University of Wisconsin - Madison
Department of Biomedical Engineering

MRI-Compatible Cardiac Exercise Device

Final Report

Nick Thate – Leader
Evan Flink - Communicator
Tongkeun Lee - BWIG
Andrew Hanske - BSAC

Client: Professor Naomi Chesler, Department of Biomedical Engineering
Advisor: Professor John Webster, Department of Biomedical Engineering

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I. Abstract

The goal of this project is to develop an exercise device that can be used by patients in a magnetic resonance imaging (MRI) scanner in order to better understand and assess pulmonary hypertension. Currently, there is no device on the market that allows a patient to exercise during a cardiac MRI scan. A design was created which utilizes a stepping motion with adjustable weight resistance, and allows for a patient to exercise inside the MRI bore. The device was tested in a model MRI bore by four different subjects, and successfully raised their heart rates from initial values of 60-65 beats per minute (bpm) to 130, 128, 118, and 146 bpm. Subjects with a range in height from 5'7" to 6'3" effectively tested the exercise device in an actual MRI machine. These results demonstrate that this design is able to raise the heart rate of fit individuals and can accommodate patients with a wide range of heights. In the future this design could be improved by increasing its durability and decreasing its overall size, however this initial design was a success and shows promise to develop into a marketable product.

II. Problem Statement and Design Specifications

In order to better understand the effect of exercise on patients with pulmonary hypertension, Professor Naomi Chesler would like to use magnetic resonance imaging (MRI) to accurately measure changes in blood pressure and flow of the pulmonary arteries during exercise. Our task is to develop an MRI-compatible exercise device for patients undergoing cardiac MRI scans. It should allow the patient to exercise while lying within the MRI bore and have adjustable workloads so patients of varying fitness levels can generate a sufficient increase in cardiac output and heart rate.

There are several design requirements that the device must meet in order to be used effectively in a clinical setting. First and foremost, all materials should be MRI-compatible. This means that no ferrous metals, such as steel or iron, can be used. In addition, the device must be reasonably sized to allow for easy transportation and storage, and have a weight that, when combined with patient weight, is less than the MRI scanner weight limit of 150 kg. Of all major MRI models currently on the market, the smallest distance from the bed to the top of the bore is 42 cm [1]. Therefore, the device will be designed with these specifications so that it can be used with any scanner.

Another critical design specification is for the device to have an adjustable workload. Since the study will involve patients of a wide variety of fitness levels, the resistance level should be both measurable and variable for each patient. Moreover, the resistance should be sufficient to allow patients to reach the target heart rate zone, which is 70-80% of their maximum heart rate (220 bpm – age). The exercise motion should be natural and fluid, with no risk for patient injury. Additionally, since the patient's torso will be scanned by the MRI machine, movement of the upper-body should be minimized. For additional details on product specifications, see **Appendix A.**

III. Background Information

Pulmonary Hypertension

Pulmonary hypertension is a cardiovascular disease characterized by increased blood pressure due to narrowing in the pulmonary arteries. This will lead to overworking and enlargement of the right side of heart (seen in **Figure 1**), as well as low blood oxygen concentration. Some potential causes of pulmonary hypertension are HIV infection, lung or heart valve disease, certain diet medications, and any condition that causes chronic low oxygen levels in the blood, among others [2]. Major symptoms of pulmonary hypertension include shortness of breath and light-headedness during activity, fast heart rate, swelling of the lower extremities, bluish color of the lips or skin, chest pain or pressure, dizziness, fainting, weakness, and fatigue [2]. To diagnose pulmonary hypertension, ECG, CT scans of the chest, and nuclear lung scans, as well as physical examinations, are performed [2].

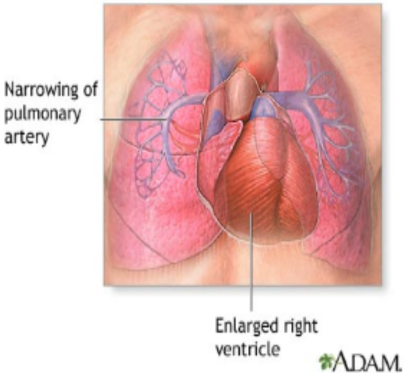

Figure 1 : The effects of pulmonary hypertension effects on the heart and pulmonary arteries [2]

Image courtesy of PubMed Health: http://www.ncbi.nlm.nih.gov/pubmedhealth/PMH0001171/

Currently, there is no specific treatment for pulmonary hypertension. Rather, the major goal of treatment is focused on controlling the symptoms of the disease. Professor Chesler is interested in determining how exercise affects the blood pressure of pulmonary hypertension patients, in order to better understand the disease as well as assess the severity in each patient. A common way to execute this study is to have patients exercise outside of the MRI bore and then quickly perform the scan. However, this method is flawed because the time difference allows the patient's heart rate and blood pressure to recover from the effects of exercise. Her study will use MRI scanning to test the pulmonary blood pressure before, during, and after specific exercise. Therefore, she requires an MRI-compatible exercise device that can be used within the bore while a patient is being scanned.

Competition and Past BME Designs

Several exercise devices have been designed for use with an MRI scanner. Lode B.V. provides several MRI-compatible devices that allow patients to exercise prior to MRI scans. These machines use a variety of exercise options, including cycling, ankle flexion, push/pull (seen in **Figure 2**), and up/down motions [3]. However, the major problem with these devices is that they are much too expensive; the lowest price found was $28,000 [4]. In addition, most cannot be used during a cardiac MRI scan.

