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Department of Biomedical Engineering

MRI-Compatible Cardiac Exercise Device

Final Report

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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. Our client, Professor Naomi Chesler, would like to use MRI to accurately measure changes in pulmonary blood pressure and flow during exercise. Currently, there is no device on the market that allows a patient to exercise during a cardiac MRI scan. The final design was based on our previous prototype which utilized a stepping motion with adjustable weight resistance. Major modifications made to the previous design include: a block housing for the bearings; backpack, foot, and hand straps to secure the patient; a stopping mechanism to hold the lever arms in place; and base tracks to improve compatibility with the sliding MRI couch. The final device was tested outside the MRI bore to determine the maximum achievable heart rate increase. Subjects were able to raise heart rates from initial values of 73, 74, 70, and 68 beats per minute (bpm) to 119, 143, 122, and 110 bpm, respectively. Subjects with a range in height from 5'7" to 6'3" effectively tested the exercise device in a 3 Tesla, 70 cm MRI scanner. Real-time MRI scans were taken while a subject was exercising in the bore and provided evidence of pulmonary artery area change during exercise. This can be used to assess stiffness and blood pressure of the pulmonary artery. These results demonstrate that this device could be used with pulmonary hypertension patients in the future to characterize, diagnose, and assess the progression and severity of the disease.

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 be adjustable so patients of varying fitness levels and sizes 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]. However, the bore of the 3 Tesla scanner at the UW Hospital that we will be using for testing has a height of 50 cm. The device will be designed to meet the specifications of both MRI scanners.

Another critical design specification is for the device to be adjustable for the specific user. The device should accommodate a variety of patient sizes. Since the study will involve subjects of differing fitness levels, the resistance level should be both measurable and variable for each patient. Moreover, the resistance should be sufficient to increase cardiac output enough to see physiological changes in the pulmonary artery through real-time MRI. 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 lowered systemic 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].

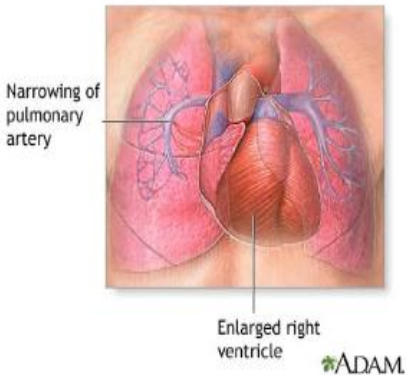


Figure 1 : The effects of pulmonary hypertension on the heart and pulmonary arteries [2]

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 pulmonary blood pressure and cardiac output 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 because the patient is too far into the bore, limiting their range of motion.

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.

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_ergom

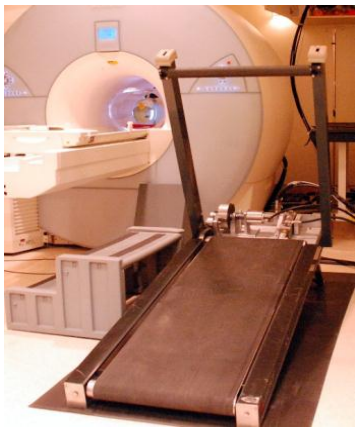


Figure 3: The MRI-compatible treadmill, designed by a team at Ohio State [6]

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

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 idea. Because of this, the team had to design a completely new prototype.

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 many flaws. A major 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. Another 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. 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, significantly less than the desired value. Due to these shortcomings, a more effective prototype is still needed.

