An MRI-Compatible Leg Exercise Device for Assessing Cerebral Blood Flow Responses to Exercise

Final Report

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Team Members

Katherine Lake: Team Leader
Henry Hu: Communicator
Kelsi Bjorklund: BWIG
Jacob Stangl: BSAC

Client

Dr. Bill Schrage

Advisor

Michael Toepke, PhD

Abstract

Our client, Dr. William Schrage, is an Assistant Professor of Kinesiology for the University of Wisconsin – Madison and a part of the Cardiovascular Research Center as a specialist in vascular biology. He has proposed a study that examines changes in cranial blood flow during patient exercise. This study incorporates the utilization of a Magnetic Resonance Imaging (MRI) device in order to view cranial blood flow and blood vessel diameters. Our client has proposed that we develop a non-ferromagnetic exercise device that will allow a patient to exercise while undergoing a MRI scan. After testing past designs, we determined a pulley device was the best option and constructed a prototype of the design. We tested the prototype on three different patients of varying heights and after several iterations and design changes determined that it effectively raises the heart rate and minimizes head movement. After testing, we constructed the final design and tested it within an MRI. MRI scans reveal that the final design effectively increases heart rate in a wide variety of patients and allows researchers to gather clear images during exercise. Data from the scans demonstrate that the patient tested showed an average of a 22% increase in blood velocity and blood flow during exercise as opposed to at rest, indicating that Dr. Schrage's study will reveal new facts about changes in blood flow during exercise.

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Background

Client Description

Dr. William Schrage is an Assistant Professor of Kinesiology for the School of Education at the University of Wisconsin – Madison[1]. His research focuses on how arterial blood flow is controlled during exercise. He is also investigating how cardiovascular conditions caused by aging or high blood pressure can change or impair blood flow. Our client is interested in determining if regular physical activity improves blood flow and blood vessel function and uses both human and animal models. Dr. Schrage is also affiliated with the Cardiovascular Research Center at the University of Wisconsin – Madison, where he focuses on vascular biology.

Throughout Dr. Schrage's career he has published work in numerous peer-reviewed journals and is currently interested in studying how cranial blood flow changes during exercise. As cranial blood flow is best observed with a magnetic resonance imaging (MRI) device, any exercise device used must be MRI-compatible. A wide range of patients are to use this device and so it must fit a range of heights and fitness levels. Consequently, our client has proposed that we design an exercise device that increases the heart rate to 120-130 beats per minute (bpm), the typical working heart rate, while a patient is within an MRI.

Current Devices

Marketed Devices

The MRI compatible exercise devices produced by Lode BV are the main competition to our device. The Lode Ergometer products are utilized by many studies but each product has several shortcomings[6,7]. GE scanners have smaller bore sizes than Phillips and Siemens brand scanners, and so the cycling ergometer is not compatible with GE scanners and the MRI

Ergometer Push/Pull is not compatible with the newest GE scanners. Additionally, Lode Ergometers are priced near $50,000, limiting availability to researchers[3].

Past Prototypes

Three MRI compatible exercise devices have been created. The first, built by a BME Design group in Fall 2009, utilized a cycling motion to create the resistance necessary to elevate heart rate and is shown in **Figure 1**. This prototype was designed to be used while a patient was receiving a chest MRI, which severely limited the range of motion within which a patient could exercise. The range of motion was so impeded that most patients were unable to exercise within the MRI bore using the cycling device, rendering the device useless for chest imaging during exercise.

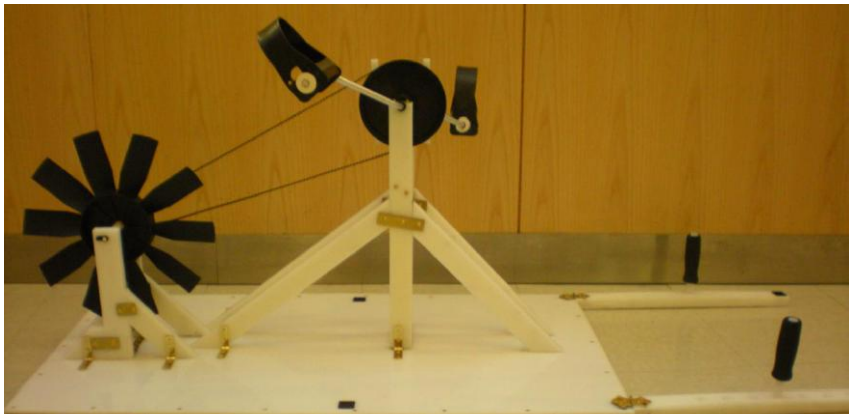


Figure 1: Picture of Fall 2009 Design

The user's feet are affixed to pedals and rotate in a cyclic motion similar to the motion of riding a bike. Handholds, shown on the right, can be used by the patient for increased stability and comfort.

The BME design team altered the design for Spring 2010 and developed a stepping exercise device, shown in **Figure 2**, that could be used while performing a chest MRI scan. Resistance bands attached to pedals were used to increase the heart rate of a patient and two hand grips were included to assist in patient stability and improve patient

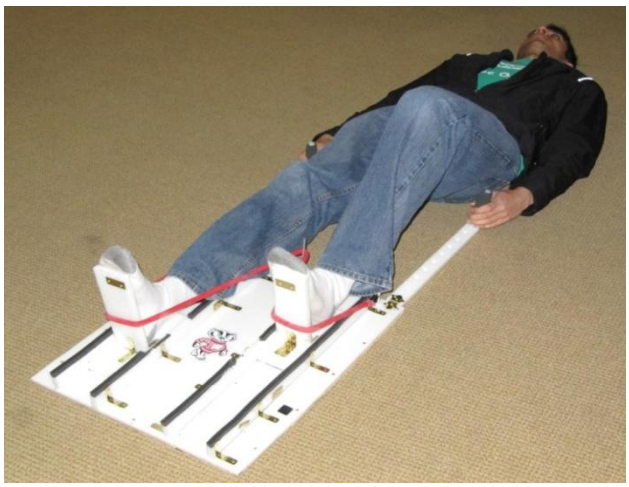


Figure 2: Picture of the Spring 2010 Design

The user exerts force downward against foot braces to work muscles and increase the heart rate. The foot braces are attached to tracks to ensure controlled movement.

comfort. This design required a minimal range of motion within the MRI but did not utilize the principles of dynamic exercise or create a natural-feeling movement. Additionally, significant forces were exerted along the anteroposterior body axis so if utilized, this device could create enough artifact in MRI images so that the images are rendered unusable.

The Fall 2010 BME design team created an exercise device that allowed patients to exercise while receiving an MRI scan of the brain. This MRI scan leaves the legs of most patients outside of the MRI bore, thus increasing the range of potential exercise movements. This design consisted of two pivoting levers with weights attached at one end, as shown in the schematic in **Figure 3**. The lever design used the principles of dynamic exercise and minimized forces applied along the anteroposterior body axis in order to minimize head movement and MRI artifact. However, this design did not allow a patient to exercise with a natural feeling motion. Upon analysis, this device was found to create the greatest acceleration when the knee is at the highest and lowest points during exercise. To counter this acceleration and prevent knee hyperextension, patients were forced to generate the greatest amounts of force at the highest and lowest point of the motion, which correspond to areas where the major leg muscles are highly contracted or

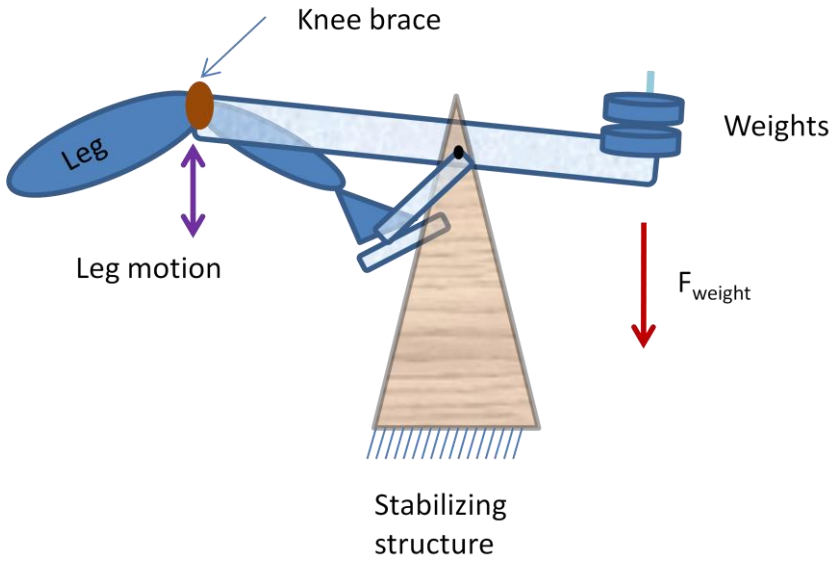


Figure 3: Diagram of the Fall 2010 Design

The knee is attached to a large lever with weights at the opposite end. Each foot is supported at a platform that stabilizes the leg while in motion.

extended. Highly extended or contracted muscles produce relatively small amounts of force, and so during exercise patients were unable to exercise efficiently and increase their heart rate to 120-130 bpm[2].

