getting the data we needed, but it was really rewarding to look at the final project and know that we had tested and obtained results for what we had originally set out to analyze.
The most difficult part was performing statistical tests on the data once it had been collected and drawing meaningful conclusions from the models.
The most difficult part was coming up with an interesting idea that could fill the given time without being too ambitious and difficult to work with. The most fulfilling aspect of the project was being able to apply our previous experience in an original experiment, and getting data that made sense and taught us and others more about how the body works and the intricacies of modeling.
The most difficult part of the final project was figuring out how to generate interpretable data from the raw data that was collected. The most fulfilling aspect was plotting the experimental and theoretical meshes and seeing that both followed the same general trends. It kind of made all the late nights and lack of sleep worthwhile.

All of the modules encouraged students to find creative solutions to open-ended questions. The fact that there was not one "correct" answer but multiple correct approaches was difficult for many freshmen. Some students complained about not knowing what to do in lab. One such freshmen comment is provided below:

"toward the beginning of the course, it was very confusing on what to do or how to proceed with the project"

By the end of the semester students realized that heading in the wrong direction can sometimes be the more valuable learning experience as one freshman noted:

"it is okay to fail. I have not failed enough in my life, I would say, and the idea of failing certainly makes me uncomfortable…However, I know that failing is far more helpful for me intellectually than succeeding, and I embrace the opportunity to fail many, many more times before I get it right."

After completion of the final project, students felt more comfortable with failing and could effectively use the results of their failures to improve their projects.

Grading and Student Feedback

The freshmen Modeling and Design course is taught using team-based projects designed to maximize active learning. For each module, the freshmen have access to a one page summary of essential physiological information, instructional videos on how to use the equipment, and links to relevant resources in physics, math, computer programming, etc. The course director (faculty), teaching assistants, and upperclassmen lab managers encourage the students to work together to solve each module from multiple perspectives.

One of the most important aspects of the course is giving students the opportunity to learn from their failures. We aim to create an atmosphere of creativity and comradery among the BME freshmen. This requires open-ended team-based projects and freedom from grade-induced stress. Detailed rubrics are posted for each of the projects. The goal of the course is for freshmen to become comfortable modeling physiological systems, working in teams, and writing and presenting their work. If a team is not happy with their project grade, they may work with their teaching assistant and lab manager to re-submit the report without penalty. Most of the final grade (95%) comes from team projects as depicted in Table 10.

Table 10- Grading for Team Projects and Individual Assignments

Team Projects	95%
Human Efficiency Model (written report)	15%
Arm Model (written lab report)	15%
Foam Core (Oral presentation, demonstration, lab notebook)	20%
Cardiovascular System Model (written lab report)	20%
Independent Project (poster and presentation)	25%
Individual Assignments (pass/fail)	**5%**
Matlab Assignment	
Attendance at Thursday seminars	
Post-module reflections (five, one for each module)	
Submission of peer reviews (five, one for each module)	
Online certification in lab safety, HIPAA, and Human Subjects Research (IRB)	

In order to ensure that each student is graded fairly, individual grades are weighed using a peer review system [18]. More importantly, peer reviews are used to identify students who are having problems fitting in with their group and address these problems early in the semester. The value of cooperative learning has been well documented and faculty members work with the teams to ensure that each team member is learning and contributing. In any course which is graded 95% through team projects there are bound to be issues. However, most students enjoyed the teamwork, as indicated in Table 11. In the survey, 99% of students felt their team worked well together (n=116, 23 teams), and only 4% would have preferred to work on their own.

Table 11 - Teamwork

How did you feel about working on a team?	%
My team worked well together, shared the work load, and learned from each other	67%
My team worked well together, but we did not share the work load. Some team members always did more or less than others.	29%
My team worked well together, and shared the work load, but I would have preferred to work alone. I do not feel I learned much from my teammates.	3%
My team did not work well together and team projects were stressful.	1%

At the end of the semester, students were asked to rate each module on a scale of 1 to 5, with “1” indicating a useless learning activity, while a rating of “5” was considered an excellent learning experience. Table 12 (n=116) shows the end-of-semester anonymous survey results for the five modules.

