Hands-on Experiments: Engineering and the Human Body

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Abstract

The human body is an exquisite combination of interacting systems which can be analyzed using multidisciplinary engineering principles. We have developed a series of hands-on modules that introduce freshman engineering students to chemical, mechanical, and electrical engineering principles through application to the human body. Students are engaged in the scientific discovery process as they explore the engineering systems within the human body using exciting hands-on "reverse engineering" methods. The modules explore respiration, metabolism, pulmonary mechanics, the cardiovascular system, work and power, electrical signals, biomechanics, and mechanics of materials. Through the investigation of these systems, students learn basic concepts of mass and energy balances; fluid flow; work, energy, and efficiency; forces and levers; material strength and stresses; and electrical signal processing. This paper describes each module and includes an outline of the relevant measurements, calculations, and engineering principles.

Introduction

This project is an integrated effort by the Faculty of Engineering to develop effective methods for teaching engineering from an applied, multidisciplinary point of view. The basis of the project is the fact that the human body is an exquisite combination of interacting systems which can be analyzed using multidisciplinary engineering principles. We have developed a series of hands-on modules that introduce chemical, mechanical, and electrical engineering principles through application to the human body. Students are engaged in the scientific discovery process as they explore the engineering systems within the human body using exciting hands-on "reverse engineering" methods. This project borrows measurement techniques and laboratory experiments widely used in fields of health sciences and exercise physiology, modified to address engineering principles [1]. This paper provides an overview of all the modules that will be introduced in the Spring 2002 Freshman Clinic course at Rowan.

Rowan University is pioneering a progressive Engineering program that uses innovative methods of teaching and learning to prepare students better for a rapidly changing and highly competitive marketplace, as recommended by ASEE [2]. Key features of the program include: (1)

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multidisciplinary education through collaborative laboratory and course work; (2) teamwork as the necessary framework for solving complex problems; (3) incorporation of state-of-the-art technologies throughout the curricula; and (4) creation of continuous opportunities for technical communication [3]. The Rowan program emphasizes these essential features throughout the curricula, beginning with the introductory freshman engineering course. One indicator of the success of our innovative program is the 85% retention rate of our first graduating class, from entering the program in 1996 to graduation in 2000.

Rowan's two-semester Freshman Clinic sequence introduces all freshmen engineering students to engineering in a hands-on, active learning environment. Engineering measurements and reverse engineering methods are common threads that tie together the different engineering disciplines. Previous reverse engineering projects have involved common household products such as automatic coffee makers [4, 5, 6], hair dryers and electric toothbrushes [7]. This project introduces the human body as a multidisciplinary engineering system that can be (noninvasively) reverse engineered.

Module Descriptions

Module #1: Respiration:

The air we inspire is approximately 21% O_2 and 79% N_2, while the expired gas from the lungs is contains approximately 75% N_2, 15% O_2 and 4% CO_2 and 6% H_2O. The lungs serve as a mass transfer device that separates O_2 and N_2, and allows the exchange of O_2, CO_2, and H_2O. The objectives of this module are (1) to introduce the lungs as a mass transfer device, (2) to use gas analysis to investigate the rate of O_2 consumption and CO_2 production under various breathing conditions, and (3) to perform simple mass balances on the lungs.

Gas sensors are be used to measure the concentrations of inspired and expired O_2 and CO_2. The average volumetric ventilation flow rate is measured using a turbine gas flowmeter. Data are collected during various exercise levels and at rest, with exercise performed on a cycle ergometer.

From the concentration and flow rate data, students calculate the total rate of O_2, CO_2, and N_2 inspired and expired. Students also calculate the rate of O_2 consumption and CO_2 production during respiration using mass balances.

