Measuring Cardiovascular Alterations During Academic Exercises with Undergraduate Biomedical Engineering Students

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Abstract

As part of our undergraduate training in Biomedical Engineering, we have developed a series of courses, Longitudinal Design Teams, where groups of students at various levels of their education work together to solve problems at the interface of engineering and biology. The teams function under a pseudo-corporate structure which encourages the solution of practical problems through both theoretical and experimental approaches. We report on one set of IRB-approved experiments, in which student volunteer subjects wore Holter© monitors to record instantaneous heart rate alterations induced during an introductory Physics I exam (N=4) and during a class-based engineering competition requiring mild physical activity (N=6). Data was also collected during presentations (N=2) before a panel of faculty members and professionals. In addition, heart rate (N=15) and acceleration (N=9) data were obtained at several amusement park rides, each of which induced an orthostatic stress on the cardiovascular system. All data was analyzed using custom software developed by students that accurately determined instantaneous heart rate using pixel counting methods and without using any signal processing. Average heart rate values were calculated during intervals to examine global trends as well as instantaneous results. Results showed that in general, undergraduate students observed a significant increase in heart rate before an exam as well as during the final minutes of an exam; however, these trends were neither uniform among subjects nor a measure of their academic performance. As expected, zero gravity conditions induced by several seconds of free fall on amusement park rides increased arterial blood pressure while decreasing measured heart rate. During the deceleration phase of the ride students experienced negative "G" forces that induced a precipitous decrease in arterial blood pressure and a concomitant neurally-mediated increase in heart rate. We believe that our Longitudinal Design Team concept is an effective model for active learning. New students entering the department become excited about engineering, have the opportunity to apply theory taught in coursework to real-life problems, and become familiar with the synergetic design process, all while working in a team setting. Upperclassmen apply what they have studied in a culmination of their undergraduate education, learn to communicate information effectively in a way that new students can easily understand, and recognize the individual skills of each contributing team member so that a quality product results.

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1. Introduction

Over the last five years, the biomedical engineering program at Johns Hopkins University has developed a set of undergraduate courses called Design Teams[1]. In these courses, teams of students at all levels-from freshman to senior-work together solving problems involving biomedical engineering design. One of our goals in these courses is to introduce biomedical measurement and experimentation to freshman. Another goal is to empower upperclassmen to be creative in proposing and designing experiments. As a result, a number of team-oriented activities take place in the fall semester, including the following:

1) An experimental protocol was designed with upperclassmen guidance to evaluate the cardiovascular alterations induced during exercise. Flexibility was given to students when designing protocols to promote creative thinking. Teams devised protocols investigating heart rate, body temperature, and blood pressure. Some teams quantified the recovery time taken for each measurement to return to baseline levels, and modeled this as an exponential decay. Other teams normalized observed responses to baseline or maximum values. Upperclassman students presented the results and fielded questions from faculty and team leaders.
2) A foamcore 'competition' was used to introduce the design process to undergraduate students. Students engineered and constructed devices that would transport a ping pong ball around the four sides of a square at least four meters in length using limited materials. Scaled drawings with tolerances were created for each device prior to construction, and material properties were tested. The project culminated in a 'competition' in which students displayed and used their devices.
3) Student volunteers were instrumented with non-invasive Holter© monitors and accelerometers during amusement park rides. Cardiovascular alterations induced by changes in G-forces were compared with predicted acceleration changes deduced via mathematical and physical relations. Students were taught how to analyze results scientifically to show statistically significant or strongly suggestive results.

Since heart rate measurement was part of all of these experiments, we decided to explore the possibility of scientifically analyzing the effects of academic exercises on students' heart rate. It has been well-studied and shown that daily activities and stresses can significantly alter cardiac function[2]. Mental stressors including public presentation, mental arithmetic, and exam performance[3] are also known to contribute to these effects, but it is not yet known to what extent these changes occur. It is expected that heart rate will increase under a mental stress, similar to the way in which it increases under physical stress such as exercise, due to both an adrenal response and a greater oxygen demand by the body. If left untreated for a prolonged period of time, a condition of mental-stress induced myocardial ischemia may develop, similar to the exercise ischemia[3]. The mechanisms regulating the deviation of heart rates include baroreceptor control of sympathetic and parasympathetic activity as well as adrenal contributors. We studied these changes in response to orthostatic stresses such as those accompanying an amusement park ride as well as mental stresses that accompany an exam or proposal presentation. Our hypothesis is that mental and gravitational stressors will induce heart rate changes that will vary considerable from subject to subject. This paper describes the experiments conducted by

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undergraduate students to evaluate these changes; the next section continues with a description of our methods.