Table 12 - Overall Student Rating of the Five Modules

How valuable of a learning experience was this model?					
Rating	Human Efficiency	Cardiovascular System	Arm Model	Foam Core	Independent Project
1= useless	3%	0%	4%	2%	0%
2= poor	9%	3%	13%	6%	4%
3= average	27%	23%	31%	22%	8%
4= good	42%	43%	39%	37%	30%
5= excellent	19%	30%	11%	33%	58%
Average Rating	3.7	4.0	3.4	3.9	4.4

Over the course of the semester, at least 81% of students rated the learning experience as "average", "good" or "excellent" for all five modules. The freshmen felt their final project, the one they chose entirely on their own, was the best learning experience, with 58% rating the project as "excellent". Interestingly, the arm model received the lowest ratings. However, many students stated that they used the ideas from the arm model, specifically developing a free body diagram and analyzing the impact of multiple variables, during their final project. The results from Table 12 are shown graphically in Figure 13, which clearly depicts how much the students felt they learned from their independent projects.

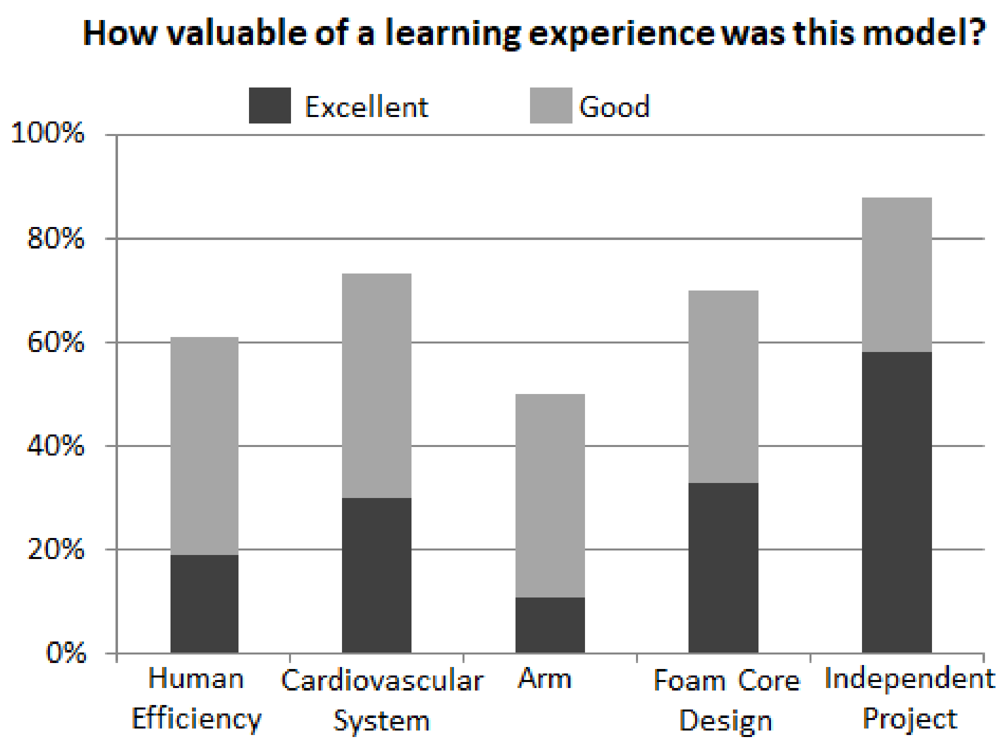

Figure 13: Percentage of freshmen rating each of the five modules as excellent (black) and good (gray). The independent project was rated an "excellent" learning experience by 58% of the students.

We also surveyed freshmen on whether the course had met its goals. Specifically, we asked whether the course provided students:

- a concrete basis for a career choice in BME,
- a solid introduction to modeling physiological systems,
- exposure to the opportunities available within the university through faculty lab visits and guest speakers to assist with developing career goals
- academic and career mentoring through meetings with BME faculty, the course TAs and upperclassmen lab managers.
- opportunities to develop relationships with peers and learn from each other in a cooperative experience

The data in Table 13 indicate that 84% of students (n=116) “strongly agree” or “agree” that the course did achieve these goals.