Figure 2: The Push/Pull version of the Lode B.V. MRI Ergometer [3]

Image courtesy of Lode B.V. http://www.lode.nl/en/applications/mri_ergometry

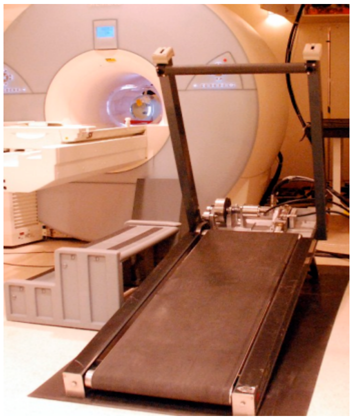

Figure 3: The MRI-compatible treadmill, designed by a team at Ohio State [6]

Image courtesy of MedCity: http://www.medcitynews.com/2009/05/commercialization-ramps-up-on-ohio-state-university-treadmill-used-for-mri-heart-tests/

Another current product, the MRI-compatible treadmill, was designed by a team at Ohio State University. It is essentially a separate treadmill outside of the scanner that has been completely modified to be compatible with the MRI environment [5]. This device can be seen in **Figure 3**. However, since exercise does not occur within the bore, this device has the problem of patient recovery between exercising and scanning, as mentioned above. Therefore, this device gives less accurate results than Professor Chesler desires.

Several UW-Madison Biomedical Engineering design teams have attempted similar projects in the past. One team spent two semesters (Fall 2009 and Spring 2010) working on a project with the same purpose and developed two prototypes. The first prototype was a cycling device, shown in **Figure 4**. The design team made a critical error by not designing the bike to fit the dimensions of the MRI bore. Therefore, when they attempted to test their prototype, the user's knees hit the edge of the bore which prevented them from completing the cycling motion. This resulted in the ultimate failure of their cycling design

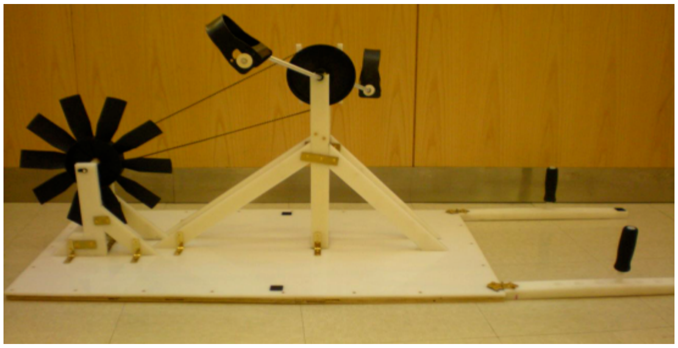

Figure 4: The cycling device developed by a UW-Madison biomedical engineering design team in Fall 2009 [7]

Image courtesy of UW-Madison BME Design: http://bmedesign.engr.wisc.edu/websites/project.php?id=29 idea. Because of this, the team had to design a completely new prototype.

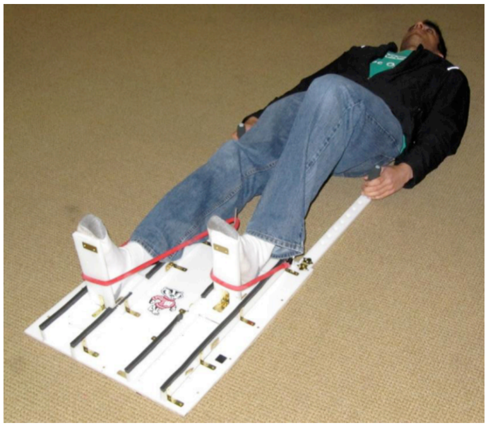

Figure 5: The stepper design, developed by the same group as the design in Figure 4 [8]

Image courtesy of UW-Madison BME Design: http://bmedesign.engr.wisc.edu/websites/project.php?id=295

Their second prototype was a stepping motion device that used two sliding foot pedals with fitness gear adjustable resistance tubes for the resistance (**Figure 5)**. The stepping motion of the device could be successfully completed while the user was in the MRI scanner; however, this prototype had several flaws. A major problem with the prototype was the large amount of friction generated between the foot pedals and the track. The design team did not mitigate this friction, leaving the two polyethylene surfaces to rub against each other during the motion. This decreased the smoothness of the stepping motion and reduced user comfort. Another problem with the prototype was the lack of support for the foot pedals. The foot pedals were held up by a thin brass facet and the resistance bands. This proved to be insufficient to withstand the force generated by the user. During testing and use following prototype completion, both pedals were broken. This shows that this prototype would have never withstood multiple patient trials. In addition to these structural defects, the prototype failed to generate sufficient resistance to allow the user to reach the target heart rate during exercise. According to the previous group's tests, the three subjects reached maximum heart rates of 88, 91, and 86 bpm [8]. That is only about 43-45% of their maximum heart rates, just barely more than half of the desired value. Due to these shortcomings, a more effective prototype is still needed.

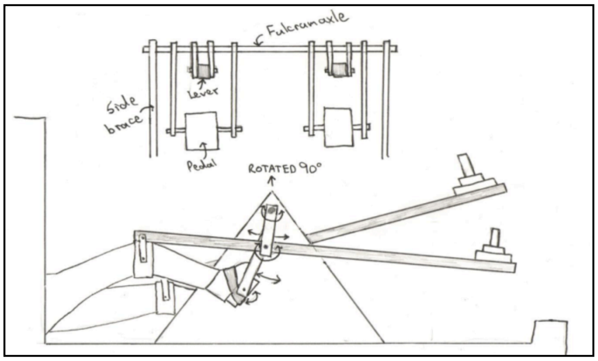

Figure 6: The device designed by a Fall 2010 UW-Madison biomedical engineering design team [9]

Image courtesy of UW-Madison BME Design: *http://bmedesign.engr.wisc.edu/websites/project.php?id=332*

In the fall of 2010, a separate BME design team developed another MRI compatible exercise device (**Figure 6)**. This team designed their prototype for patients that would be subjected to MRI scans of the brain [9]. The nature of these brain scans allows for more of the patient's body to be out of the MRI bore. Therefore, it is likely that this prototype would not work for the reduced space restraints of a cardiac MRI scan without modification. In addition, this device has several other flaws. It is quite bulky, which makes transportation and storage exceedingly difficult and may intimidate patients. In addition, this device features an unnatural loading mechanism, where the resistance pulls up on the user's knees. This strange method of loading would most likely lead to increased patient discomfort. Given these reasons, a modification of this design will not be pursued.