Problem Motivation

Magnetic Resonance Imaging (MRI) is a crucial component of the medical field; it provides a deeper insight into the workings of the human body and allows researchers to observe blood flow and other bodily processes in greater detail than alternative methods would allow. Exercise-induced increased cerebral blood flow can be analyzed to determine if cerebral blood flow patterns differ in patients suffering from obesity or pre-diabetes. MRI can then be used to study global cerebral blood flow patterns and blood vessel diameter[6]. Currently, one MRI compatible exercise device is marketed but its high cost limits availability to researchers and the device does not allow the user to exercise while inside the MRI machine. Instead, the device is used to elevate the heart rate prior to scanning; the patient is quickly pushed into the MRI and scanned after exercise ends. This method is not optimal, as the heart rate returns to its original pace within a period of minutes, and MRI scans are typically ten to fifteen minutes in length. Our client would like to be able to measure the effects of exercise on blood flow during patient exercise, so the final device must be non-ferrous, MRI compatible, portable, and cost-effective. Our client has reported many researchers wish to perform MRI scans on patients with elevated heart rates, so the device must also be marketable and patentable in order to make it available to a wide range of researchers.

Design Requirements

The design requirements outlined in the Project Design Specifications in the Appendix and are explained in detail here. The device must not cause muscle strain or damage, as it will be

used by patients to exercise with for extended periods of time while within the MRI. All materials must be non-ferromagnetic to be compatible with the MRI and comply with the standards of the Food and Drug Administration.

In addition to essential safety requirements, the design must also meet a set of performance standards set forth by our client. The final design of our device should have a life in service of the duration of the study, which is approximately three years. The device must be easily disinfected and usable by patients 5’4” to 6’4” tall. The flywheel resistance must be adaptable to different fitness levels in order to raise the heart rate to 120-130bpm in all patients. Forces along the anteroposterior body axis must be minimized in order to decrease movement artifact in MRI images and the device must produce a natural feeling exercise motion in order to maximize patient comfort.

The product must be as lightweight as possible without impeding functionality or usability as it is to be positioned on the MRI bed with the patient. If the final product is too heavy, the upper weight limit of the MRI bed could limit device users to patients under a certain maximum weight. The device must fit securely onto the MRI bed, which is 25.5 inches in width and 64 inches in length. While exercising, the patient must not come into contact with the MRI bore, as this could cause discomfort to the patient or damage to the MRI or the exercise device.

Patient comfort is a major factor regulating the usability of our device. A large portion of patients become claustrophobic while undergoing a MRI scan, and patients under the additional stress of exercise may become claustrophobic faster than an average patient. The device should therefore limit straps or other restrictive devices in order to lessen patient stress during the MRI scan. In order to create a more natural feeling method of exercise, acceleration should be minimized when the leg muscles are most extended or contracted. This will allow patients to

exercise with the greatest amount of force when leg muscles are of medium length and able to generate the greatest amount of force, and will address the non-natural feeling motion of the previous design.

Design Alternatives

Prior to building and testing a chosen design, three potential product designs were created and evaluated. Each design utilized dynamic exercise and attempted to minimize forces along the anteroposterior body axis.

Beam Design

The beam system design, shown in **Figure 4**, uses several non-ferromagnetic metal beams that are linked in such a way so patients would be able to exercise by extending and contracting the legs. Resistance would be provided by concrete-based or sand-based weights

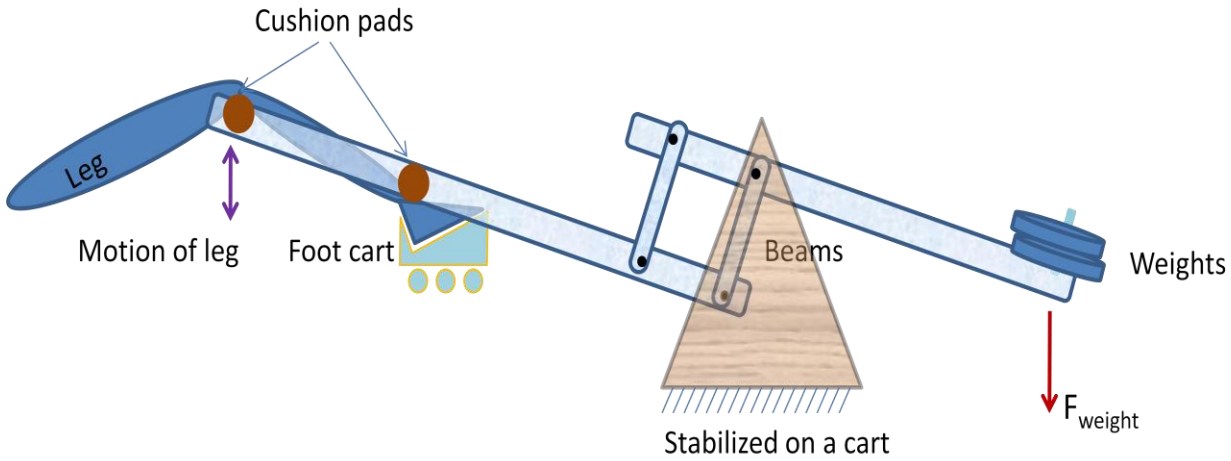


Figure 4: Beam System Diagram
The system consists of beams, a stabilizing structure, and foot cart. The beam structure transmits gravitational force generated by the weights to the knees of the patient. The foot cart eliminates friction force acting on the horizontal direction.

attached to the end of the main beams. The weights could be easily changed, providing different levels of resistance to patients with different fitness levels. The main beam would be attached to the leg at the knee, so patients would be able to utilize the quadriceps and hamstrings to work

against the weights. The beam structure would transmit gravitational force generated by the weights to the knees of the patient. A foot cart would eliminate friction force acting on the horizontal direction and ensures forces are limited to the vertical direction. The stabilizing structure would be assembled on a portable cart that could slide onto the MRI bed.

Pulley Design

The pulley system utilizes pulleys, a connection mechanism, and a fly-wheel that generates resistance to allow patients to exercise. This design also contains a rail track system that eliminates frictions on patients' feet while their legs are exercising. The design is shown in **Figure 5**. The pulleys transform the vertical motion generated by patients' legs into circular motion in the flywheel. The use of a flywheel will allow the legs to move in a sinusoidal rhythm and mimic the natural-feeling motion produced by an exercise bike. This will also allow the user to adjust the device to an individual rate of exercise, which will improve patient comfort and mimic other commonly used exercise devices. Inertia generated by the flywheel will cause the device to move whether the patient is exerting a vertical force or not; this will provide the user with a smoother exercise experience. A rubber break or resistance band on the fly-wheel system will generate resistance and allow researchers to adjust the work load on patients.

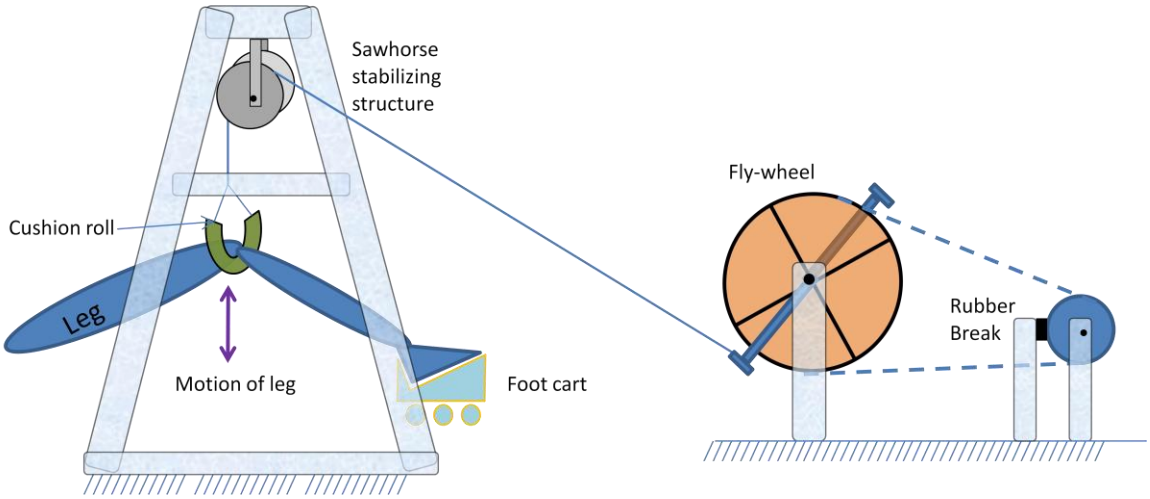


Figure 5: Pulley System Diagram

The system consists of pulley, a stabilizing structure, a fly-wheel system and foot cart.