2. Materials and Methods

Instrumentation and Experimental Design

To test the effects of mental loading on heart rate, a group of six volunteer freshmen were equipped with Holter© monitors (Applied Cardiac Systems, ACS) for the duration of an introductory Physics midterm exam. Monitor electrodes (Medi-Trace) and conductance gel (Sigma) were placed supercutaneously on each test subject. Baseline heart rate values were determined prior to each study. Data was recorded starting thirty minutes before the start of an event and until at least thirty minutes after the end of each event. Protocols were approved by the Institutional Review Board at the Johns Hopkins University School of Medicine.

We also tested the effects of mental stress coupled with mild physical activity. Students were given two weeks to engineer, construct, and test four devices using limited foam core, rubber bands, hot glue, and wooden dowels. Two minutes were given to each team to transport a ball around each side of a square with sides of at least four feet. Faculty members and other team leaders judged teams on originality, functionality, durability, and overall performance. Volunteer subjects wore Holter© monitors during the "competition". Data was recorded on analog cassette tapes and printed using an ACS Holter Reader.

In an additional experiment, students rode amusement park attractions at Six Flags Great Adventure Theme Park at Jackson, NJ that would induce orthostatic stresses. Students used physical relations to predict changes in acceleration and velocity observed on a rollercoaster incorporating a 65 meter (215 foot) vertical drop and an inverted spaceship where the test subject is held upside down for one to five seconds.

Custom Software

Holter© data for all three experiments was scanned into digital files, which were analyzed via BME Experimental Lab, a custom software designed by a freshmen student (RBB) and used by all design teams. This software was developed to facilitate and improve the accuracy of data analysis. The program inputs a bitmap (BMP) image file and outputs time and instantaneous heart rate at each heart beat into a CSV (MS Excel compatible) format. It incorporates a user-friendly interface that allows significant control and flexibility when analyzing 'noisy' EKG signals. Two versions of the software are currently available: 1) user clicks on distinguishing markers separating heart beats, and 2) user draws a line over a region that is to be automatically analyzed using contrast. A feature was recently incorporated into the software to analyze combined data at any sampling rate and output an average of instantaneous heart rates, standard deviation, and standard error in each time interval. This facilitates the process of pooling data from different test subjects. A screenshot is shown in Figure 1 below.

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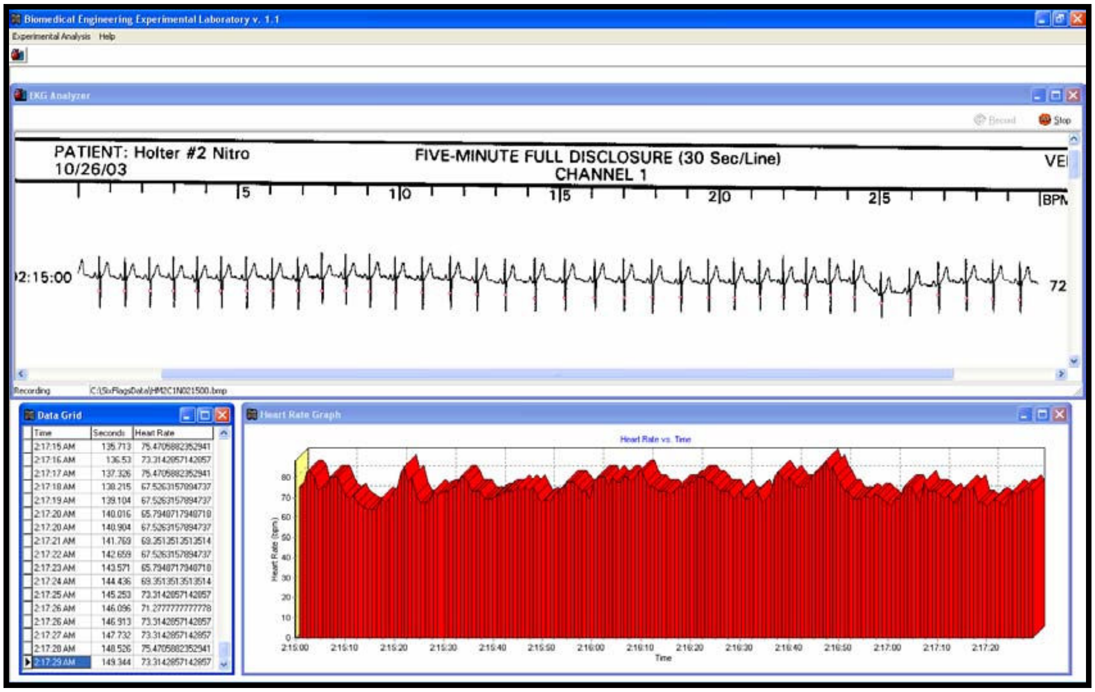