Table 13- Achievement of course goals

Do you believe the course achieved these goals?	**%**
Strongly Agree	31%
Agree	53%
Neither Agree nor Disagree	11%
Disagree	4%

Benefits to Upperclassmen Lab managers

Intensive upperclassman mentoring of the freshman is one of the hallmarks of Modeling and Design. Each upperclassman (junior or senior) lab manager is responsible for mentoring the same team of five freshmen for the entire semester. Biomedical Engineering at Johns Hopkins University has been using student-led teams successfully for many years [19]. Not only do the freshmen benefit from the upperclassmen mentoring, the upperclassmen benefit as well [20]. The 25 to 30 upperclassmen lab managers are enrolled in the two-credit course “Effective Teaching and Management of Teams” (580.411). The lab managers meet with the course director prior to each of the five modules to review the material, practice using the equipment, and discuss any team issues which might have developed.

According to the results of the Johns Hopkins University anonymous end-of-semester surveys, the upperclassmen lab managers rated the overall quality of the course as 4.6/5.0, where 5=excellent, 4=good, and 3= satisfactory, as shown in Figure 14. This is well above the school level of overall quality of 4.1/5.0. In this same survey, when asked about the intellectual challenge of the course, the average response was 4.14/5.0, which is essentially the same as the school level. Even though the lab managers had been exposed to all of the material as freshmen, they still felt this was an intellectually challenging course. Teaching the freshmen required that the lab managers thoroughly understand the details of both the physiological systems and any equipment used during that module. The survey data also indicated that the lab manager course required an average time commitment of 3.3 hours per week, which is less than most two credit courses.

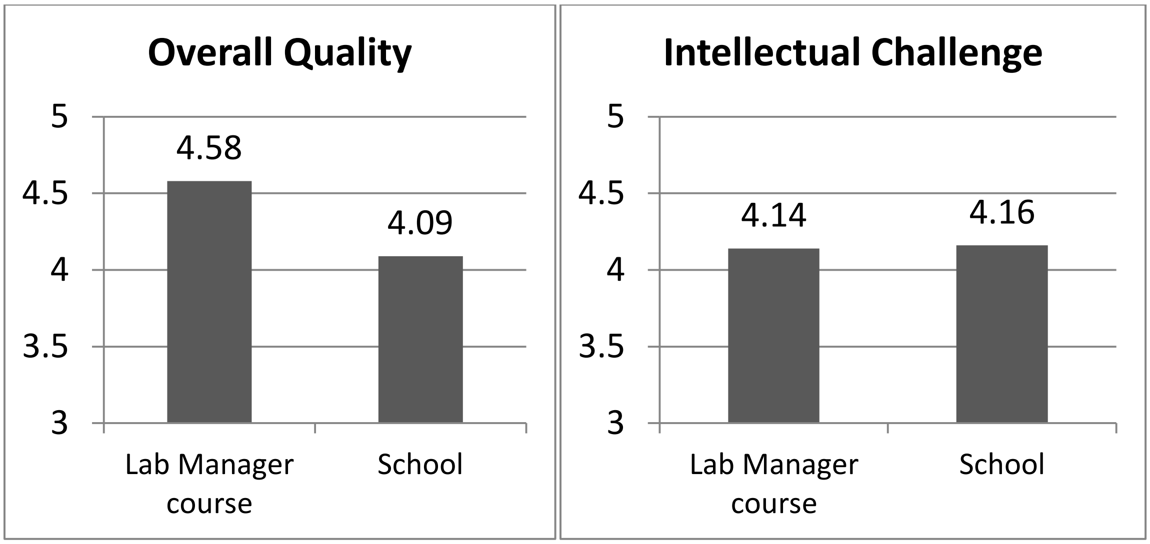

Figure 14: Upperclassmen Lab Managers - Results of end-of-semester surveys administered by Johns Hopkins University. Overall Quality of the "Effective Teaching and Management of Engineering Teams" course was 4.58/5.0, as compared to school level of 4.09/5.0. The Intellectual Challenge was essentially the same as the school level 4.14/5.0 as compared to 4.16/5.0.

The survey results in Table 14 indicate in which skills the upperclassmen felt they had grown as a result of their role as a lab manager. Every lab manager (100%) felt they improved in "providing constructive feedback", a skill which is discussed and demonstrated during the pre-module meetings. The freshmen teams are encouraged, but not required, to send their preliminary lab report to their lab manager for an ungraded evaluation prior to submission for grading. Lab managers felt that working with a small group of freshmen helped them develop leadership skills (77%) and become more confident about speaking in public (62%). It should be noted that all of the lab managers were proficient in Matlab prior to the start of the course, and were quite experienced in analyzing data, writing lab reports, using statistics, and preparing a poster, skills which they had practiced multiple times in multiple courses.