Spring Design

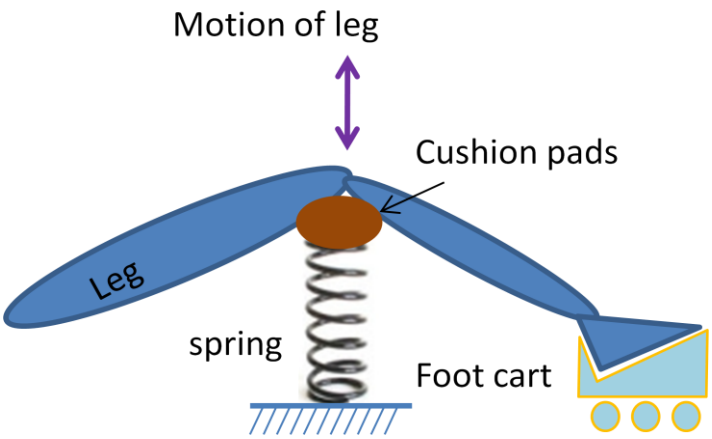


Figure 6: Pulley System Diagram

The system consists of two springs attached to a baseboard and a foot cart. Cushioned pads or braces are attached to each spring, allowing the patient to depress the spring to perform exercise.

The spring system uses springs located under the knees of the patients. Cushion pads or individual knee braces are placed on the top of the two springs ensure a soft and comfortable contact of the patients' knees and the springs. This design is shown in **Figure 6**. This is a relatively simple design that only consists two springs, one for each leg, and two foot carts, one for each foot. Springs could be adjusted in order to control the work-load of the patient. The springs would provide a resistance load similar to resistance bands used in other forms of exercise.

Design Matrix

Each preliminary design had its own strengths and weaknesses in comparison to the others. To effectively evaluate the individual points of each design, a design matrix was constructed and used to analyze each preliminary design.

The three leg exercising mechanisms were rated on a variety of design criteria. These aspects were selected because of their importance in an effective design. It was determined that certain criteria, such as effectiveness, safety, and patient comfort, were more significant, and therefore were weighed more heavily. The scores for each design in each category were added up to give a total score out of 100, which is shown in **Table 1**. Based on the point breakdown

shown below, the pulley design received the largest allotment of points and we have chosen to pursue prototyping and developing the pulley design.

Table 1: Design Matrix
The maximum point values are indicated in parentheses in the row headings. The point allotment will be discussed in the proceeding analysis.

Weight	Criteria	Beam system	Pulley system	Spring system
25	Effectiveness	22	23	18
20	Safety	15	18	13
20	Patient comfort	15	17	10
15	Portability	12	10	14
10	Cost	8	8	10
10	Durability	6	6	8
100	**Total**	**78**	**82**	**73**

Effectiveness

Effectiveness was defined as the ability of the exercising devise to give a constant resistance to patients and allow patients to elevate their heart rate around 120 beats per minute through exercise. This criterion was also defined as the adjustability of the design. It was given a weight of 25 points in the matrix, designating it as the most important category, because it determines the ultimate performance of the exercising devises. The pulley system design scored highest and received 23 points while the beam system second-highest with 22 points. The pulley system was allotted an additional point as the inertia generated by the flywheel will improve the overall smooth motion of the pulley system and allow patients to exercise in a more dynamic manner. The spring system was given the fewest points it would be more difficult to adjust the

resistance provided by the spring system than to adjust the resistance provided by the pulley system or beam system.

Safety

The final design of the device must also take safety into account. As a result of involvement of MRI scanning, the design must be safe to be used near MRI. Safety was allotted 20 points in the matrix, as a design that injures the patient or could cause damage to the MRI machine must be avoided. A safe design requires that all of the components are fabricated of non-ferromagnetic materials and that the design provides natural feeling motion to patients. The pulley system design scored highest, receiving 18 points, as the sinusoidal motion produced during exercise would feel natural to the patient. Additionally, the inertia generated by the flywheel would maintain a level of motion that would eliminate the sub-optimal contractions caused by the Fall 2010 design. The beam design received a lower score of 15 points, as the long beams required to clear the MRI bed would provide a hazard to MRI operators while the exercise device was in motion and because the device could cause muscle damage over long periods of time in a similar fashion to the Fall 2010 design. As it would be difficult to fabricate the spring system design out of non-ferromagnetic materials, the spring system received the lowest score, 13 points.

Patient Comfort

Patient comfort was an additional concern when designing different prototypes and as such was given 20 total points. It was determined to be as significant as safety, and was thus weighted the same. Many patients experience claustrophobia and an increased heart rate while within an MRI scan and an exercise-induced increased heart rate could cause increased patient discomfort and mental duress. Thus, it was imperative to design a device that would maximize

patient comfort by utilizing a natural feeling motion, rather than solely concentrating on what will raise the heart rate in the most efficient manner. The pulley system received a score of 17 in this category, as it would provide patients with a comfortable sinusoidal motion similar to the motion produced when riding a bike. The beam system received the slightly lower score of 15, as patients would experience more discomfort where the knee attaches to the beam and because the beam requires patients to exercise with an unfamiliar motion. The spring design received the lowest score of 10 points in this category, as patients would experience a large amount of force over a small area of the knee, thus likely leading to discomfort at the knee after long periods of exercise.

Portability

In conjunction with the request of our client, another component of the design matrix is portability. The final design cannot be stored within the MRI room and no modifications can be made to the MRI room itself, so each time a researcher utilizes the device it must be transported from a storage facility to the MRI suite. The MRI machine is often fully booked on any given day so device setup must be minimal in order to provide researchers with the maximum amount of scanning time. Portability was given 15 total points, as it was important to our client but not the most important category. The spring system was given the fourteen points for portability, as it was concluded that the device would not consist of much more than two springs attached to a rolling bed and two foot carts and one researcher would be able to transport the spring system with ease. The beam system would be large but consist of one apparatus and be simple for two researchers to transport and set up, so it was allotted 12 points. The pulley system would consist of two separate apparatuses, the actual stabilizing structure and the flywheel, and so would

require two researchers or a cart to transport the device. For this reason the pulley system was allotted only 10 points.

Cost

In order to make the device marketable and available to a wide variety of researchers, it must be cost effective. This design should have a low cost but use strong and durable materials. As any device developed was likely to be well under the price of the currently marketed device, cost was less important and was given 10 points. As the pulley system and beam system both contain a greater number of components, they were each given eight points. The spring system consists of few components and so is thought to be the most cost-effective, so we allotted it a perfect 10 points.

Durability

As previously stated and requested by our client, the final device must be usable for the duration of the study, at least three years. Thus, durability must be included in the design matrix, but as parts are replaceable is not a significant contributor. The use of any machine over an extended period of time causes expected wear on individual parts, but the chosen device must minimize wear to every component. Durability was given 10 points in the design matrix, as it should be considered but should not be a major factor of the design. Each design alternative has different points at which expected wear will occur; the spring design has the fewest components and so has the fewest possible points of failure and was thus awarded eight points. Both the pulley design and the beam design have several points where the design requires a repetitive motion that will cause wear to the design, and were thus each allotted six points. The pulley design would likely have a failure of the inextensible cord or the pulley, while the beam design

would likely have a failure at the center joints where the greatest amount of metal to metal contact occurs.

Testing

Preliminary Testing

In order to maximize our efficiency in designing a new alternative to the given problem, we found it necessary to perform preliminary testing on the prototype that was designed in Fall 2010. **Table 2**, **Table 3**, and **Table 4** contain this data. As is shown in the tables, only the first female patient was able to elevate her heart rate to 120, while the second male patient was not. It is apparent, however, that the ability to increase heart rate was increased with the amount of weight placed on both legs. During testing, we found this to greatly decrease the stability of the device to the point that components were actually falling off the prototype. As this was a safety hazard to researchers and patients, a safer, more stable device that can effectively raise the heart rate was required.