Figure 1: Screenshot of custom software developed to assist in Holter© monitor data analysis.

3. Results

Results for the physics midterm (N=4, Figure 2) and the graded class-based activity (N=6, Figures 3-4) are shown below. In both cases, t=0 corresponds to the start of an event (fifty minute exam or two-minute competition). Baseline levels were determined at an earlier time in resting test subjects. As can be seen, there is a sharp increase towards the end of each of the activities examined (Figure 2 and Figure 3). We also see a less substantial increase in heart rate in the few minutes prior to starting an event, when compared to baseline heart rate values.

Figures 5, 6 and 7 depict Holter monitor and accelerometer obtained at Six Flags Great Adventure.

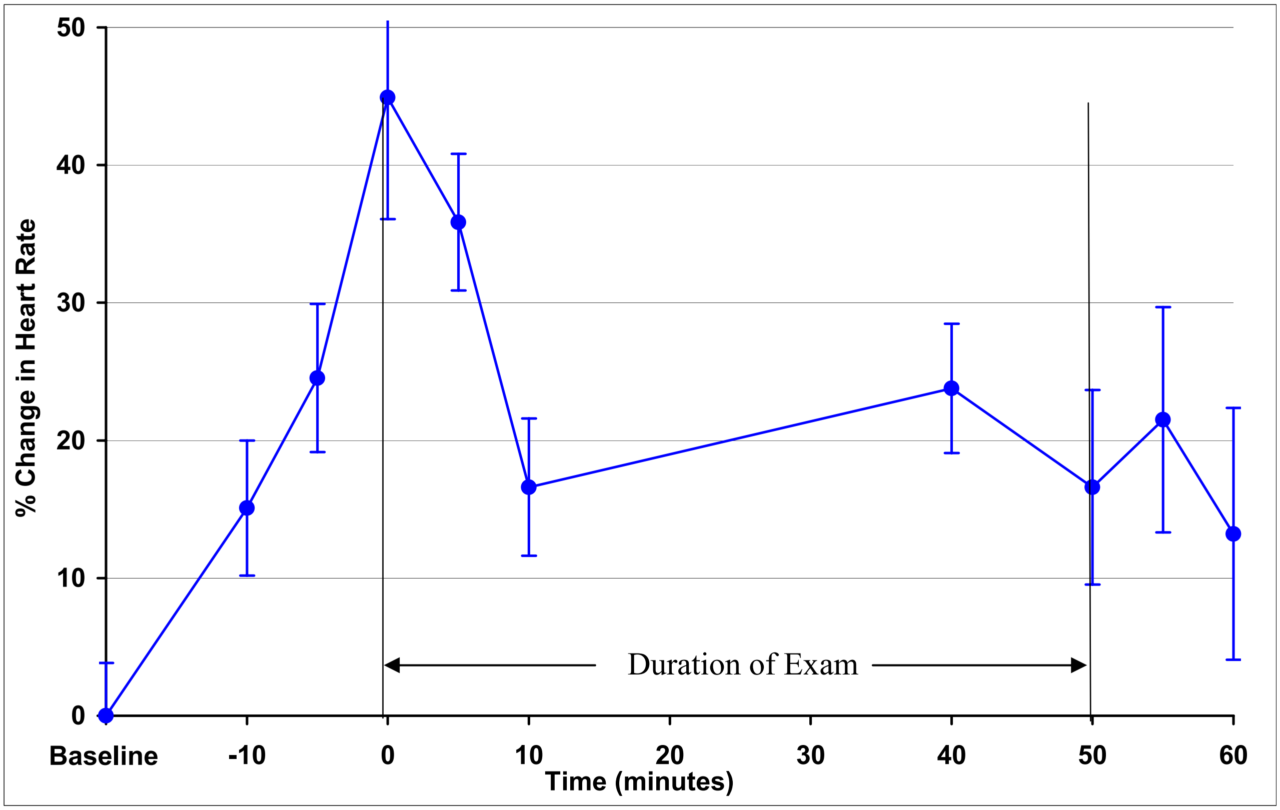

Figure 2: Average heart rate is plotted against time as a percentage change from baseline levels (Mean±SEM) during an undergraduate physics exam (N=4). Time = 0 corresponds to the start of the fifty-minute physics exam, with notable timepoints shown.

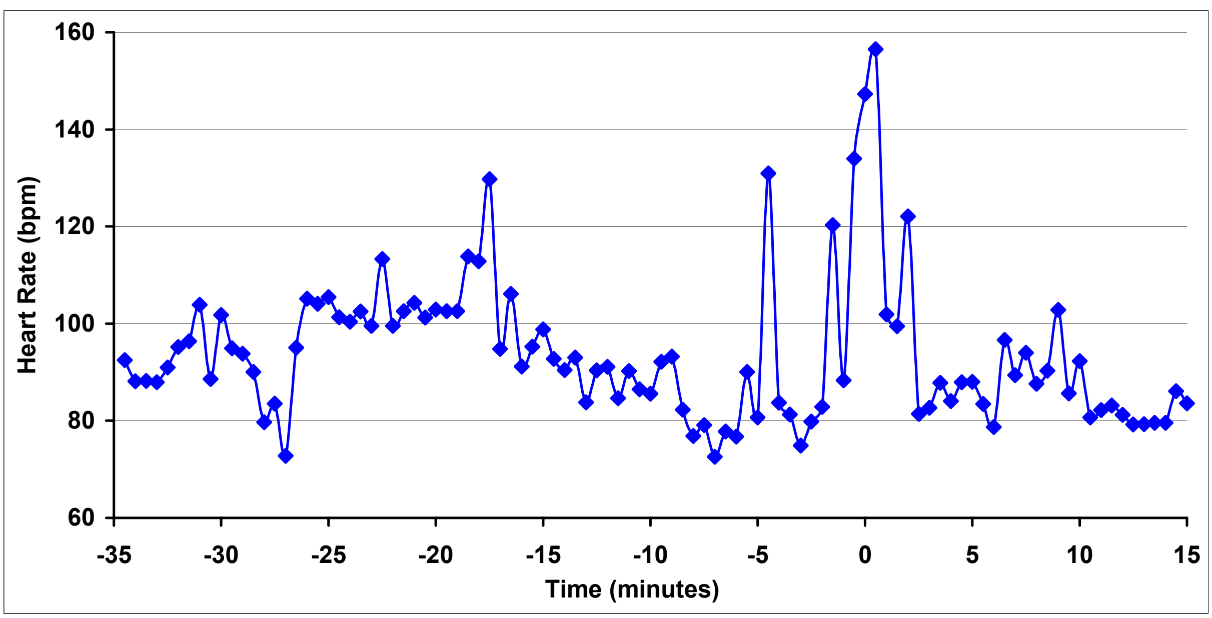

Figure 3: Average heart rate is plotted against time using a 30-second moving average during a class-based graded activity (Sample Trace).