IV. Preliminary Testing and Results

At the beginning of the design process, a model MRI bore was constructed. The dimensions of the bore were acquired in a SolidWorks file from Professor Darryl Thelen, a faculty member at the UW-Madison Department of Biomedical Engineering. The dimensions were based upon the MRI scanner located at the Wisconsin Institutes for Medical Research (WIMR). Through contact with a medical physicist at the facility, Dr. Alejandro Roldán-Alzate, PhD., the team was able to get some additional firsthand experience with the machine. From these visits, it was determined that the position of the patient within the scanner is based solely on placing the heart squarely in the center of the bore. Of the four subjects that were measured, the edge of the bore was located 26.3 inches from their heart on average. During testing, this distance was used to place the patient in the correct position inside the mock MRI bore.

A variety of exercise motions were tested within this mockup in order to assess their viability. Almost immediately the cycling motion was eliminated, as the user could not perform the motion without hitting their knees on the top of the bore. However, an assortment of motions that were possible within the bore were identified as potential options. In order to determine if these motions had the ability to raise the heart rate to the desired level, several exercise machines were experimented with at the Southeast Recreational Facility (SERF) on the UW-Madison campus. The leg extension, leg-press, stair-climber (stepper), and calf extension machines were tested. The data collected from these tests is displayed in **Table 1.**

Table 0: Initial heart rate data collected at the SERF facility using exercise machines that were chosen to best simulate the motion of the potential prototypes

	Leg Extension	Leg Press	Stepper	Calf Machine
Time (min:sec)	3:30	3:00	3:00	1:20
Work Load	90 lb (41 kg)	170 lb (77 kg)	68 rpm	160 lb (73 kg)
Heart Rate (bpm)	158	134	164	123

Given these initial test results, the leg extension, leg press, and stepper motions were identified as viable options. The calf exercise was eliminated because the desired heart rate range was not reached before the subject had to stop due to muscle fatigue and discomfort. The stepper was identified as the most comfortable motion with the least burning sensation in the muscles, and it was the most successful at raising the heart rate. The leg extension caused significant muscle fatigue, but according to the subject it was a more natural motion than the leg press. It must be stated that these results are not definitive, but they show trends that are helpful in identifying potential designs.

V. Design Options

Leg Extension Design

The leg extension design features a motion where the knees are stationary and the legs are repeatedly extended. In this design, shown in **Figure 7**, the patient's legs are laid over an adjustable support and straps placed over the ankles resist the extension motion. The resistance could come from bungee cords or resistance bands. The leg support is adjustable in the vertical and horizontal directions using a sliding pin mechanism, allowing for patients of various heights to fit comfortably into the device. One benefit of this device is the natural motion and the fluidity throughout the course of the movement. The patient would be able to extend their leg in whichever radius felt most comfortable to them. However, this same motion could cause problems because it isolates the quadriceps, which could result in muscle fatigue and discomfort.

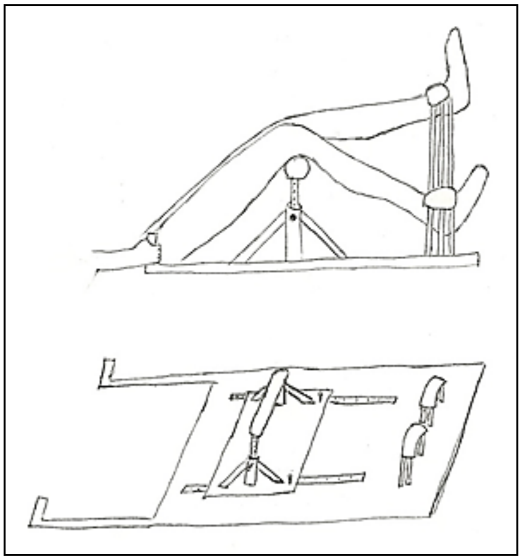

Figure 7: The leg extension design option

The relative small size and weight of this device would allow for easy transportation and storage, and ensure that the device is within the maximum load limit of 150 kg for the MRI couch. One concern for this design is the possibility of fatigue in the resistance bands between successive trials. This could cause a reduction in the resistance which could create complications when comparing different patient trials. Despite this the leg extension motion showed the ability to increase the patient's heart rate to the desired range in preliminary testing, and therefore shows promise to be a viable design.

Leg Press Design

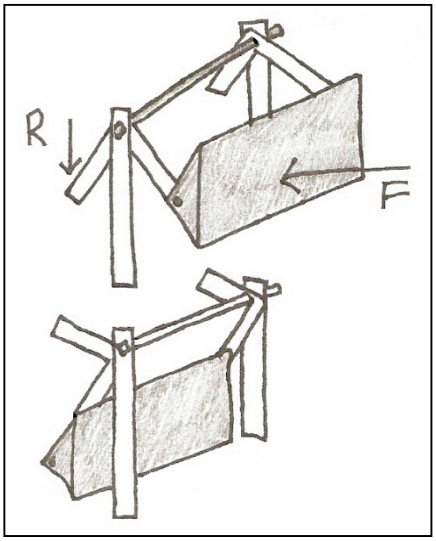

Figure 8: The leg press design option

The second design option is similar to an exercise machine called the leg press. In order to use this machine, the user pushes on the flat plate with both feet while lying in the supine position and holding the upper body still. When force is applied to the plate, it will rotate forward while the resistance causes the plate to push back against the patient's feet. This motion can be seen in **Figure 8**. After performing the preliminary exercise tests, it was determined that this design had the potential to effectively raise the heart rate to the target zone. Also, this design would be fairly easy to fabricate and would most likely be the most durable of the three. However, there are some drawbacks to this design. First, this type of exercise is meant for weight lifting and not aerobic exercise, so performing the motion repeatedly is somewhat unnatural and causes muscle fatigue and burning. Second, this specific design would be the largest of the three designs, which is not ideal because there is a weight restriction and the client would like the device to be small. Finally, while performing the exercise, this device produces the most upper body movement, which is undesirable because the chest area is being scanned.