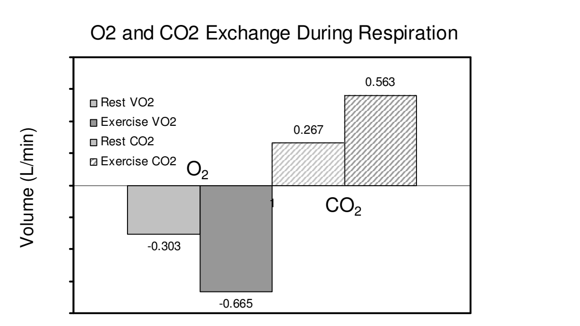

Figure 1. Gas Exchange Rates During Respiration

Typical student results, as shown in Figure 1 reveal that oxygen consumption at rest is about 0.30 L/min, compared with about 0.67 L/min for mild exercise (30W breaking power). The volumetric rate of carbon dioxide consumption is about 0. 27 L/min at rest and 0.56 L/min during exercise.

Students reinforce basic concepts of concentrations, moles, and ideal gas law. Mass balances are learned by application to the breathing process, and students are introduced to process simulation using this simple example.

Module #2: Metabolism
Oxygen consumed during respiration is transported by blood to the body, where it is used by cells to produce energy through the oxidation of carbohydrates and fats from food. The reaction stoichiometry and thermodynamics are well known, and the rate of energy production may be calculated from the rate of O_2 consumption. This energy is used to maintain the function of the body (basal metabolism) and to do external work (exercise). Since the energy expended used during metabolism becomes heat, which is dissipated from the skin, the basal metabolic rate is proportional to body surface area. The objectives of this module are (1) to investigate the chemical reactions involved in metabolism (2) to determine energy expenditure at rest and during exercise from gas exchange measurements, (3) to compare energy value of food consumed with energy expenditure, and (4) to determine the mechanical efficiency of cycling activity.

Energy is released as fats and carbohydrates react with oxygen to produce carbon dioxide and water. The rate of energy expenditure (EE) is related to the rate of O_2 consumption ($\dot{V}\,O_2$) and heat of reaction. For a typical mix of fats and carbohydrates:

$$\text{EE} = \dot{V}O2 \cdot 4.862 \frac{\text{kcal}}{\text{liter oxygen}}$$

From their calculations of the rate of O_2 consumption, students calculate the rate of energy expenditure at rest and during exercise. Metabolic rates are a function of body surface area and are often tabulated for various activities in [J/m^{2}s]. To compare their calculated metabolic rates with literature values, students use a correlation to determine their body surface area in terms of mass M and height H [8]:

$$SA = \left[0.202 \frac{\text{m}^{1.275}}{\text{kg}^{0.425}}\right] * M^{0.425} * H^{0.725}$$

Additional knowledge of the rate of CO_2 consumption permits the calculation of the percentage of calories burned from carbohydrates and from fat [9]. The cycle ergometer used for the exercise test indicates braking power (equal to the rate of work done by the subject). If the metabolic energy expenditure is known, the efficiency of the human body as a machine is calculated by:

$$h = \frac{\text{work done}}{\text{energy consumed}} = \frac{\text{power}}{\text{rate of energy expenditure}}$$

Finally, students determine the energy equivalent of their food intake for one day. By applying the First Law of Thermodynamics, the net change in energy equivalent of body fat is determined:

Change in energy equivalent of body fat	**=**	**energy consumed**	**–**	**daily energy expenditure**

Based on the same typical students results provided in Module #1, the resting energy consumption is 82.8 kcal/h, compared with 184.2 kcal/h for mild exercise. The efficiency of the cycling activity is about 23%.

Table 1.. Gas exchange measurements and calculations at rest and during cycling exercise. : $\dot{V}^{out}$, $y_{O_2}^{in}$, . $y_{O_2}^{out}$, $y_{CO_2}^{in}$, and $y_{CO_2}^{out}$ are measured experimentally at BTPS conditions. $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are calculated at STP. (Ambient Conditions: T=20°C, P=759 mm Hg, RH=47%)

Measured variables				Calculated Variables			
Power (W)	$\dot{V}^{out}$ (L/min)	$y_{O_2}^{out}$	$y_{CO_2}^{out}$	$\dot{V}_{O_2}$ (L/min)	$\dot{V}_{CO_2}$ (L/min)	EE (kcal/min)	**EE (kcal/h)**
0	13.08	0.185	0.023	0.25	0.23	1.38	**82.8**
30	**20.50**	**0.175**	**0.031**	**0.62**	**0.52**	**3.07**	**184.2**

In this module students learn principles of stoichiometry, heat of reaction, mass and energy balances, and dimensional homogeneity. The concept of a correlation is introduced to estimate the body surface area. Concepts of work, power, and efficiency are also taught through calculation of human efficiency.