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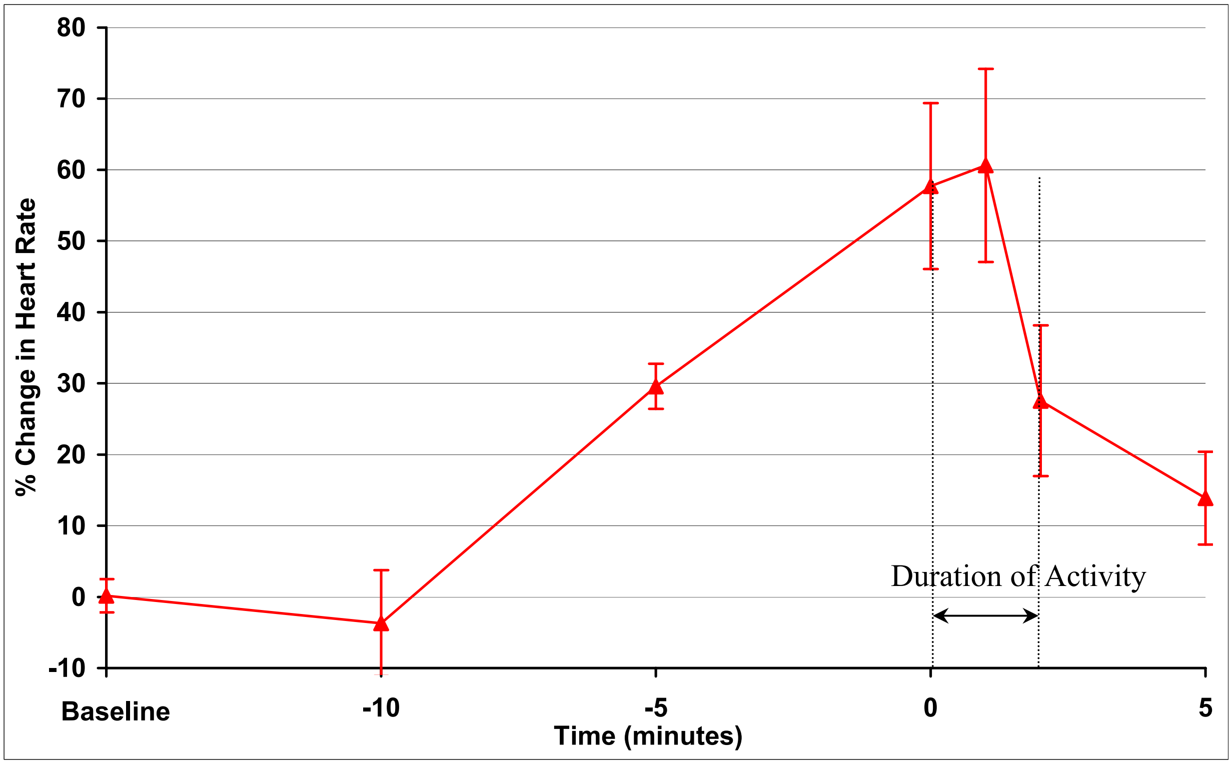

Figure 4: Average heart rate is plotted against time as a percentage change from baseline levels (Mean±SEM) during a graded class-based activity requiring mild physical exertion (N=6). Time = 0 corresponds to the start of the two-minute activity, with notable timepoints shown.