Time elapsed (min)	Heart rate (bpm)
0	93
2:00	103
3:10	111
4:30	110
5:30	118
6:00	115
6:30	115
7:30	120
8:30	115
9:00	116
10:00	119

Table 2: Patient 1. Female. Height: 5'5" 11lbs on each leg. Patient exercised for ten minutes and was able to successfully raise heartbeat to 120 bpm

Time elapsed (min)	Heart rate (bpm)
0	83
1:10	98
3:15	100
4:14	98
5:00	97
5:30	101

Table 3: Patient 2. Male, Height: 6'0" 11 lbs on each leg.

Patient exercised for five minutes and was unable to successfully raise heart rate to 120 bpm.

Time elapsed (min)	Heart rate (bpm)
0	89
1:00	100
1:30	106
3:30	100
5:00	105
5:30	106

Table 4: Table 3: Patient 2. Male, 6'0" 15 lbs on each leg

Patient exercised for over five minutes and was unable to successfully raise heart rate to 120 bpm. Device failure occurred while testing.

MRI Testing

After constructing the initial prototype, it was taken to a research MRI at the Wisconsin Institutes for Medical Research (WIMR). The prototype's dimensions were analyzed and one patient entered the MRI to determine if the prototype could be effectively used to exercise while within the MRI. Further heart rate tests did not occur because the single main board of the prototype was found to be impeded by a part of the MRI bed; when a patient was slid in to the MRI, a small structure at the bottom of the sliding bed did not allow a flat board to sit on the length of the bed. In order to maximize the width of the triangle stabilizing structures and minimize the risk of patient energy, it was then determined that the final design should use separate stabilizing structures for the flywheel and the triangle support structures.

After a second prototype was constructed, a research MRI at the WIMR was once again used to test the device. The dimensions of the device were such that the device fit perfectly on the MRI bed and both stabilizing structures were lightweight enough to be easily lifted by one person. Three patients were tested while within the MRI and the pulse of each patient was measured using pulse oximetry. The results of the test are shown in **Table 5**.

Patient	Height	Maximum Heart Rate (bpm)	Time to Increase (Min:Sec)
1	**5'6"**	**120**	**5:30**
2	**6'**	**118**	**4:20**
3	**5'11"**	**115**	**3:30**

Table 5: Height and Maximum Heart Rate Attained
The time each patient required to attain their maximum heart rate is also indicated.

Each patient attained a high working heart rate; although the attained heart rates are lower than the desired 120-130bpm, the patients examined were relatively young and in good health, and so higher heart rates will likely be observed in hypertensive or obese patients. Each patient required a short amount of time to attain the increased heart rate, which demonstrates that the

total amount of time a patients spends exercising will likely be less than eight minutes. A shorter scan is desirable because it increases patient safety by minimizing patient discomfort and claustrophobia.

Patient 3 was chosen to undergo further testing and use the prototype during an MRI scan. Initial scans of Patient 3 at rest were first taken to determine baseline blood velocity and blood flow measurements. Patient 3 was positioned so that the left and right exterior and interior carotid arteries and the left and right vertebral arteries could be examined. In **Figure 7**, the paired white circles on the outer area of the scan are the left and right exterior and interior carotid arteries and the two individual white circles on the inner area of the scan are the left and right vertebral arteries. These arteries direct blood flow to the brain and so are what Dr. Schrage would likely observe in actual research studies. MRI images of the initial scan show that Patient 3 made few movement during the scan and so no major motion artifact can be observed in Figure 7. Movement artifact is observed in MRI scans as fuzzy white areas, or ghosting, around the outside of the image or as decreased sharpness within the image itself. These were performed while Patient 3 was as still as possible within the MRI and before Patient 3 had begun exercising. Further scans were then performed after Patient 3 had attained a steady working heart rate of 110-120bpm. The actual images acquired during the scan can be seen in Figure 8.

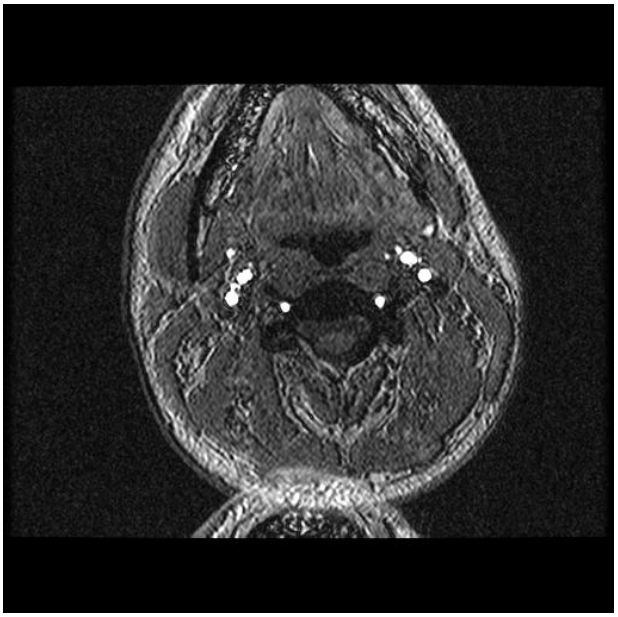


Figure 7: Initial Scan of Patient 3 at Rest

The sharp image indicates that Patient 3 was moving very little during the scan.

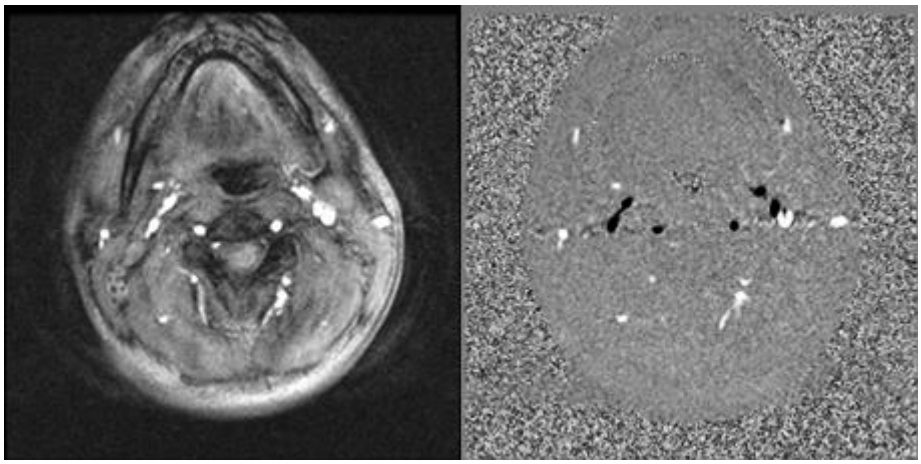


Figure 8: Scan of Patient 3 During Exercise
The faint white blur around the first image is caused by movement during the MRI scan. Both images were taken during the scan, but the image on the left displays magnitude and location information while the image on the right displays velocity information.

The data collected during the scan was analyzed by Dr. Alejandro Roldan, an MRI specialist who assisted with testing. Dr. Roldan used a computer script to decode embedded data in the MRI scans to determine that, on average, a 22% increase in blood flow and blood velocity occurred in each of the six arteries tested when Patient 3 began exercising. This is consistent with previously performed transcranial Doppler ultrasound studies, which have demonstrated that on average the blood velocity and blood flow increase 10% to 30% in the middle cerebral artery in response to exercise[7].

Figures 9 and 10 show in graphical form the blood flow in the left vertebral artery and the blood flow in the exterior carotid left artery dependent on time. Each point on the graph shows the average flow value at that point in the cardiac cycle. A patient's increased heart rate during exercise is represented as the decreased amount of time one cardiac cycle requires for completion. **Figure 10** shows two cardiac cycles that are almost identical, except for the flow values, which demonstrate that minimal distortion of data was created when the patient began exercising. **Figure 9** shows some distortion of the exercise blood flow data around 250 ms, which could be explained by Patient 3's head movement during the scan.