A few quotes from the upperclassmen lab managers include:

"As a senior looking back on this class, I realized how much it actually sets the stage for some upper level classes, which was really interesting. I was able to appreciate each module and understand its significance to biomedical engineering way more this second time around. It was also a blast working with my team"

"For me, the best part of being a lab manager is being able to inspire the Freshmen and share my experience with them as someone who is two years older than them. In addition to being able to help them with their lab, what I enjoyed the most was when they asked for advice regarding

research and classes and future BME career options. I was able to share with them my experiences with research, internships, and classes"

Table 14 – Lab Manager Skills

Please indicate which of the following skills you feel you improved as a lab manager for this course. Check all that apply.	
Providing constructive feedback in a useful manner	100%
Leadership skills	77%
Speaking in public	62%
Developing models of physiological systems	46%
Making assumptions	46%
Designing an experiment	38%
Organizational skills	38%
Analyzing data	8%
Writing a lab report	8%
Using statistics to demonstrate significance	8%
Preparing a poster	8%
Using Matlab	0%

Not only did the lab managers benefit from the being with the freshmen, the freshmen benefitted from working with upperclassmen. Survey results indicated that 93% of the freshmen felt "My lab manager was a great resource and helped us obtain and analyze our data in lab." Lab managers are taught to ask the freshmen questions without giving them the answers. The freshman quote below summarizes the ideal lab manager:

"Our lab manager provided enough guidance to help us but not too much."

In the end –of-semester survey (Table 15), 100% of lab managers indicated they would recommend the course.

Table 15 – Lab Manager Course Recommendation (Fall 2016, n=22)

Would you recommend this course to other BME students?	
Yes - I would recommend this teaching experience to everyone in BME.	82%
Yes - But I would only recommend this course to certain people	18%
Somewhat - only students interested in teaching would benefit from this course	0%
No - I did not think this course was useful for me personally	0%

Over 90% of our BME students engage in undergraduate research, and most have summer internships. The lab managers provide crucial mentoring on obtaining a lab position, deciding on a focus area, finding a summer internship, and choosing extra-curricular activities. The relationship between the students and lab managers extends well beyond the classroom, often for years.

Conclusions

During an eight-year period, from 2007 through 2014, freshmen/sophomore student retention within the Johns Hopkins Biomedical Engineering program averaged 94% (92% of the females and 95% of the males), These retention rates are certainly much higher than the national average of 50% for STEM, although highly competitive schools have greater retention rates in general, closer to 88% [21]. Both the survey data and the student comments indicate that the freshmen enjoyed working in teams, learned from each other, and were able to solve complex problems as a group that they would not attempt alone. The quality of the final projects, the course survey results, and the high retention rate within the BME program all reinforce the value of exposing freshmen to multiple, complex, open-ended problems their very first semester.

The inclusion of upperclassmen lab managers has proven to be an essential component of the course's success, providing crucial guidance during the modules and mentoring in BME. By the time the freshmen finish the course they have a network of resources and are prepared to get started as biomedical engineers.

Acknowledgement

The author would like to acknowledge the support of the Johns Hopkins University Center for Education Resources for the award of a Technology Fellowship to support BaDoi Phan, Emily Rencsok, and Monica Rex in the development of online videos and handouts for this course.

References

[1] W.C. Wong, E.B. Haase, "A Course Guideline for Biomedical Engineering Modeling and Design for Freshmen." *In: 26th Southern Biomedical Engineering Conference SBEC 2010, April 30 - May 2, 2010, College Park, Maryland, USA.* IFMBE Proceedings, vol 32. Springer, Berlin, Heidelberg Herold K.E., Vossoughi J., Bentley W.E. (eds) https://link.springer.com/chapter/10.1007/978-3-642-14998-6_15

[2] D. Hestenes," Toward a modeling theory of physics instruction." *American Journal of Physics* 55, pp 440-454 (1987) http://aapt.scitation.org.proxy1.library.jhu.edu/doi/pdf/10.1119/1.15129

[3] D. Christensen, "Bringing An Integrative Modeling Experience To A Freshman Biomedical Engineering Course" *ASEE 2004 Annual Conference*, Salt Lake City, Utah. [Online]. Available: https://peer.asee.org/13198