Stepper Design

The third and final design is called the stepper, which was inspired by a stair-climber exercise machine. This design uses two levers, one for each foot, which the patient pushes against separately while in the supine position. When the patient pushes on the lever arm closest to them, it will rotate around a center axis, similar to the leg press, and there will be resistance pushing back against their feet. The stepper design can be seen in **Figure 9.**

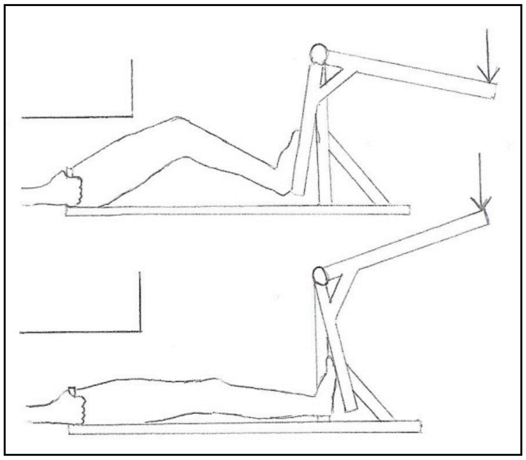

Figure 9: The stepper design option

This particular exercise device has many positive attributes. First, a similar exercise machine was able to easily raise the heart rate to the target zone during preliminary exercise testing, and the test subject described the motion as natural and comfortable with little to no muscle burning. Secondly, compared to the stepper design prototype fabricated by the past BME design team, this design will allow for a smoother motion with reduced friction. Although this design has many positives, there are also some negatives. The stepper device is composed of many moving parts that may require glass bearings, so there is more opportunity for pieces to break or wear out.

VI. Design Selection

In order to determine the best design to pursue for the remainder of the semester, the merits of the leg extension, leg press, and stepper design ideas were all weighed using a design matrix (**Table 2)**. Seven different criteria were deemed important for an effective design: patient comfort, motion mechanics, effectiveness, durability, ease of assembly, size/weight, and cost. Each of these criteria was then given a weight that corresponded to that criteria's relative importance. The three that were given the most weight were patient comfort, motion mechanics, and effectiveness.

Patient comfort is extremely important for this device because there is already some level of discomfort involved with being inside of the potentially claustrophobic MRI bore. The exercise device should not add to that by being uncomfortable or strenuous to use. Motion mechanics was defined as how natural and fluid the motion is for the patient. It should be feasible for even the most un-athletic of patients. Finally, the design must be able to raise the patient's heart rate to the target zone effectively. Therefore, effectiveness was considered one of the most important criteria.

Each of the designs was rated on a 0-10 scale for each of the seven criteria. These scores were then multiplied by their weight and totaled, giving an overall design score on the same 0-10 scale. The design matrix, complete with each design's scores, can be seen below in **Table 2**.

Table 1: The design matrix used to weigh the pros and cons of each design option, which ultimately resulted in the stepper design being chosen

Weight	Criteria	Leg Extension	Leg Press	Stepper
0.2	Patient Comfort	6	7	9
0.2	Motion Mechanics	9	7	8
0.2	Effectiveness	8	7	9
0.15	Durability	6	8	7
0.1	Ease of Assembly	8	7	6
0.1	Size/Weight	9	6	8
0.05	Cost	9	7	7
	Weighted Average	**7.65**	**7.05**	**8**

As seen in the design matrix above, the stepper design scored the highest, with a score of 8/10. It was followed by the leg extension (7.65/10) and the leg press (7.05/10). It managed high scores in the three most highly weighted categories, which helped lead to it being chosen as the best design.

VII. Final Design

The final design chosen to be pursued this semester was the stepper design. It is composed mostly of ½ inch (1.27 cm) thick high-density polyethylene (HDPE), aluminum, and brass, which are all non-ferrous materials and MRI compatible. The base of the device is 2 feet by 3 feet (0.6096 m x 0.9144 m) and has three, vertical, 2 foot (0.6096 m) tall I-beam supports on it. The L-shaped lever arms are 1.75 feet (0.5334 m) long on the foot pedal side and 3.5 feet (1.0668 m) long on the weighted side. These were also made into I-beams in order to add structural integrity and strength to the device. The lever arms rotate around an aluminum rod on acetal and glass bearings. PVC pipes with a diameter of 2.25 inches (5.715 cm) were used around the rod, along with two rubber stoppers at each end, to provide lateral stability for the lever arms. Additionally, diagonal supports and brass L-brackets were added to each vertical I-beam to add strength to the device. A SolidWorks model of the exercise device can be seen in **Figure 10**. Another feature that was added to the device was a yoga mat on the bottom in order to increase patient comfort while lying down as well as help secure the person and device in position. Parts of the yoga mat were also used to provide padding on the foot pedals for patient comfort. Finally, two

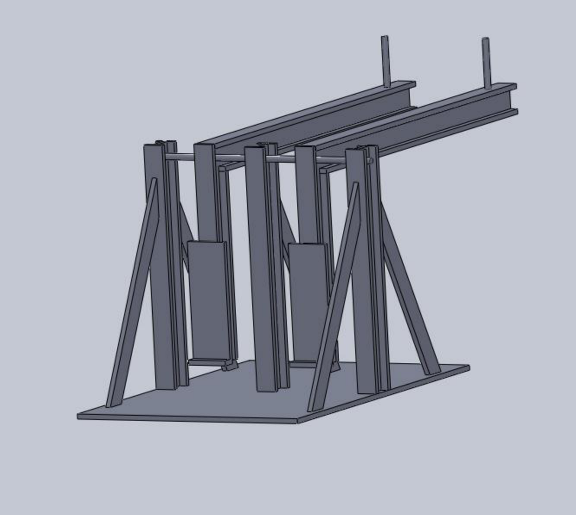

Figure 10: SolidWorks model of the design

nylon straps were attached to the base of the device for the patient to grip during exercise. This reduces chest movement, which minimizes motion artifacts during a cardiac MRI scan. A full bill of materials and costs can be seen in **Appendix B**.