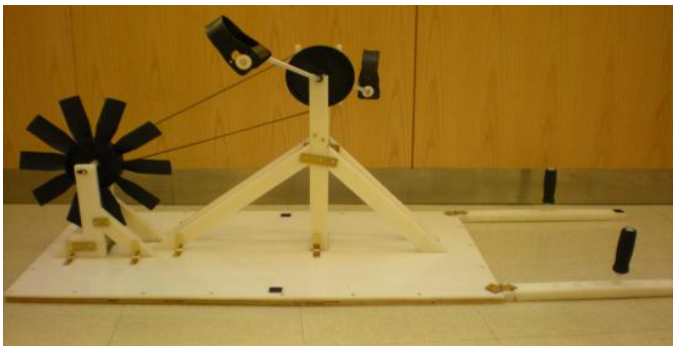


Figure 4: The cycling device developed by a UW-Madison biomedical engineering design team in Fall 2009 [7]

Image courtesy of UW-Madison BME Design:
http://bmedesign.engr.wisc.edu/websites/project.php?id=29

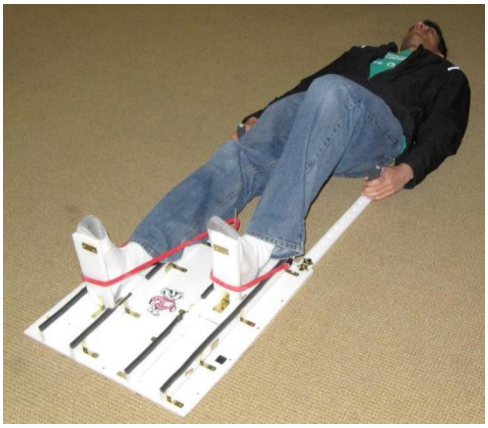


Figure 5: The stepper design, developed by the same group as the design in Figure 4 [8]

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

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, 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. Also, this device features an unnatural loading mechanism, where the resistance pulls up on the user's knees. This strange method of loading would lead to increased patient discomfort. The device also had some ferrous components and it exhibited unwanted lateral swaying of the weights during use. Given these reasons, a modification of this design was not pursued.

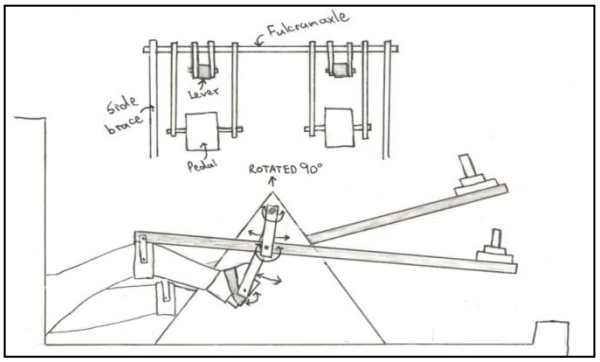


Figure 6: The device designed by a Fall 2010 UW-Madison biomedical engineering design team intended for scans of the head [9]

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

IV. Previous Prototype

Design

In addition to the two design teams mentioned, our team worked on this same project during the previous semester (Spring 2011). The final prototype that we constructed can be seen in **Figure 7.** It was composed mostly of 1.27 cm (1/2") thick high-density polyethylene (HDPE) assembled with brass screws and fasteners, to ensure MRI compatibility. The user would lie on the attached yoga mat and perform an alternating stepping motion to raise the plastic, concrete-filled weights on the L-shaped lever arms. The vertical supports and the lever arms were constructed as I-beams in order to add structural integrity and strength. Each lever arm rotated around an aluminum rod on a single acetal and glass bearing. Finally, two nylon straps were attached to the base of the device for the patient to grip during exercise. These straps and the yoga mat were meant to hold the patient to the device. Professor Chesler

approved of the stepper design and was happy with the progress made on the project, so this design was used as a platform for the new design.