Figure 9: Blood Flow in Left Vertebral Artery Dependent on Time

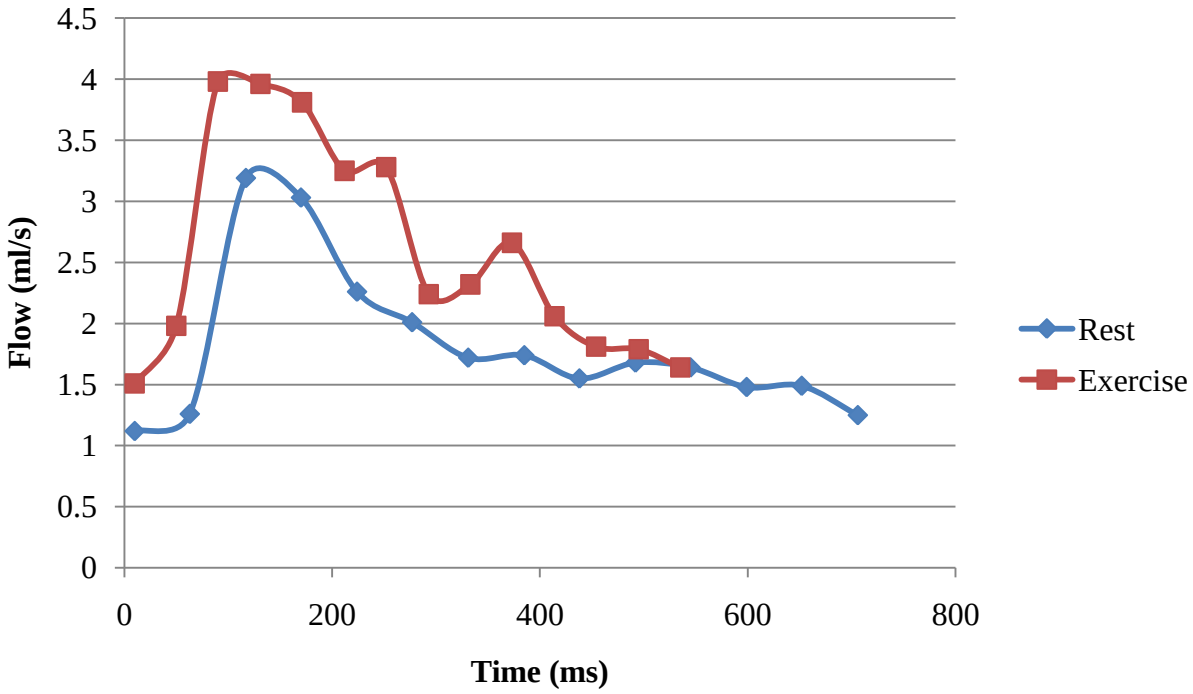
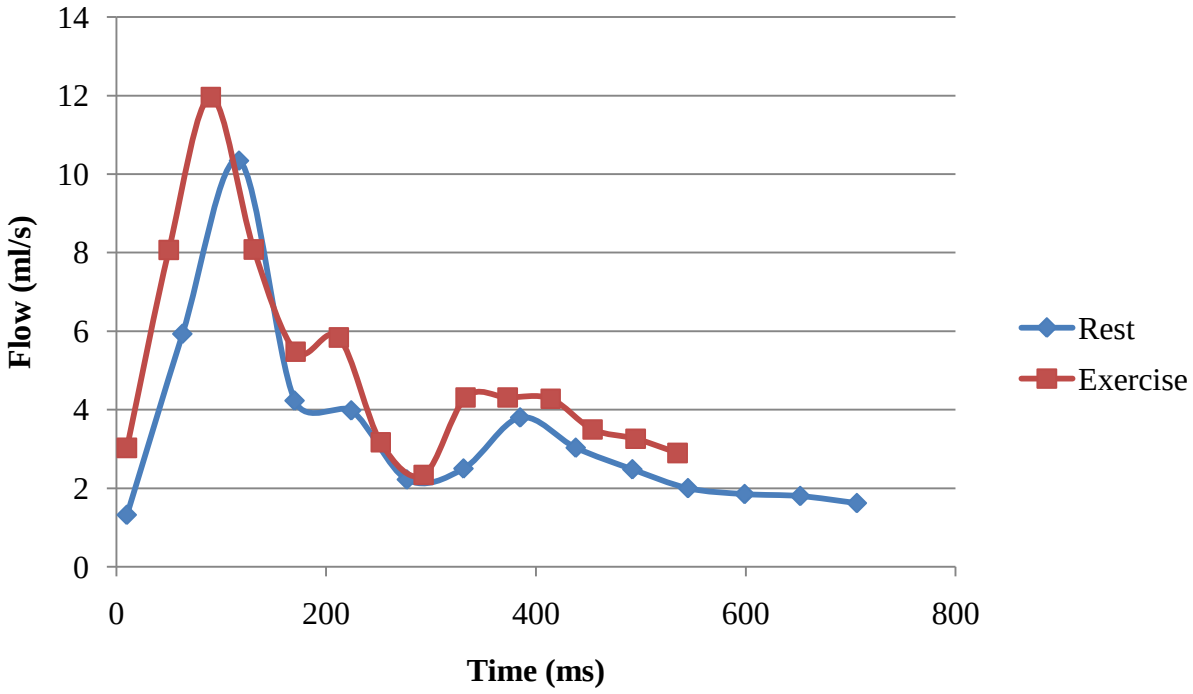


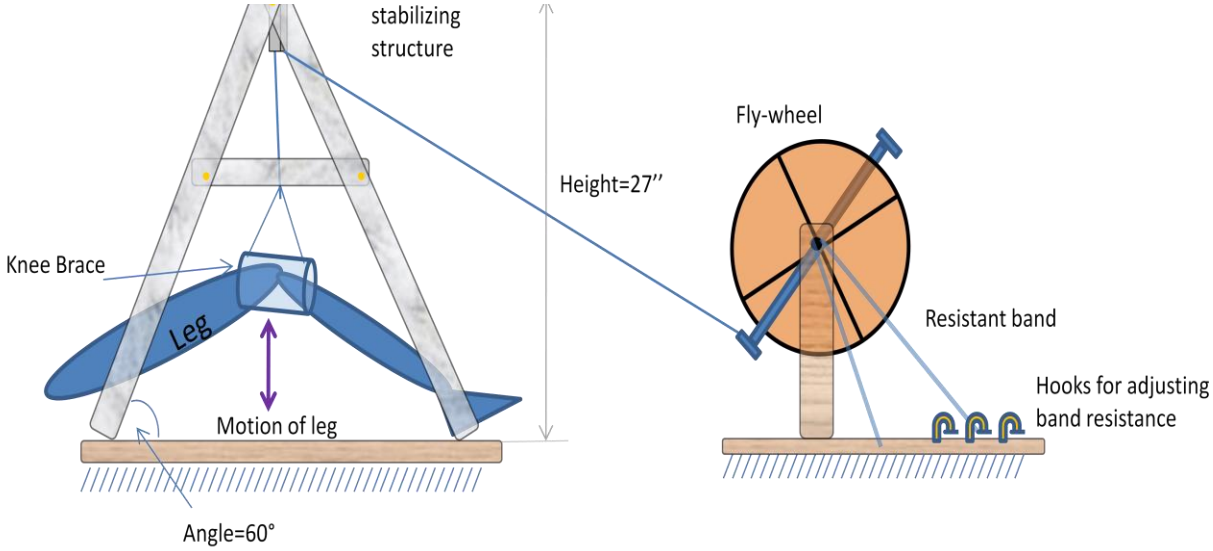
Figure 10: Blood Flow in Exterior Carotid Left Artery Dependent on Time



Final Design

The final system, a schematic of which is shown in **Figure 11**, is comprised of three components: a triangular supporting structure, a flywheel attached to a baseboard, and two removable knee braces. **Figure 14** and **Figure 15** show additional pictures of the device. The following final components were chosen after further research and reconsideration of preliminary designs. The design consists of two major pieces instead of the previously discussed one; this change was made to accommodate the sliding board on an MRI table. The board typically contains a raised structure at the end that is used as an emergency release to allow fast removal of a patient, and so cannot be modified or removed. Two pieces also improve the motility of the design; one MRI technician is now easily able to lift two small parts on to and off of the MRI bed. This improves the design's functionality and ergonomics and also minimizes the number of researchers required to perform a scan.

Figure 11: The Overall Design
The design consists of two triangular stabilizing structures, two knee braces, and a movable flywheel.