Two options were considered as sources of resistance for the device: resistance bands and weights. Resistance bands are lightweight and portable, however they offer variable resistance at different stretch lengths and can fatigue over time. Weights are heavier and harder to transport, but they offer consistent resistance throughout the entire exercise motion. Additionally, weights facilitate determining the power produced by the subject during exercise. Ultimately, due to these benefits and the client's preference, weights were chosen as the mode of resistance.

VIII. Prototype Testing and Results

Exercise Testing

After the prototype was constructed, it was subjected to several forms of testing to determine its effectiveness. First, calculations were made to determine the relationship between the power produced by the patient and two variables: added mass and exercise cadence (rate). Each subject was positioned in the mock MRI bore model according to the specifications measured in the MRI at WIMR. The difference in vertical displacement of the weighted ends of the lever arms at maximum and minimum patient leg extension was measured experimentally by taking the average of the four test subjects; averaging to be a 15 inch (0.381 m) range. Then principles of trigonometry, center of mass, and conservation of gravitational potential energy were used to determine the amount of work the patient must put into the system in order to perform one stepping motion. This was then multiplied by the exercise cadence in order to determine the power produced by the user. All of these calculations can be seen in further detail in **Appendix C.** The final relationship was determined to be

$$P=R[0.05606J*minkg*secm+0.06857(J*minsec),$$

where P is power produced (Watts), R is exercise cadence (steps/min), and m is the added mass (kg). This gives a good estimate of the power produced during exercise, as a function of added mass and exercise cadence. Some assumptions made in these calculations include the fact that exercise is always characterized by the same range of motion, that the extended leg position leaves the foot pedal at a 90 degree angle with the ground, and that the subject fully extends their leg each repetition.

This equation was then used to calculate the power produced at a variety of added masses and exercise cadences. All possible combinations of added mass (with the available weights) and cadences ranging from 60 to 180 steps/min were evaluated using the MATLAB code seen in **Appendix D.** The results are summarized in **Table 3** below.

This table can be used as a guide to select a proper weight and cadence to produce a desired amount of power. In addition, the graphs in **Figure 11** illustrate the linear relationships that exist between power produced and both exercise cadence and added mass when one of those variables is held constant.

Table 3: Power produced for a variety of mass-cadence combinations

Power Produced for Various Combinations of Mass and Cadence (Watts)														
Exercise Cadence (steps/minute)														
		60	70	80	90	100	110	120	130	140	150	160	170	180
Added Mass (kg)	0.00	4.11	4.80	5.49	6.17	6.86	7.54	8.23	8.91	9.60	10.29	10.97	11.66	12.34
	1.14	7.95	9.27	10.60	11.92	13.25	14.57	15.90	17.22	18.55	19.87	21.20	22.52	23.85
	2.00	10.84	12.65	14.46	16.26	18.07	19.88	21.68	23.49	25.30	27.10	28.91	30.72	32.52
	3.14	14.68	17.12	19.57	22.01	24.46	26.91	29.35	31.80	34.24	36.69	39.14	41.58	44.03
	3.64	16.36	19.08	21.81	24.54	27.26	29.99	32.72	35.44	38.17	40.89	43.62	46.35	49.07
	4.77	20.16	23.52	26.88	30.24	33.60	36.96	40.32	43.68	47.04	50.40	53.76	57.12	60.48
	5.64	23.08	26.93	30.78	34.63	38.47	42.32	46.17	50.02	53.86	57.71	61.56	65.41	69.25
	6.77	26.89	31.37	35.85	40.33	44.81	49.29	53.77	58.25	62.73	67.21	71.70	76.18	80.66

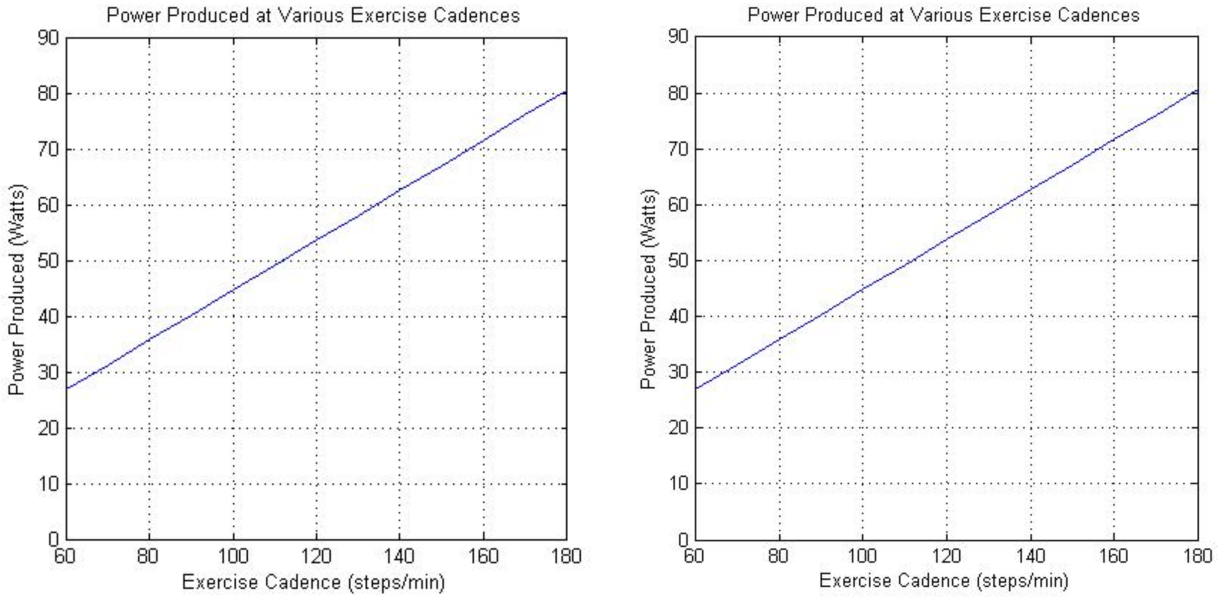

Figure 11: Graphs of power produced for changing exercise cadences with constant m = 6.77 kg and changing added masses with constant R = 130 steps/min