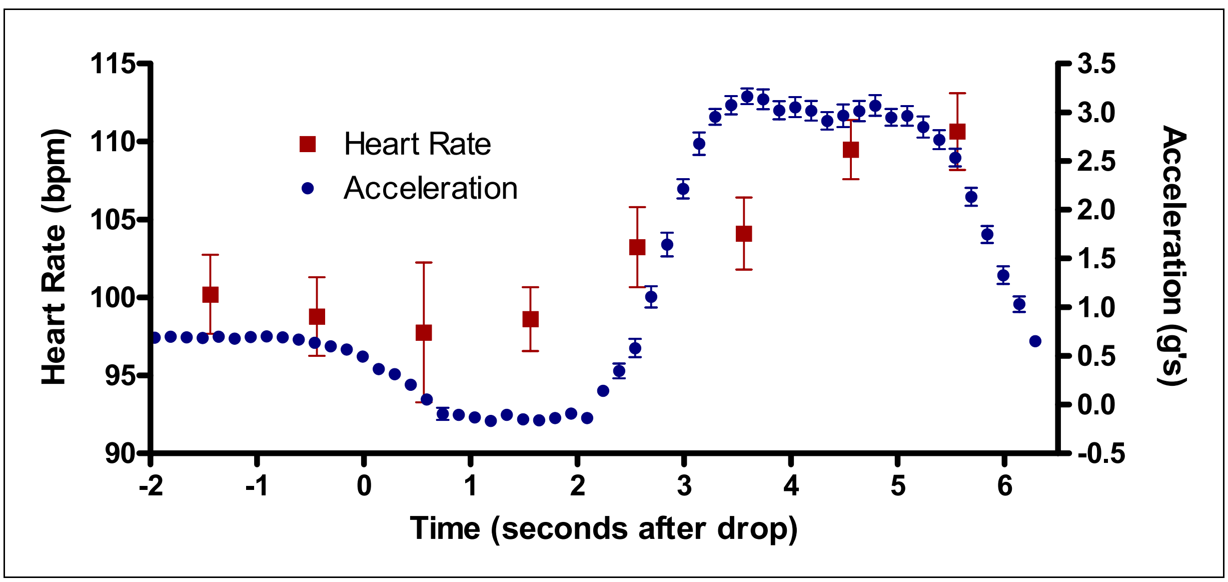

Figure 5: Heart rate and acceleration were continuously recorded during a 65 m (215 ft) vertical drop on the rollercoaster Nitro (N=6). Time was adjusted so time = 0 was the top of the drop. Data was pooled and plotted (Mean±SEM) from multiple trials, and the first dataset was removed to minimize anticipatory effects and an adrenaline response. We observed a sharp increase in heart rates following exposure to a high g-force environment (see Figure 6).

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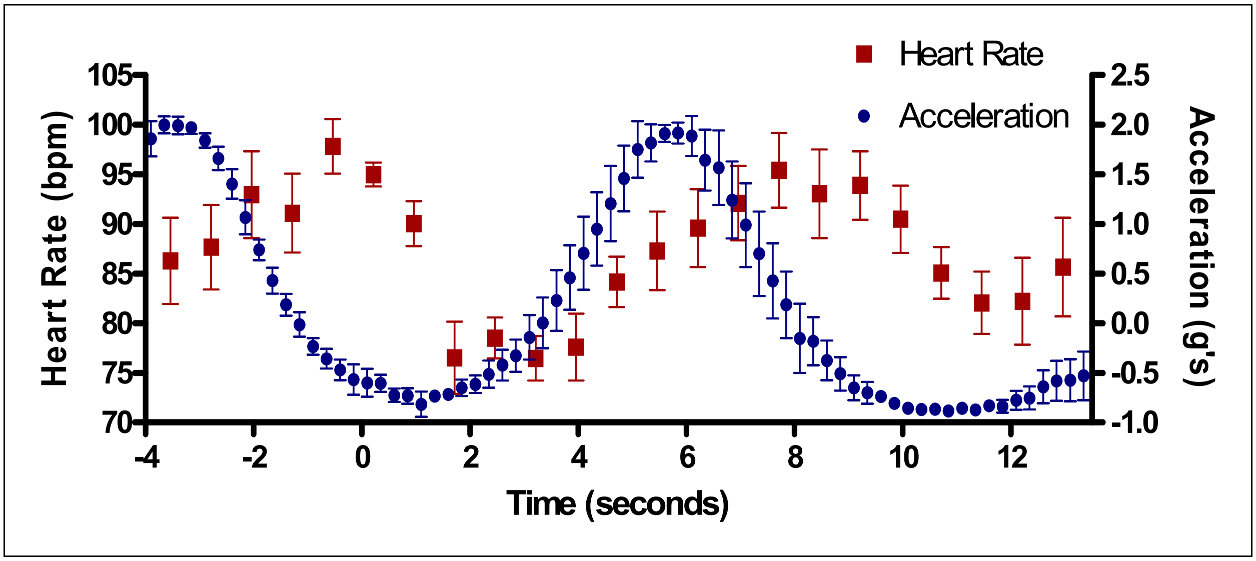

Figure 6: Heart rate and acceleration were continuously recorded during an amusement park ride in which a test subject was inverted (N=4). Trials in which the test subject was inverted for approximately one second were pooled and plotted vs. time (Mean±SEM). Changes in heart rates