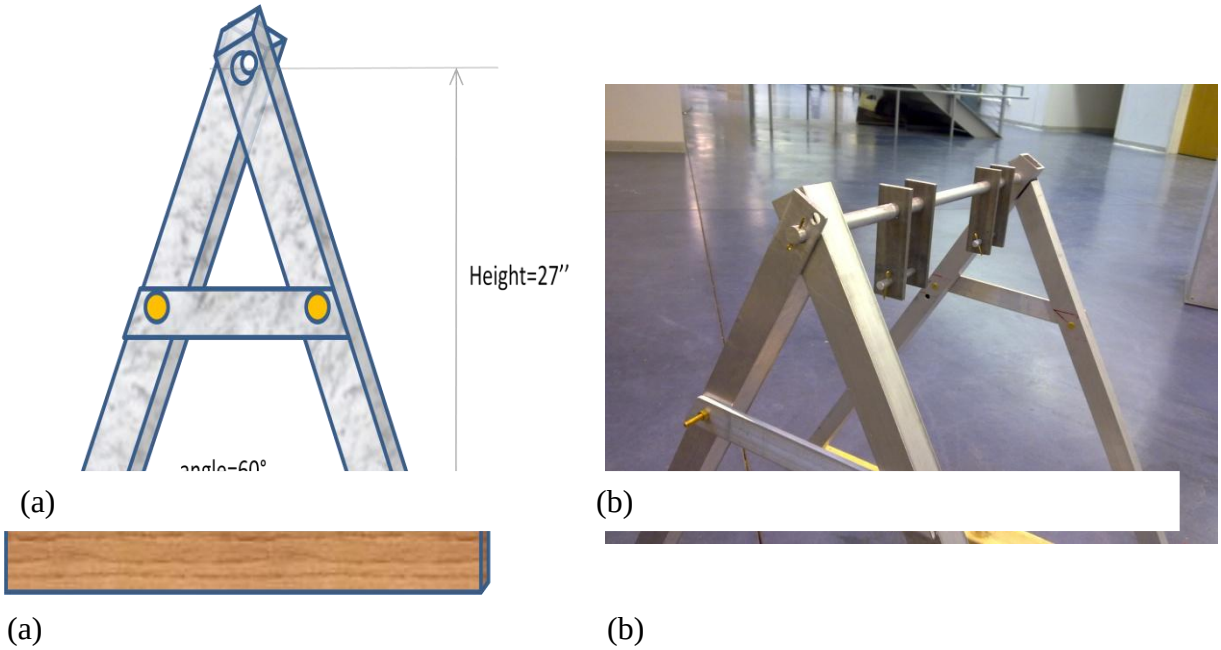


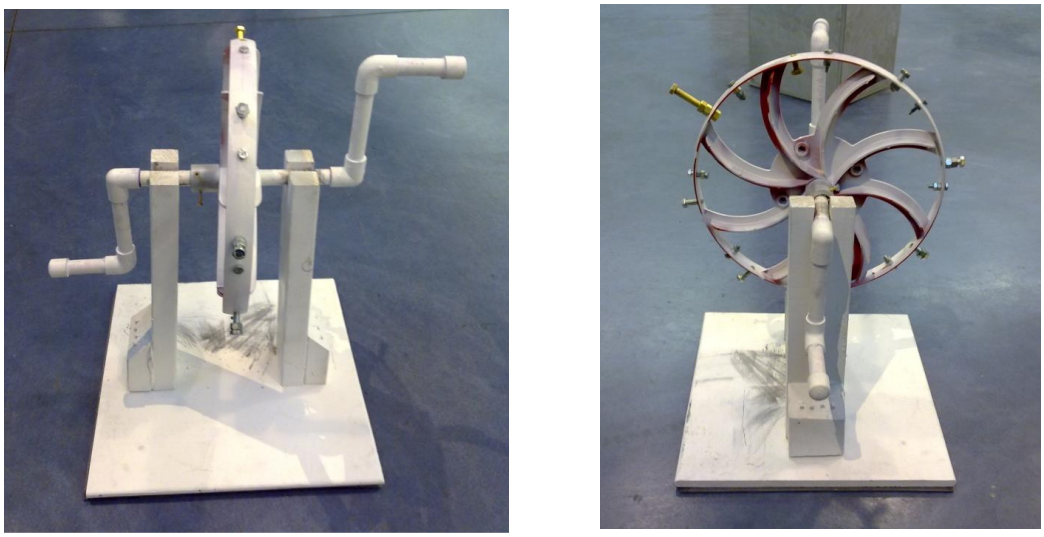
Figure 12: Triangular Supporting Structure Design.
(a). A schematic of the triangular structure design. (b). A picture of the completed structure.

The first component, a triangular supporting structure, was fabricated out of the non-ferromagnetic material aluminum beams and brass bolts and is shown in **Figure 12**. 2”x4” wooden beams make the base of the triangle and were used to support the aluminum beams and also prevent the aluminum beams from damaging the MRI bed. A yoga mat was affixed to the bottom side of the 2”x4” beams in order to provide extra protection for the MRI bed and to increase the coefficient of friction between the bed and the stabilizing structure. The height of the triangular structure is 27 inches (0.685m) from axle to the baseboard. The angle between aluminum beam and horizontal wooden beam is 60 degrees. The structure is 2 feet (60.9cm) wide, which is the maximum width of the MRI bed. The structure sits on the stationary outside of the MRI bed and does not contact the sliding patient bed, so if the sliding patient bed moves unexpectedly the triangle stabilizing structures should not move or injure the patient.

As shown in **Figure 13**, an aluminum bar was used as an axle to connect the two triangular aluminum structures. Connected to the axle are four rectangular aluminum pieces. A small aluminum was used to connect two pairs of two aluminum pieces, and this pulley-like structure is used as the supporting mechanism for straps to go over.

Figure 13: A Sketch Of An Aluminum Axle Design.
The aluminum square pieces were connected to the axle, and two smaller aluminum bars were connected between each pair of square pieces. This created two pulley-like structures.

Another component of the system, the flywheel, is shown in **Figure 14** and was used to induce a natural feeling motion. Theoretically, if flywheel's mass is relatively large, it could store the rotational energy caused by a patient's movement. Once a patient applies force on the side bars of the flywheel, the flywheel will rotate accordingly. When the side bars become parallel to the horizontal plane, the inertia of the flywheel would continue the rotation and allow the patient to exercise without stopping. This mechanism is essential in order to provide the patients with a natural feeling motion.

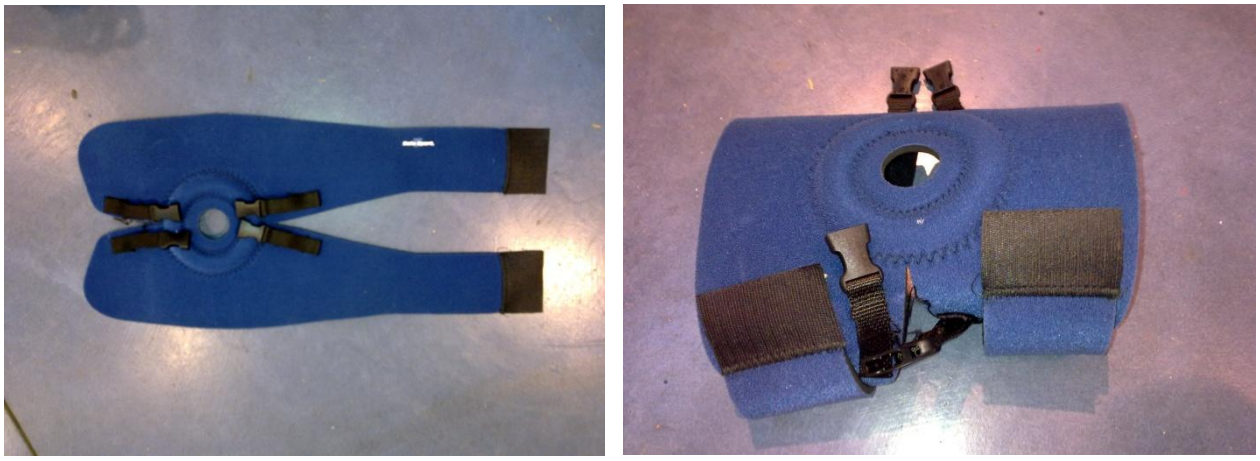


(a) (b)

Figure 14: The Flywheel Design
Two views of the plastic flywheel with peripheral bolts, a PVC axle, and a wooden baseboard. (a). A transversal view of the flywheel. (b) Front view of the flywheel.

Brass bolts were installed on the periphery of the flywheel in order to increase its inertia. Powdered graphite was applied to the area where the axle contacts the wooden supporting structure in order to reduce rotational friction. Ideally, a resistance band should be applied on the axle of the flywheel and used to control the flywheel's rotation. The adjustable resistance could be changed depending on the health condition of the patient or heart rate that the MRI scanning requires. However, because of the time limitations, the resistance band idea was not implemented this semester.