Module #3: The Cardiovascular System

The cardiovascular module introduces students to the function of the heart as a pump, and to blood as the fluid that transports O_2 to the body. They explore how the heart increases pumping capacity (heart rate and the heart stroke volume) to transport more O_2 to the body. (1) to measure cardiac output (blood flow rate) using the Indirect Fick Method, (2) to measure blood pressure at different elevations, (3) to investigate each term in the mechanical energy balance through application to the cardiovascular system.

Students perform blood pressure measurements using a sphygmomanometer, and measure heart rate at rest and during exercise. Cardiac Output (CO) is determined using Fick's method for Non-Invasive Cardiac Output[10]. This method uses time-dependent measurement of carbon dioxide concentration during carbon dioxide rebreathing for indirect determination of cardiac output.

Each term in the mechanical energy balance below is investigated using their experimental measurements.

$$\frac{1}{2\alpha}\Delta v^2 \quad + \quad g\Delta h \quad + \quad \frac{\Delta P}{\rho} \quad + \quad \hat{W} \quad + \quad \hat{E}_F \quad = 0$$

Hydrostatic pressure effects are investigated by measuring blood pressure in the arm at different elevations relative to the heart as shown in Figure 2.

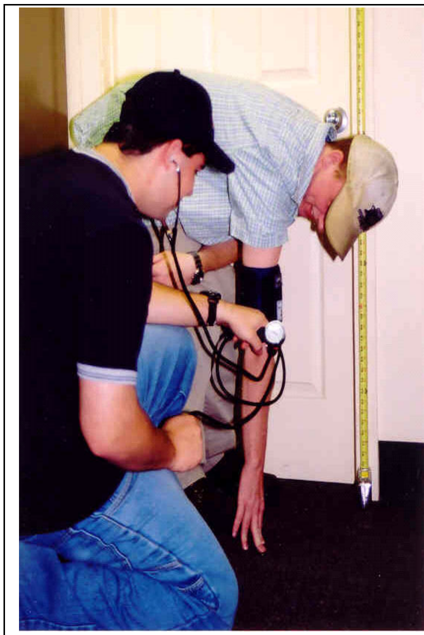

Figure 2. Students measuring blood pressure below heart level. The hydrostatic pressure results in a blood pressure higher than that at heart level.

The interconversion of kinetic energy and pressure is be illustrated through the calculation of pressure changes in an aneurysm and a stenosis (a bulge and a narrowing in an artery, respectively). A stenosis is shown schematically in Figure 3, and calculated values for the pressure decrease at rest and during exercise are shown in Table 2. for these calculations, the blood flow rate is measured experimentally, and typical arterial dimensions are used. The pressure decrease associated with the stenosis causes the stenosis to narrow further; eventually a fluttering can occur as the reduced pressure causes the stenosis to close in on itself.

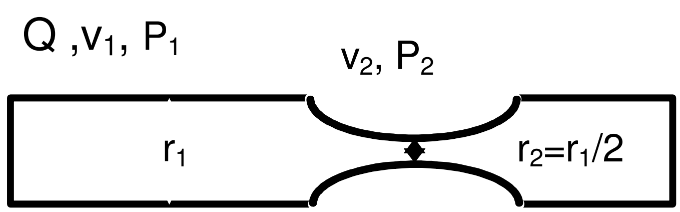

Figure 3. Diagram of a stenosis, or narrowing of an artery, showing local changes in velocity and pressure

Students also discover the linear relationship between heart rate and O_2 consumption as both increase with exercise, as both rise to meet the body's increased demand [9]. .

Table 2. Pressure decrease in a stenosis during rest and exercise. Artery dimensions are typical values taken from literature.