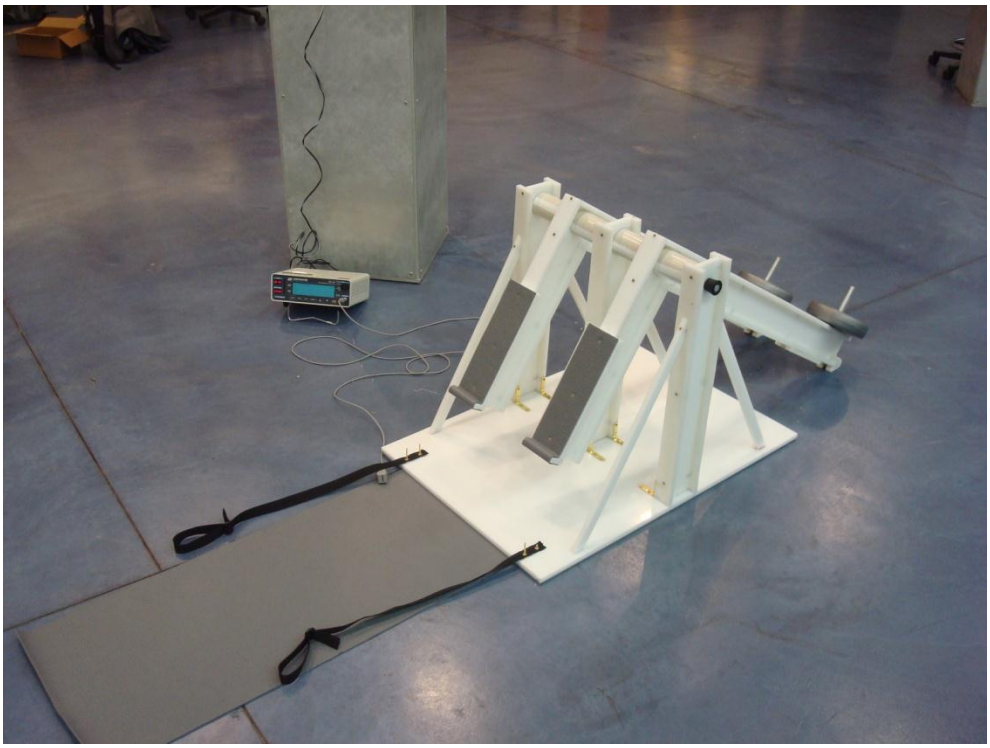


Figure 7: The prototype developed during the Spring 2011 semester

Problems

Though the previous prototype was fairly effective, there were areas in which the device required improvement. One of largest issues with the previous prototype was the poor lateral stability of its L-shaped lever arms. When the device was tested, the subject's feet had a tendency to move the foot pedal laterally as a natural effect of exercise. Due to a lack of restriction, this movement caused the lever arm to sway and sometimes fall off of the bearing. This resulted in an even more unstable motion and posed a durability problem. This unstable motion caused the patient to focus on stabilizing their movement instead of exercising to their fullest potential.

Another major problem was the fact that the patient would move away from the device during testing. This occurred because the force of the weights pushing back on the subjects was greater than the forces holding them in place. When Professor Chesler tested the prototype, she took an image of the pulmonary arteries prior to beginning testing. Her final images ended up being almost 6" away from this initial image due to this movement. This severely hindered the ability to acquire and compare images for analysis. In addition, when the subject slides away from the device, it takes them out of their optimal range of motion, reducing their ability to reach the highest possible cardiac output.

A few additional problems made the prototype cumbersome to use and adjust. For one, it did not rest entirely on the sliding portion of the couch, so it required two people to lift and adjust its position whenever the patient was moved. Also, when the patient used the device, the weights would slide back and forth on their fixtures because the diameters of the aluminum rods were thinner than the holes in the weights. Lastly, the length of the lever arms made it slightly awkward to carry during transportation.

V. Lateral Lever Arm Stability Designs

Track-Guided

In order to improve the major problem of lateral lever arm stability, three design alternatives were developed. The first was the track-guided design **(Figure 8)**. This design utilizes a semicircular piece of material under the existing lever arms that slides through a block of HDPE, creating a track for the lever arm to rotate through. By using a track to guide the lever arms, their movement would ideally be limited to a single plane. The track-guided design would be cost effective because the original prototype could be used and only materials for the tracks would need to be purchased. However, there were some drawbacks to this design. The constant friction of the semicircular piece sliding through the HDPE block would wear down the surfaces and could cause durability problems. Additionally, this design is only an indirect solution to the problem of lever arm stability. Since the original lever arms would still be used, they could still fall off of the bearings if lateral movement is not completely eliminated.