The final components of our completed design are the two knee braces. Shown in **Figure 13**, the knee brace's size is adjustable with Velcro and will fit a wide variety of patient legs. Plastic buckles were affixed onto the knee brace in order to connect the brace with the inextensible strap that attaches to the flywheel. This design changes the distribution of pressure from single strap to a large surface, and therefore increases patient comfort for the duration of exercise. The braces are made of neoprene, a durable and non-ferromagnetic material and are commonly used to treat sports injuries.



(a) (b)

Figure 13: Knee Brace With Plastic Buckles.
(a) Unwrapped knee brace from top view. (b) Wrapped knee brace.

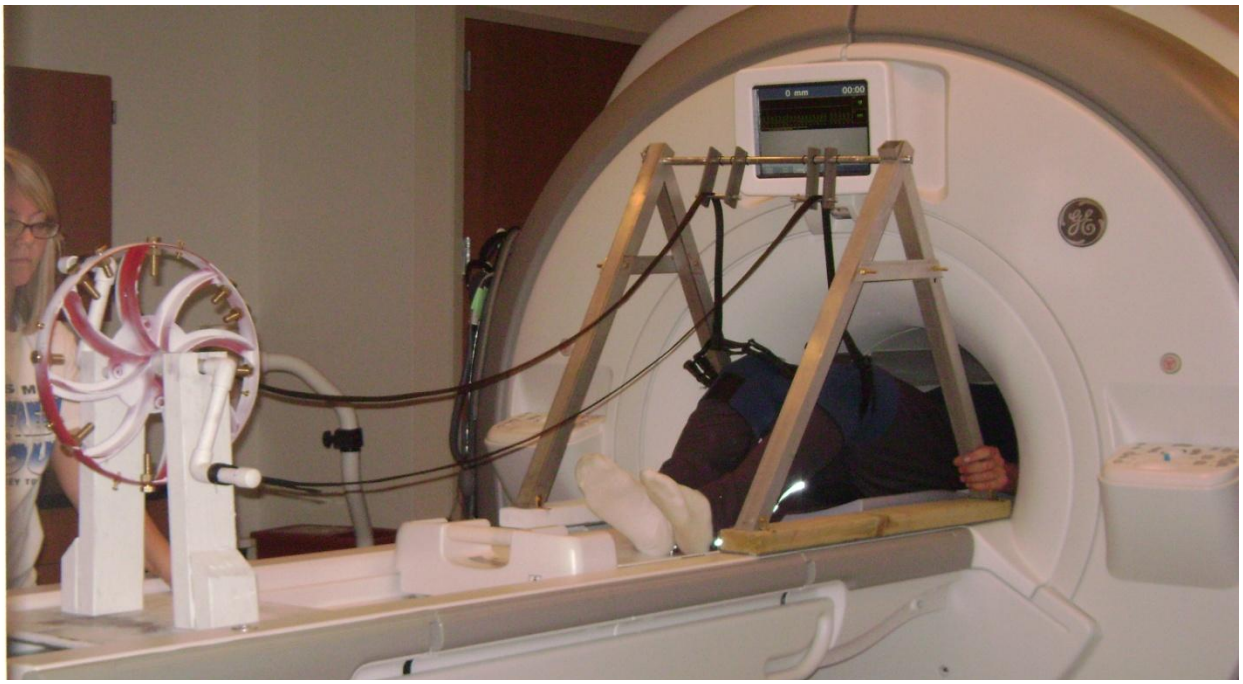


Figure 14: The Device In Use
Patient 3 is within the MRI using the device to exercise. Another member of the team is holding the flywheel at the end of the MRI to ensure the flywheel does not move during the test.

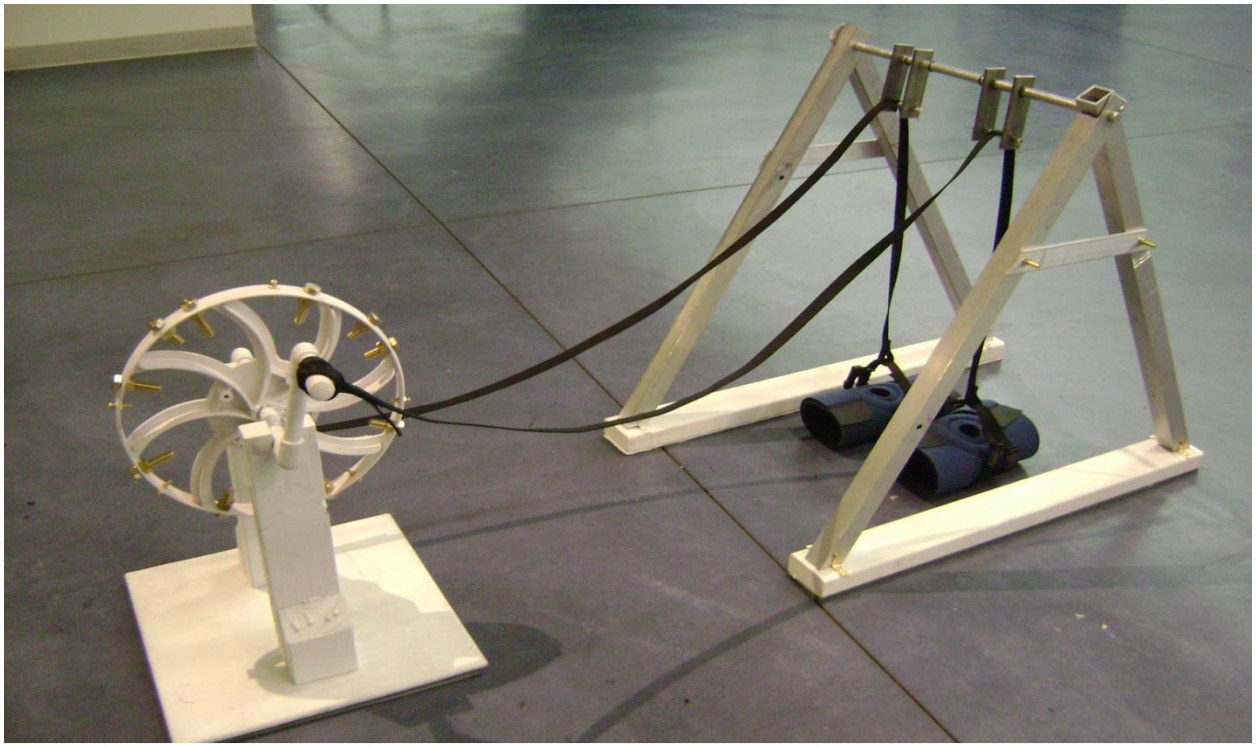


Figure 15: The Device
The device is laid out as it would be on an MRI bed. The patient's legs are inserted in to the knee braces and moved up and down to exercise.

Time Management

Tasks	January		February				March				April				
	21	28	4	11	18	25	4	11	18	25	1	8	15	22	29
Meetings															
Advisor															
Client															
Team															
Product Development															
Research															
Brainstorming															
Design Matrix															
Design Prototype															
Order Materials															
Fabricate Prototype															
Testing															
Deliverables															
Progress Reports															
PDS															
Mid Semester PPT															
Mid Semester Report															
Final Report															
Final Poster															
Website Updates															

Table 6: Summary of Time Management
A graphic detailing the design team's progress throughout the semester.

Throughout the early part of the semester, our time was divided fairly evenly between researching, brainstorming and designing our device. However, as the end of the semester approached we spent a majority of our time ordering and shopping for parts, as well as fabricating and testing our prototype. A detailed summary of our activities can be found in **Table 6**. Our team found that although we had our overall design set fairly early in the semester it took a fair amount of time to attain the correct parts necessary to build a functioning device. We also ran into an unexpected problem with the original prototype that was built. After moving it to the correct facility for testing, a part broke and brought to our attention the fact that one baseboard was not sufficient to support the device. To ensure maximum stability, the device was redesigned and rebuilt on two baseboards. Upon completion of this final component, the

device went through a series of tests with three separate test subjects. The final design was completed to allow sufficient time to schedule and perform an MRI scan test, which went on to demonstrate the device needed no further modifications as sufficient data could be collected from the MRI scans taken during exercise.

Costs

We initially had a $1000 budget for purchasing materials. A summary of the funds spent to complete the project is listed in **Table 7**. The initial prototype cost $70 and subsequent additions and modifications to the prototype cost $220.38. Additional materials, including the brass bolts and white paint finish, cost $77.99. In total, we spent $381, $619 under budget. We were fortunate enough to have a flywheel donated by Dr. Kreg Gruben, a professor in the Kinesiology department; this donation allowed us to focus more on the whole design rather than on the design and fabrication of a flywheel. The cost of the actual MRI scan, while unknown, should also be factored in to our budget and would increase the amount of money spent on the design and testing.