Pressure decrease in a stenosis					
	Q (L/min)	r1* (cm)	V1 (cm/s)	P1 (mm Hg)	P2 (mm Hg)
Rest	4.9	1.6	10	78.3	66.4
Exercise	10.2	1.6	40	86.0	37.0

A typical volumetric blood flow rate is 5.0 L/min at rest, and the average blood pressure of our typical student was 78.3 mm Hg. Assuming that the return pressure is close to zero, the power of the heart is 0.63 W. Similar measurements during exercise reveal an increase in flowrate to 10.2 L/min, accompanied by a slight increase in pressure to 86.6 mm Hg. The power of the heart during exercise is 1.45 W. Since the efficiency of the heart is known to be about 10%, the actual rate of energy consumption is 6.3 W at rest and 14.5 W during exercise, about 8% of the total energy expenditure. Pressure measurements at different elevations above and below heart level reveal that the blood pressure increases about 23.6 mm Hg for every foot below heart level.

Module #5: Electrical Signals from the Heart

The rhythmical pumping action of the heart is controlled by an electrical signal initiated by spontaneous stimulation of muscles in the sinoatrial (SA) node. The rate of these signals is increased or decreased by nerves in response to the body's O_2 demands. These signals initiate depolarization and repolarization of the heart muscle, causing current flow within the torso. An Electrocardiogram is a recording of the electrical potentials between two points on the body's surface, and is commonly used as a diagnostic tool to monitor electrical activity through each part of the heart's cycle. The objectives of this experiment are (1) to determine the pulse rate from an ECG and (2) to determine the effect of signal sampling frequency on the ECG output and (3) to write a simple computer program to calculate the pulse rate from the electrical signal data..

Using a ECG system with electrodes placed on the wrists and ankles, students monitor the electrical potential as a function of time and determine heart rate. Calculation of the time interval between different portions of the wave, as well as the ratio of amplitudes of different portions of the wave will be made. Students will observe differences in ECG outputs with increased or decreased signal sampling rates, and differences in resting versus exercise ECG output. A typical ECG is shown in Figure 4.

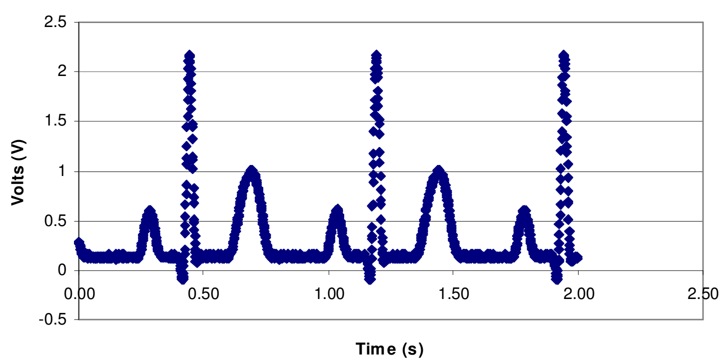

Figure 4. Electrocardiograph. Heart rate can be determined by counting the number of cycles per minute.

Module #6: Work and Power

This module provides an introduction to the calculation of work, power, and efficiency through measurement of light weightlifting exercise. The objectives of this module are (1) to calculate work and power requirements for lifting weights and (2) compute and compare efficiencies of lifting weight with two arms versus lifting half the weight with one arm.

Students record the weight on a bar to be lifted; the total weight is small (10% of body weight). One student lowers and raises the bar from the chest to full extension using both arms. Another student measures the length of the full arm extension and time to complete one repetition. Since the force and distance traveled are both in the vertical direction, work can be calculated as force multiplied by distance and power as work divided by time. Next students take the same measurements using half of the weight and only one arm. The one and two arm bench press lifts are repeated for a heavier weight. The efficiency (weight lifted/body weight) versus the number of repetitions for a given body weight can be calculated and graphically represented allowing students to compare efficiencies of each other as well as the body's efficiency of moving light weights compared to heavy weights.

Students learn how to calculate work, power, and efficiency through simple measurements of force, distance, and time.

Module #7: Biomechanics

Many of the muscle and bone systems of the body act as levers. These levers may be classified as first class (the head), second class (the foot), and third class (the forearm). The objectives of this module are (1) to use equations of mechanics to compute static and dynamic forces and moments produced by the bicep when lifting weights and (2) to examine advantages and disadvantages of the arm as a third class lever versus first and second class levers.