Determining the maximum attainable heart rate that could be achieved through exercise with the device was the next step in exercise testing. The four test subjects were once again positioned in the mock MRI bore, and instructed to use the device for ten minutes without rest. A pulse oximeter was used to continuously measure their heart rates. The test setup used can be seen in **Figure 12.**

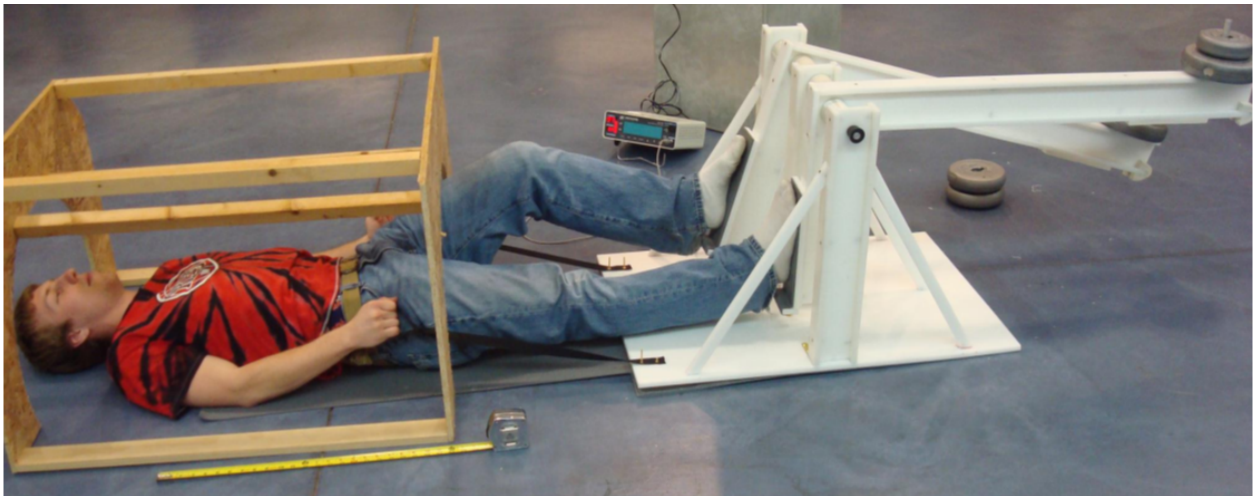

Figure 12: The test set-up used for exercise testing

For the purpose of this testing, 14.9 pounds (6.77 kg) of mass was added to the end of each lever arm. In addition, subjects were instructed to exercise according to the pace given by a metronome, set at 130 steps/min. This is equivalent to approximately 58 Watts of power, according to **Table 3.** On average, the test subjects were able to increase their heart rate from a resting heart rate of 61.75 bpm to 130.5 bpm. The complete results of this testing can be seen in **Table 4**.

The test subjects, on average, were able to reach 65.58% of their maximum heart rate through exercise with this prototype. This is quite close to the original goal of 70-80%. Moreover, the data recorded may be artificially low because a pulse oximeter is not the most accurate method for collecting heart rate data when the subject's finger is constantly moving during exercise. In addition to this potential error, many patients with pulmonary hypertension are generally not in as good of physical condition as the four subjects who tested the device. Less fit individuals tend to have their heart rates increase more rapidly during heavy exercise; therefore, it should be easier for them to reach the target heart rate zone.

Table 4: Resting, exercising, and % of maximum heart rates for four subjects

Subject	Resting HR (bpm)	Exercising HR (bpm)	% Max. HR
1	65	130	65.33
2	62	128	64.32
3	62	118	59.30
4	58	146	73.37
Average	**61.75**	**130.50**	**65.58**

MRI Testing

MRI testing was executed at the WIMR MRI laboratory. Two of the four subjects were tested to verify whether the function of the prototype is physically compatible with the MRI bore. With the aim of validating the potential for use with a wide range of user heights, the shortest and the tallest individuals were tested. The first subject was 5'8" (172 cm) tall and the second one was 6'3" (191 cm) tall.

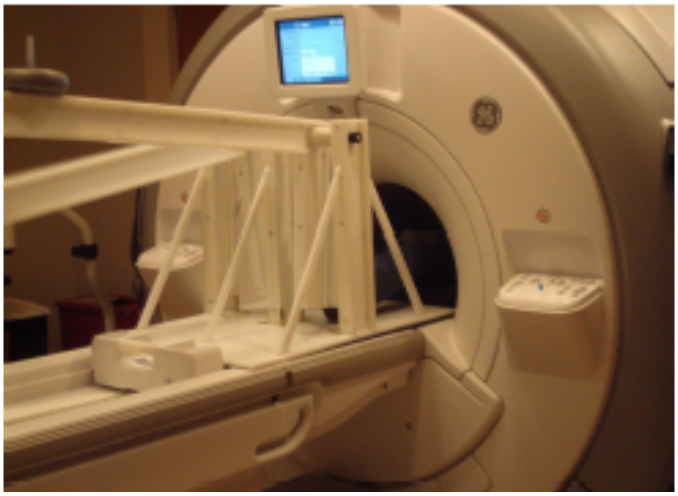
Figure 13: Testing of the prototype within the WIMR MRI bore

In order to carry out the test, the subjects were instructed to lie straight on their back on the MRI couch. All requisite scanning coils and padding that are used in normal cardiac scans were put into place. The position of the prototype was set to an adequate position relative to the user to ensure the correct range of motion. The exerciser was positioned in such a way that the foot pedals on the prototype were perpendicular to the ground when the subjects fully extended their legs. Once the position of the exerciser was set, the patient was moved into the MRI bore so that their heart was in the center of the bore. **Figure 13** shows the device being used successfully within the scanner at WIMR.