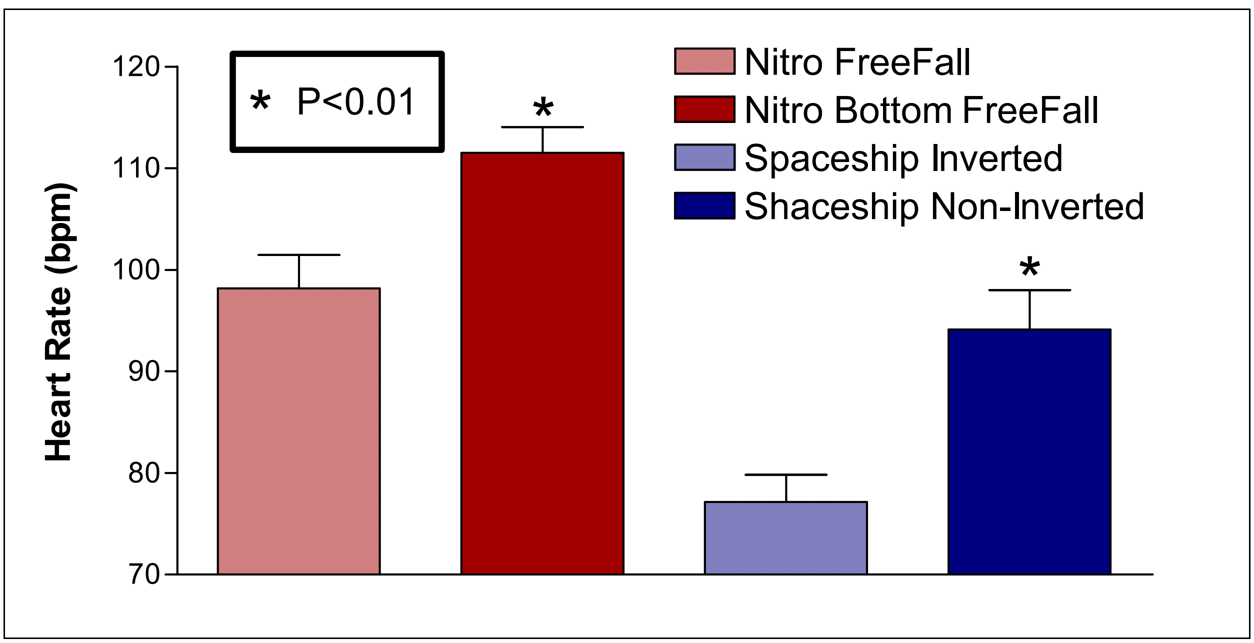

Figure 7: Average heart rate was significantly higher during the vertical drop (98.2±1.34, mean±SEM) than after exposure to a high g-force (111.5±1.03). Average heart rates were significantly lower following test subject inversion (77.16±1.33) than when the test subject was not inverted (94.1±1.94). A student t-test was used to determine statistical significance at a level $p<0.01$.

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4. Discussion

Observed increases in baseline heart rate correlate to the phenomenon of a neurally-mediated anticipatory response, which may be seen in Figure 4 (sample trace). There is a gradual increase in heart rate measured prior to starting each activity, followed by a return to near-baseline levels within several minutes. We observed no correlation between the percentage increase in heart rate and the academic performance of the student on an exam. Interestingly, three of the five subjects undergoing mild physical activity during the class-based competition had heart rates decrease prior to starting the activity, before the anticipatory response was evident.

Similar studies have shown an increase in heart rate and a greater tendency towards an ischemic event for control subject under mental stress[4]. Various studies have used wall motion indices and left ventricular ejection fraction in much the same way that we have used heart rate and echocardiography in quantifying transient changes. However, regardless of the scale used, rates of ischemia, which can be measured via increases in heart rate, are much higher in those subjects who are influenced by mental stressors[3].

Zero gravity situations, induced by several seconds of free fall on amusement park rides, decreased measured heart rate (figure 4). During the deceleration phase of the ride students experienced negative “G” which induces a precipitous decrease in arterial blood pressure and a concomitant neurally mediated increase in heart rate. In some subjects, a correlation was seen between the percent increase in heart rate and the subject’s familiarity or comfortability with the particular ride. However, this was not seen to be a global trend. Our heart rate results coincide with the cardiovascular alterations observed very early by Peterson[5] in a canine model as well as those reported quite recently by Morita[6] using Sprague-Dawley rats in freefall. Although these other groups chose to include invasive measurements of intrathoracic pressure, aortic diameter, or left ventricular volume, both their results and ours give the same final answer, which is that positive G-forces induce a decrease in heart rate and negative G-forces induce an increase in heart rate. Future studies conducted within our course will include a more diverse group of volunteer subjects as well as a wider array of experimental protocols to better understand the mechanisms of action for the changes we have observed.