[4] C. L. Dymm , A.M. Agogino, O. Eris, D. D. Frey, L.J. Leifer, "Engineering Design Thinking, Teaching, and Learning", *J Engr. Education*, 94(1) pp. 103–120 (2005) [Online]. Available: DOI: 10.1002/j.2168-9830.2005.tb00832.x

[5] J. Clement, "Model based learning as a key research area for science education", *International Journal of Science*, 22:9, 1041-1053 (2000), [Online]. Available: DOI: 10.1080/095006900416901

[6] D. Jonassen, J. Strobel, C. B. Lee, "Everyday Problem Solving in Engineering: Lessons for Engineering Educators", *J Engr. Education*, 95(2) pp. 139–151 (2006), [Online]. Available: http://dx.doi.org/10.1002/j.2168-9830.2006.tb00885.x

[7] C. L. Dymm, "Engineering Design: So Much to Learn", *Int. J. Engr. Ed*. Vol. 22, No. 3, pp. 422-428, 2006 [Online]. Available: https://www.ijee.ie/articles/Vol22-3/01_ijee1784.pdf

[8] R. H. Allen, W. Tam, A.A. Shoukas "Empowering Biomedical Engineering Undergraduates to Help Teach Design" *Proceedings of the 26th Annual International Conference of the IEEE EMBS* San Francisco, CA, USA, September 1-5, 2004 http://ieeexplore.ieee.org.proxy1.library.jhu.edu/stamp/stamp.jsp?tp=&arnumber=1404435

[9] Prince, M (2004), "Does Active Learning Work: A Review of the Research*", J Engr. Education*, 93(3), 223-231

[10] Felder, R.M. and Brent, R. (2003), "Designing and Teaching Courses to Satisfy the ABET Engineering Criteria", *J of Engr. Education*, 92 (1), 7-25

[11] Prince, M and Felder, R.M. (2006), "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases", *J of Engr. Education*, 95(2), 123-138.

[12] BioPac Systems, Inc. Pulmonary Function Lab I https://www.biopac.com/curriculum/l12-pulmonary-function-i/

[13] A. Guyton, "Regulation of Cardiac Output." *New Engl J Med*, 277:805-812 (1967) http://www.nejm.org/doi/full/10.1056/NEJM196710122771509

[14] M.S. Malhotra, S.S. Ramaswamy, S.N. Ray, T. N. Shrivastav, "Minute ventilation as a measure of energy expenditure during exercise." *J of Applied Phys* Vol 17, No 5 p.775 (1962) http://www.physiology.org/doi/10.1152/jappl.1962.17.5.775

[15] E.J. Jones, P.A. Bishop, A.K. Woods, J.M. Green, "Cross-sectional area and muscular strength: a brief review." *Sports Med*. 38(12):987-94 (2008) doi: 10.2165/00007256-200838120-00003

[16] Center for Disease Control, "Heart Disease Facts" https://www.cdc.gov/heartdisease/facts.htm

[17] R. Yung, M. Mudgett, E. Haase "A Device to Simultaneously and Accurately Measure Heart Rate and Acceleration", *Biomedical Engineering Society Annual Meeting, Minneapolis, Minnesota* (2016) Abstract #2342

[18] Kaufman, D. B. and Felder, R.M. (2000), "Accounting for Individual Effort in Cooperative Learning Teams", *J. Engr. Education*, 89 (2), 133–140 (2000) http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.449.7023&rep=rep1&type=pdf

[19] R. H. Allen, S. Acharya, C. Jancuk, A.A.Shoukas, (2013) Sharing Best Practices in Teaching Biomedical Engineering Design. *Annals of Biomedical Engineering*, Vol. 41, No. 9, pp. 1869–1879. DOI: 10.1007/s10439-013-0781-y

[20] E. Haase, "Enhancing the Freshman Experience with Upperclassmen Lab Managers: a Win-Win Situation", Paper presented at *2017 ASEE Mid Atlantic Section Spring Conference*, Morgan State University, Baltimore, Maryland. https://peer.asee.org/29255

[21] Chen, X. (2013). STEM Attrition: College Students' Paths Into and Out of STEM Fields (NCES 2014-001). National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education. Washington, DC. https://nces.ed.gov/pubs2014/2014001rev.pdf