Although at least two people were needed to securely set the prototype during exercise, the prototype was certainly compatible with the MRI table and bore with regards to size and weight. Additionally, in spite of the limited space inside of the bore, the subjects were able to accomplish the desired exercise motion without any trouble. The subjects did not report any problems relative to comfort of motion or safety issues. During exercise testing in the model MRI bore, the subject would occasionally slide backwards due to the force of the added resistance. However, while inside the actual scanner, the position of the subject stayed constant due to the chest strap and cushions, regardless of the amount of weight added to the machine.

Overall, the MRI testing validates the compatibility of the prototype with the MRI scanner. Subjects with a range of heights are able to use the prototype. Also, it was verified that the prototype provides comfortable motion without any risk of subject injury as well as an effective range of motion in spite of the limited space.

IX. Future Work

The prototype provided promising initial results; however, there are still several improvements that could be made. The most important of which is to increase the durability of the device. During testing, if the subject tried to move their feet laterally, the components on the aluminum rod, such as the PVC braces, glass bearings, and rubber stoppers, would experience a large amount of lateral forces. After many repetitions, these forces would slowly push these components apart. The newly created spaces between the parts reduced the effectiveness of the PVC braces and eventually caused the lever arms to detach from the bearings. In the future, the rubber stoppers on the ends will be replaced with a more permanent fastening mechanism and the bearings will be removed entirely. The bearings were the sole source of weakness in the prototype and are not critical to the rotating motion. The reduction in friction provided by the bearings proved not to be worth the durability issues they presented, and in fact the additional resistance provided by the friction might actually improve the device.

The effectiveness of the exerciser could also potentially be enhanced by increasing the patient's range of motion and providing the option to add more resistance. In the current prototype there are a few inches between the foot pedals and the base. If this space was reduced by lowering the pedals, the patient would have a greater range of motion and thus be able to generate more work per repetition. The patients work output could also be increased by allowing them to add even more resistance. Currently the maximum amount of non-magnetic weight available to be put on the device is 14.9 pounds (6.77 kg) per lever arm. In the future, more weights could be procured or resistance bands could be added to increase the maximum amount of resistance the device could supply. With this increased resistance, the length of the lever arms could potentially be decreased without compromising the effectiveness of the exerciser. This would make it less bulky and ameliorate the transportation of the device.

The first prototype already gave the user a comfortable exercising experience, but with several adjustments there could be even greater patient comfort. One simple improvement is to replace the nylon straps with better hand grips. Another more difficult change would be to employ a mechanism that would synchronize the lever arm movements so that if one of the levers were pushed the other would move back towards the user. This would make it easier for the patient to keep a steady pace and it would force them to exercise with an alternating stepping motion.

Finally, the device could be improved by adding ways to automatically track and measure the stepping rate of the patient during the exercise. This data would help determine the power the patient is producing and it could be used to tell the patient to either decrease or increase their pace. After these changes are made, the device will be used by members of the design team during an actual MRI scan to acquire data on blood pressure and flow during exercise. International Review Board (IRB) approval for human testing will then be attained in order to utilize the device in clinical trials on patients with pulmonary hypertension. Overall, the prototype proved to be a success and satisfied all of the major design requirements. Following implementation of the discussed improvements, this design has great potential to become a marketable product.

X. References

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XI. Appendix A: Product Design Specifications

Problem Statement

In order to better understand the effect of exercise on patients with pulmonary hypertension, Professor Naomi Chesler would like to use magnetic resonance imaging (MRI) to accurately measure changes in blood pressure and flow of the pulmonary arteries during exercise. Our task is to develop an MRI-compatible exercise device for patients undergoing cardiac MRI scans. It should allow the patient to exercise while lying within the MRI bore and have adjustable workloads so patients of varying fitness levels can generate a sufficient increase in cardiac output and heart rate.

Client Requirements

- MRI-compatible
- Comfortable exercise motion in supine position
- Sufficient resistance to increase heart rate and cardiac output
- Adjustable workload

Design Requirements

1. Physical and Operational Characteristics
    a. *Performance requirements:* The device should provide a natural exercise motion that can be performed while the patient is within the MRI bore. The workload provided must increase the patient's heart rate to >70-80% of their maximum predicted heart rate, which is equal to 220 beats/min minus the patient's age. It needs to be adjustable for various patient fitness levels and heights (150-200 cm).
    b. *Safety:* All materials must be MRI-compatible (non-magnetic) for the safety of the patient, scanner, and medical staff. The exercise motion cannot put the patient at risk for injury during use.
    c. *Accuracy and reliability:* The design should provide consistent workload settings from patient-to-patient. All patients should be able to reach the target heart rate.
    d. *Life in service:* The device must be able to withstand clinical use for five years.
    e. *Shelf life:* N/A
    f. *Operating environment*: The design will be used in clinical or research settings in the presence of an MRI scanner and ECG leads.
    g. *Ergonomics:* The motion should be natural, fluid, and controlled without any undesirable friction.

  h. *Size:* The device must allow for exercise within the bore of any MRI scanner. The standard measurements of the bore are 42 cm from the couch to the top and 60 cm in width.
  i. *Weight:* The weight on the couch cannot be greater than 150 kg, so the device will not exceed 25 kg. Individual components should not weigh more than 15 kg to ensure portability.
  j. *Materials:* All components must be durable and made of non-ferrous materials.
  k. *Aesthetics, appearance, and finish:* The device should be quiet and not intimidating to the user.