Students first measure the length of the arm segments and compute their mass and moment of inertia. The students model the lower arm as a third class lever with forces from an external weight and muscle force from the bicep. Using equations of equilibrium, the static forces necessary to hold the arm fixed with an attached weight will be calculated. Students determine the effect of the force the bicep must exert as the weight is moved along the length of the lower arm. Students also redesign the arm as a second or first class lever and explain the advantages and disadvantages of these configurations. Using a 3-D biomechanics motion capture system developed at Rowan, students receive acceleration measurements by measuring displacement over time. The students formulate the equations of motion and use the acceleration and mass measurements to calculate the dynamic forces and moments.

Students learn to conduct analysis of forces and moments in static and dynamic conditions.

Module #8: The Skeletal System

Nature has done an exquisite job of engineering a skeletal system to perform a variety of functions such as support, locomotion, protection of internal organs, and chemical storage. Bones are a composite comprising collagen and bone mineral, which contribute tensile strength and rigidity respectively, and allow the bones to provide support while maintaining sufficient flexibility to prevent them from breaking easily. The objectives of this module are to investigate the material properties of synthetic bones and cow bones through (1) measurement of displacement as a function of transverse force and (2) evaluation of stiffness and strength of the materials through the evaluation of Young's Modulus of Elasticity.

The stiffness of synthetic bones is measured using a cantilever bone bender system. Students measure the bone dimensions and the force and deflection of an end-loaded bone. The moment of inertia is calculated using the equation:

$$I = \frac{1}{4}(r_0^{\,4} - r_i^{\,4})$$

The deflection of the bone is related to the applied force, stiffness of the material and the moment of intetia of the object:

$$Dy = -\frac{FL^3}{3EI}$$

The stiffness of the synthetic bone is determined using a plot of applied force vs. deflection.

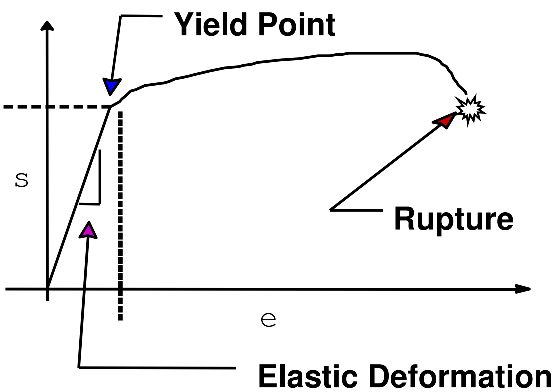

Figure 5. Stress-strain plot used to determine the ultimate tensile strength of bones.

Bone strength of real (cow) bones is measured using a transverse load on simply-supported bones. The stress can be calculated using:

$$s = \frac{FLD}{8I}$$

In this experiment, the ultimate tensile strength is determined increasing the applied force on the bone until it breaks.

Through the analysis of bone materials, students are introduced to tensile and compressive stresses and strength of materials. They gain an awareness of the issues involved in the design of new engineering biomaterials, and compare the properties of real (cow) bones to synthetic bones.

Module #9: Running Shoe Materials

In this module, students investigate the effectiveness of running shoes as shock absorbers for the human body. Students gain an understanding of forces, compression, stress, strain, and mechanical properties of material. The specific objectives of the experiment are (1) to measure axial deformation of different running shoe soles as a function of applied force, (2) to generate Stress-Strain plots as used in the analysis of elastomeric materials, and (3) to determine and compare the Modulus of Elasticity of different running shoe soles.

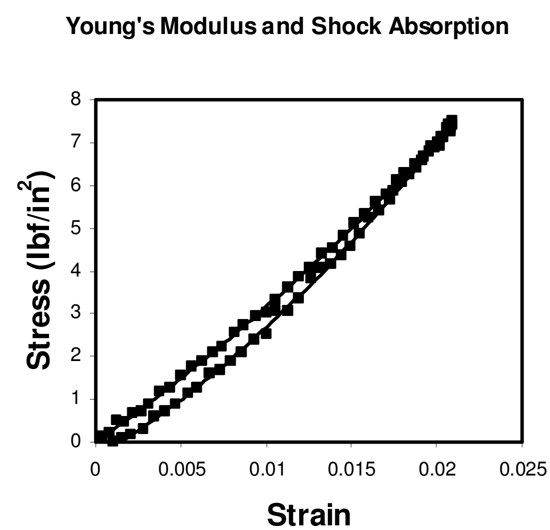

Figure 6. Stress-strain plot for running shoe soles. Modulus of elasticity is determined from the slope of the plot.