Date	Item	Cost	Comments
02/25/2011	Particle Board	$10	Smooth surface used with socks to simulate foot cart
02/25/2011	6 2x4 Beams	$10	Preliminary support structure
02/25/2011	Sawhorse Clamps	$7	Preliminary support structure
02/25/2011	2 Pulleys	$10	
02/25/2011	Foam Insulation	$2	Preliminary leg cushions
02/25/2011	Metal Rod	$5	For attaching pulleys to support structure
02/25/2011	Clothesline	$5	Non-ferromagnetic and inextensible; suggested by Dr. G
02/25/2011	Misc. Hardware	$7	Washers, nuts, and bolts
03/31/2011	50’ Nylon Webbing	$24.00	From McMaster.com, part number 3510T11
03/31/2011	10’ Hook and Loop	$8.65	From McMaster.com, part number 95005K813
03/31/2011	6 Slide-Release	$34.44	From McMaster.com, part number

	Buckles		29705T82
03/31/2011	2 Flat Belt Pulleys	$21.78	From McMaster.com, part number 6235K64
03/31/2011	2’ Plastic Roller Chain	$20.50	From McMaster.com, part number 6846K412
03/31/2011	24-tooth Nylon Sprocket	$20.77	From McMaster.com, part number 60425K52
03/31/2011	15-tooth Nylon Sprocket	$12.74	From McMaster.com, part number 60425K167
03/31/2011	2 FLA EZ-ON Knee Wraps	$77.50	From Thebraceshop.com, size Universal, SKU 37-307
04/05/2011	Gorilla Glue	$5.95	From Home Depot
04/05/2011	27 Brass Hillman Fasteners	$12.50	From Home Depot
04/05/2011	Aluminum Nails	$3.99	From Home Depot
04/08/2011	Wooden Dowel	$2.99	From Ace Hardware
04/08/2011	8 Brass L Brackets	$8.99	From Ace Hardware
04/25/2011	10 Brass Bolts (1/2” x 2” and 1/2 “ x 1.5”); 10 ½” Brass nuts, 3’ Aluminum 5/8” rod, 3/8” Brass rod, white spray paint	$70	Purchased with Dr. Schrage

Table 7: Accrued Costs

The bulk of our budget was spent at McMaster.com, as the site allowed us to order specific parts and quantities.

Future Work

Throughout the course of this semester we worked to develop a device that not only effectively exercised patients and increased their heart rate but also minimized head motion to an extent that an exercising patient could be scanned within an MRI. It was demonstrated that the device was effective in raising heart rate, and that increased blood flow and blood velocity could be observed in an exercising patient as the effect of a patient’s motion on the data collected from the scans was minimal. We have built a prototype that should effectively raise the heart rate of most patients, but testing showed that some patients were unable to truly achieve the target working heart rate and so the eventual goal of the device has not yet been realized.

Although we designed and built a large and heavy flywheel, the inertia generated while a patient exercises was not yet sufficient to keep the wheel moving in a fluid manner. If a patient does not keep a consistent rhythm while performing exercise, the flywheel can become stuck and remain motionless or abruptly change direction. This creates a non-natural feeling motion and makes it increasingly difficult for a patient to continuously exercise. A concrete or ceramic flywheel would be heavier and thus store more inertia during rotation. The concrete or ceramic flywheel would not require the addition of brass bolts and would therefore be less expensive and less complicated to manufacture.

The addition of a resistance band could also improve the ability of our device to increase a patient's heart rate. The device was tested by three fit patients who are able to perform greater amounts of work than hypertensive or obese patients, so it is not known for certain if the device will be able to effectively raise the heart rate of less fit patients. However, if a resistance band was added, the amount of work a patient would perform could be altered depending on the amount of resistance provided. The resistance band could also use a sensor to calculate the work performed based on the rotations per minute of the flywheel.

Another problem discovered during device testing was the tendency of the flywheel to abruptly switch its direction of motion. This created a motion that the patients described as un-natural and far from the ideal natural-feeling motion we were attempting to create. A mechanism could be added to the device that only allows the wheel to rotate in a single direction; the mechanism used could be similar to the gears on a fixed wheel bike that only allow the back tire to rotate in one direction. Additionally, a low-friction contact surface could be created between the patient's feet and the bed. Initial designs discussed 'foot carts,' but it was found that the use

of foot carts was superfluous. Simpler ideas include giving the patient low-friction socks or placing a low coefficient of friction surface underneath the patient's feet.

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Appendix

An MRI-compatible leg exercise device for assessing cerebral blood flow responses to exercise (Leg Exercise)

Project Design Specifications
03/09/2011

Group Members: Katherine Lake, Henry Hu, Kelsi Bjorklund, Jacob Stangl

Advisor: Michael Toepke, PhD

Function:

Traditionally, transcranial Doppler ultrasound can be used to measure human cerebral blood flow in response to environmental stress or exercise. Exercise-induced increased cerebral blood flow can then be analyzed to determine if cerebral blood flow patterns differ in patients suffering from obesity or pre-diabetes. Transcranial Doppler ultrasound is limited in that it only measures middle cerebral artery velocity. Magnetic Resonance Imaging (MRI) can be used to also study global cerebral blood flow patterns and blood vessel diameter, but any exercise device used in an MRI must be non-ferromagnetic. We aspire to design and test a durable, non-ferrous exercise device that utilizes dynamic exercise and that is able to raise the average patient's heart rate to 120-130bpm for a minimum of eight minutes.

Client Requirements:

- Must be non-ferromagnetic and fit on a standard MRI bed
- Must increase heart rate to 120-130bpm for a minimum of eight minutes
- Must minimize head and chest movement

1. Physical and Operational Characteristics

A. **Performance requirements**: The product must increase the heart rate of the user to 120-130bpm for a minimum of eight minutes but not allow significant movement along the anteroposterior axis.
B. **Safety**: The product must be non-ferromagnetic, stable, and safe to use in an MRI machine. The product cannot cause muscle injury in patients.
C. **Accuracy and Reliability**: The product must allow researchers to take precise and accurate images of blood vessel diameter and measure middle cerebral artery velocity.
D. **Life in Service**: The product must be usable for three years while undergoing frequent use.
E. **Operating Environment**: As the device is to be used while an MRI is in progress, no ferromagnetic materials may be used in construction.
F. **Ergonomics**: As this device will be used by a range of patients at varying heights and fitness levels, ergonomics is extremely important. The final product must allow patients to exercise using a "natural-feeling" motion. The product must also adjust to

fit male and female patients of average heights, from 5'4" to 6'4". The device must also have minimal set-up and be portable and simple for technicians and patients to operate.

G. **Size**: The product must be small enough to fit onto the standard MRI bed and should be positioned to ensure that a patient's movement during exercise is not restricted by the MRI bore.
H. **Weight**: The product should be as lightweight as possible without impeding functionality or usability as it is to be positioned on the MRI bed with the patient. A heavy product may limit the weight of potential research subjects or be difficult to transport and set up.
I. **Materials**: No ferrous materials can be used in the final product, as this device is to be used within 30 ft of a MRI. The materials that contact patients must be easily sterilized with alcohol to ensure cleanliness and allow the device to be used by multiple subjects.
J. **Aesthetics, Appearance, and Finish**: The product should be simple for both patients and researchers to use. The device should look professional and if possible, match the appearance of the MRI.

2. Production Characteristics

A. **Quantity**: One device should be constructed.
B. **Target Product Cost:** A similar prototype cost $275.50 so a new device should be under a budget of $1,000.

3. Miscellaneous

A. **Standards and Specifications:** If marketed, the final product will require the approval of the Food and Drug Administration.
B. **Customer:** The intended user is an exercise research study patient and will vary in fitness level and height. Thus, the product must be compatible with many different body types, be simple to operate, comfortable for the user and provide researchers with a way to adjust the resistance and applied workload. The product should also ensure head and neck stability in order to minimize any artifact in images captured by the MRI. Each of these requirements must be considered in designing a final product.
C. **Patient-related Concerns:** In order to be useful to researchers, the product must meet the terms of all and any Food and Drug Administration provisions relating to its design and use. It must not be harmful to the user in any way and it must allow a patient to exercise in a 'natural' motion. As multiple users are to exercise with the same device, it should be easily disinfected to prevent cross-contamination.
D. **Competition:** Similar products currently on the market do not allow a patient to exercise while being scanned and can cost upwards of $50,000, making these products ill-suited for many researchers. This device will allow researchers to observe cerebral blood flow during exercise and thus could become a competitor to these other products.