Our goal was to encourage all team members to employ creativity and analytical thinking when designing protocols for experiments, and to develop the skills necessary to do this independently in the future. In addition to its educational value, the data obtained may be useful from a scientific perspective. It is difficult to balance the necessity to have a standard protocol for compiling and publishing data with the goal of developing independent thought. In these series of experiments alone, it was difficult to ensure that the protocols were all following a set of standardized rules This led to obvious complexities in pooling the data collected from different teams. Although the custom analysis software aided in having the data standardized, a more rigorous system must be implemented if the results of future experiments are to be submitted for journal publication. It is our hope that future experiments can be designed around the new constraint of having certain aspects of the protocol standardized between different teams, the responsibility of which falls primarily on the future team leaders of the course. This endeavor has proven to be educational for all involved and has set the groundwork for future student contributions.

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5. References

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6. Biography

ANKIT D. TEJANI
Mr. Tejani is a senior in the Biomedical Engineering department, specializing in Materials Science with an interest in cardiovascular bioengineering and the role of calcium cycling within the failing myocardium. He serves as a team leader for one of the Design Teams, a program with which he has been associated for the past four years, and is currently designing a ventilator alarm system. He will enter a PhD program in molecular medicine in Fall 2004.

SETH A. TOWNSEND
Mr. Townsend is a senior in the Biomedical Engineering department, specializing in Chemical Engineering with research focused in determining the cardiovascular alterations induced by exposure to microgravity. He currently serves as a team leader for a Design Team that is developing a real-time urinalysis system to detect acute renal failure. He will enter a PhD program in the biological engineering division at M.I.T. in Fall 2004.

PETER J. GOLDWINE
Mr. Goldwine is a senior in the Biomedical Engineering department, specializing in Computer Science with an interest in bioinformatics. He serves as a team leader for one of the Design Teams.

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Ms. Hoe is a senior in the Biomedical Engineering department, specializing in Electrical Engineering with an interest in wireless microfabrication. She serves as a team leader for one of the Design Teams and has been a member of a highly successful team in her junior year.

ELIZABETH L. JOHNSON
Ms. Johnson is a senior in the Biomedical Engineering department, specializing in Chemical Engineering. She serves as a team leader for one of the Design Teams and has had extensive industrial experience in the field.

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MATTHEW KUNG
Mr. Kung is a senior in the Biomedical Engineering department, specializing in Chemical Engineering. He serves as a team leader for one of the Design Teams and has been associated with the program at Johns Hopkins for three years.

MARY K. MCDONALD
Ms. McDonald is a senior in the Biomedical Engineering department, specializing in Chemical Engineering with an interest in chemical process design She serves as a team leader for one of the Design Teams and has been a member of highly successful teams in the past.

LAURA A. SPROWLS
Ms. Sprowls is a senior in the Biomedical Engineering department, specializing in Computer Engineering with an interest in digital imaging. She serves as a team leader for one of the Design Teams and leads the Hopkins Emergency Response Unit.

GARY H. TONG
Mr. Tong is a senior in the Biomedical Engineering department, specializing in Chemical Engineering. He serves as a team leader for one of the Design Teams.

RICHARD B. BOYER
Mr. Boyer is a freshman in the Biomedical Engineering department, specializing in computer algorithms. He has had extensive experience in the field of information technology and provided a highly effective digital processing program for the data analysis.

ROBERT H. ALLEN
Dr. Allen is a Senior Lecturer in Biomedical Engineering at Johns Hopkins University, and has taught and performed research in engineering design for over 15 years. He directs the Design Teams program.

ARTIN A. SHOUKAS
Dr. Shoukas is a Professor of Biomedical Engineering at Johns Hopkins University, where he has served on the faculty for over 30 years. The recipient of several engineering and medical school teaching awards, Dr. Shoukas envisioned and proposed the Design Teams program within biomedical engineering.

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