An elastomeric material returns back to its original form after undergoing deformation by stretching or compression. Elastomers also become harder to deform as both the deformation and rate of deformation increase. The tissues of the body (e.g., ligaments) exhibit many different types of elastomeric properties. The elastomeric ligaments in the foot effect a 50% energy loss when impacted, significantly reducing the force felt by a runner with each stride. The soles of running shoes are designed to use elastomeric properties to protect the body from impact.

In this module, students measure the displacement of a running shoe sole as a function of applied force. Stress and strain are calculated, and Young's Modulus is calculated from a plot of stress vs. strain. Typical results are shown in Figure 6.

Equipment

For modules 1-4 (respiration, metabolism, pulmonary mechanics and cardiovascular system), an exercise/stress test system was used. The MedGraphics CPXD system includes capability for direct oxygen and carbon dioxide measurement and ventilation rates. System add-ons include pulmonary function testing, indirect non-invasive cardiac output measurement, and pulse oximetry. The system also interfaces with a cycle ergometer (Lode Corvial) for exercise testing. This system was purchased from MedGraphics, St. Paul, MN for approximately $35,000. While this price may be prohibitively expensive for an engineering program to purchase if not used for research purposes, many universities have such equipment available in a physiology laboratory, exercise science laboratory, or medical facility.

The ECG system used in Module #5 (electrical signals from the heart) utilizes a twelve-lead ECG system manufactured by Cardioperfect. The system and associated software interface with the CPXD system described above.

A motion capture system developed at Rowan University is used in the module #7 (biomechanics). The motion capture system comprises a personal computer, motion transmitter ($450), sensor ($220 each), and PC Bird Card for motion capture data acquisition ($1,200).

The equipment for the module #8 and #9 (the Skeletal System and Running Shoe Materials) includes two universal test machines. One is a compression test machine used for testing bone in a three point beam test. The other is a MTS Model 831.10 system, which provides +/- 25 kN of force, +/- 50 mm displacement stroke and dynamic testing rates as high as 200 Hz at low amplitudes, used for testing the elastomer shoe materials.

Summary

We have developed a series of hands-on modules that introduce chemical, mechanical, and electrical engineering principles through application to the human body. Students are engaged in the scientific discovery process as they explore the engineering systems within the human body using exciting hands-on "reverse engineering" methods. This paper provides an overview of all the modules that have been introduced in the Freshman Clinic course at Rowan.

The topics introduced in these modules will be integrated throughout the engineering curriculum. Plans for vertical integration include engineering core courses, laboratory courses, and advanced senior and graduate level elective courses. In addition, a graduate level course in "Engineering Exercise" has been developed by faculty from Chemical Engineering and Health and Exercise Science.

Acknowledgements

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Jennifer Kadlowec is an Assistant Professor of Mechanical Engineering at Rowan University. She has experience in the development of multimedia courseware for dynamics and vibrations and authored ASEE publications of these works. Her research interests are experimental investigation and modeling of mechanical behavior of materials, particularly rate and temperature dependence in elastomers and biomaterials.

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Anthony Marchese is an Associate Professor in Mechanical Engineering at Rowan University, where he has been since September 1996. He has also held positions in industrial and government laboratories at United Technologies Research Center in East Hartford, CT and NASA Lewis Research Center in Cleveland, OH. Marchese has a Ph.D. in Mechanical and Aerospace Engineering from Princeton University. He also holds B.S. and M.S. degrees from Rensselaer Polytechnic Institute in Troy, NY. Marchese's research interests include chemically reacting flows, chemical kinetics, microgravity science, rocket propulsion, fire safety and refrigeration.