2. Product Characteristics
    a. *Quantity:* One working prototype
    b. *Target product cost:* $200.00

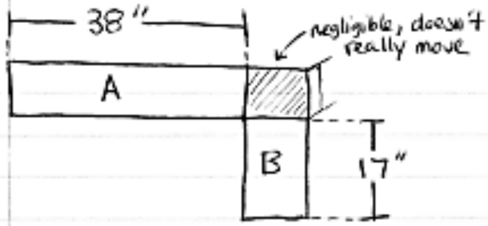
3. Miscellaneous
    a. *Standards and specifications:* Must pass inspection for use in MRI and eventually be IRB approved for human trials
    b. *Customer:* Hospitals, clinics, and research labs
    c. *Patient-related concerns:* Comfortable, safe, and durable
    d. *Competition:* Lode B.V. MRI Ergometer, prototypes from other universities, and past and present UW BME design projects

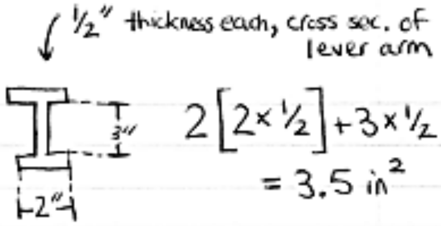
XII. Appendix B: Bill of Materials and Costs

MATERIALS	**COST**
18 ft^2 (1.672 m^2) of ½ in. (0.0127 m.) thick HDPE	$120.00
116 solid brass screws	$14.88
8 brass L brackets	$3.12
3 ft. (0.914 m.) solid aluminum rod	$17.75
20 brass nuts	$3.40
2 acetal/glass ball bearings	$21.46
2 rubber stoppers	$1.20
Yoga mat	$20.00
2.25 in. (0.0572 m.) diameter PVC pipe	FREE
Foam padding	$6.58
2 nylon straps	$2.46
2 tensioning buckles	$0.82
TOTAL	**$211.67**

* Prices listed do not include shipping and handling or sales tax

XIII. Appendix C: Derivation of Power Produced Formula



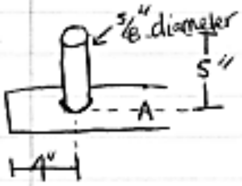


$$2\left[2\times\tfrac{1}{2}\right]+3\times\tfrac{1}{2}$$
$$= 3.5\ \text{in}^2$$

density of HDPE = $950\ \text{kg/m}^3 = 0.00095\ \text{kg/cm}^3$

volume of A = $38\times3.5 = 133\ \text{in}^3 \longrightarrow 2179.48\ \text{cm}^3$
volume of B = $17\times3.5 = 59.5\ \text{in}^3 \longrightarrow 975.03\ \text{cm}^3$

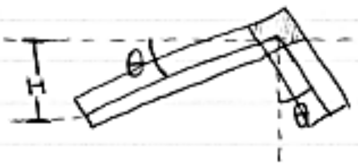
mass of A = 2.07 kg
Mass of B = 0.93 kg

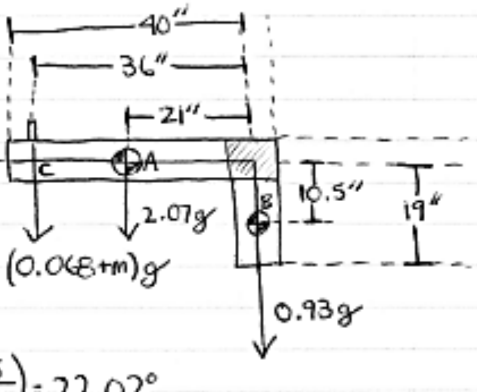


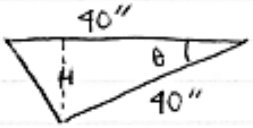
density of aluminum = $2700\ \text{kg/m}^3 = 0.0027\ \text{kg/cm}^3$
volume of rod = $\pi\left(\frac{5/8}{2}\right)^2\times5 = 1.53\ \text{in}^3 \longrightarrow 25.14\ \text{cm}^3$

mass of rod = 0.068 kg

H = 15" on average, measured experimentally

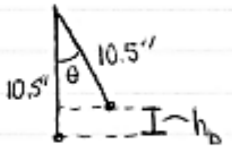






$$\theta = \sin^{-1}\left(\frac{15}{40}\right) = 22.02°$$

$h_a = 21\ \text{in}\left(\sin 22.02\right) = 7.875\ \text{in} = 0.20\ \text{m}$
$h_c = 36\ \text{in}\left(\sin 22.02\right) = 13.5\ \text{in} = 0.34\ \text{m}$



$h_b = 10.5\ \text{in} - 10.5\ \text{in}\left(\cos 22.02\right) = 0.77\ \text{in}$
$= 0.019\ \text{m}$

$$
\begin{aligned}
\Delta W &= U_{gf} - U_{gi} \\
&= m_A g h_A - m_B g h_B + m_C g h_C \\
&= 2.07\,\text{kg}\,(9.81\,\text{m/s}^2)(0.20\,\text{m}) - 0.93\,\text{kg}\,(9.81\,\text{m/s}^2)(0.019\,\text{m}) \\
&\qquad + ((0.068 + m)\,\text{kg})(9.81\,\text{m/s}^2)(0.34\,\text{m}) \\
&= 4.06\,\text{J} - 0.18\,\text{J} + 0.23\,\text{J} + 3.36(m)\,\text{J/kg} \\
&= 4.11\,\text{J} + 3.36(m)\,\text{J/kg}
\end{aligned}
$$

$$
P = \underset{\text{in steps/sec}}{\underset{\Uparrow}{R}}(\Delta W) \Rightarrow \boxed{P = \underset{\text{in steps/min}}{\underset{\Uparrow}{R}}\left(0.06857\,\frac{\text{J-min}}{\text{sec}} + 0.05606\underset{\text{in kg}}{\underset{\Uparrow}{(m)}}\,\frac{\text{J-min}}{\text{kg-sec}}\right)}
$$

XIV. Appendix D: MATLAB Code to Evaluate Power Produced

```matlab
% Set up the range of values for added mass and exercise cadence
m=[0 1.14 2 3.14 3.64 4.77 5.64 6.77];
R=[60 70 80 90 100 110 120 130 140 150 160 170 180];

% Set up the table for power produced
P=zeros(8,13);

% Fill in the table using the calculated equation for power produced
for X=1:8
for Y=1:13
    P(X,Y)=(R(Y))*(0.05606*m(X)+0.06857);
end
end
P

% Plot the relationships between power produced and both added mass and
exercise cadence, when the other is held constant
mc=6.77;
Rc=130;
Pmc=R*(0.05606*mc+0.06857);
plot(R,Pmc)
axis square
Prc=Rc*(0.05606*m+0.06857);
figure
plot(m,Prc)
axis square
```