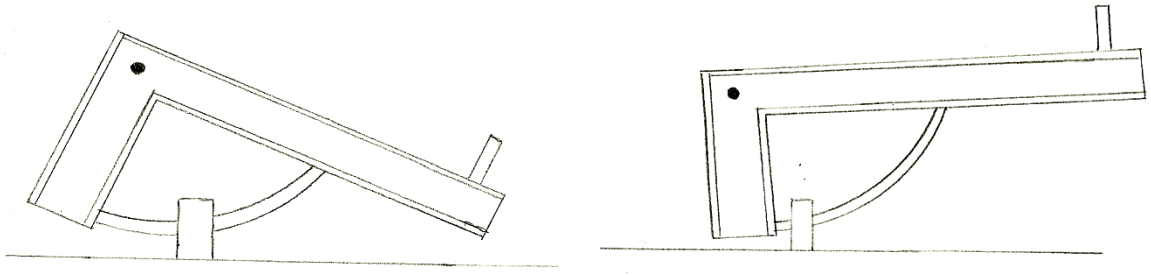


Figure 8: The track-guided design for lateral lever arm stability

Block

The second design to limit lateral movement of the lever arms was the block design **(Figure 9).** This design utilizes lever arms of the same dimensions as the past prototype, but there is not just one point of articulation with the aluminum rod. The web of each I-beam at the interface with the aluminum rod would be filled with two blocks of HDPE. Each block would contain one glass and acetal bearing, and would be capped by an additional sheet of HDPE in order to hold the bearings in place. The two

bearings per lever arm provide two points of articulation with the aluminum rod, allowing for increased stability. The distance between the two bearings generates sufficient reaction forces to counteract any lateral lever arm movement. Additionally, the friction and wear on the interface between the lever arm and aluminum rod would be reduced due to the presence of bearings.

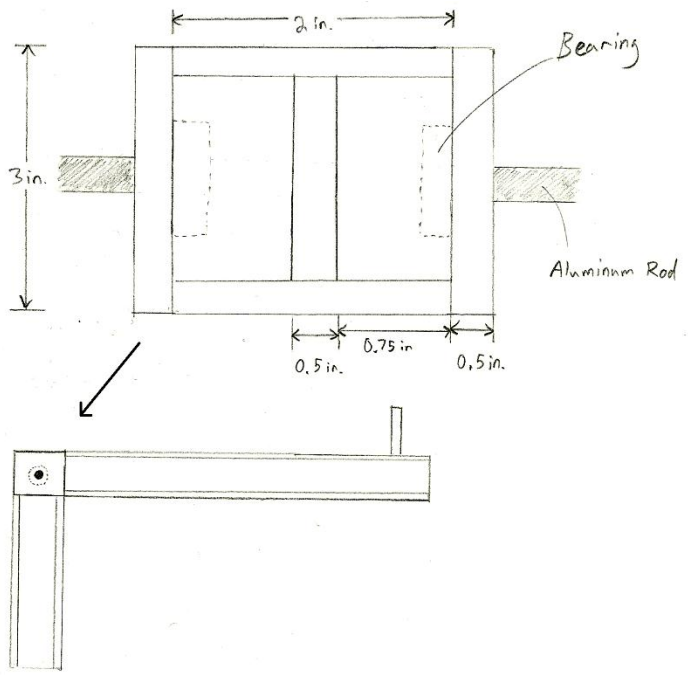


Figure 9: The block design for lateral lever arm stability

Arc-Support

The third alternative to fix the stability issues with the lever arms was the arc-support design **(Figure 10).** This idea utilizes two arcing supports beginning at the vertical member of the lever arm and extending to the aluminum rod, providing an additional two points of contact with the aluminum rod. The two additional supports would create greater reaction moments that would limit the lateral motion of the lever arms. This design would also be a cost effective choice because the original prototype could be used and only materials for the arcs would need to be purchased. However, this design would produce a lot of friction between the arc supports and aluminum rod because bearings could not be incorporated without encountering the same problem occurring in the current prototype. Also, if the patient does try to move their feet laterally, the forces on the arcs could cause them to break, depending on their dimensions.

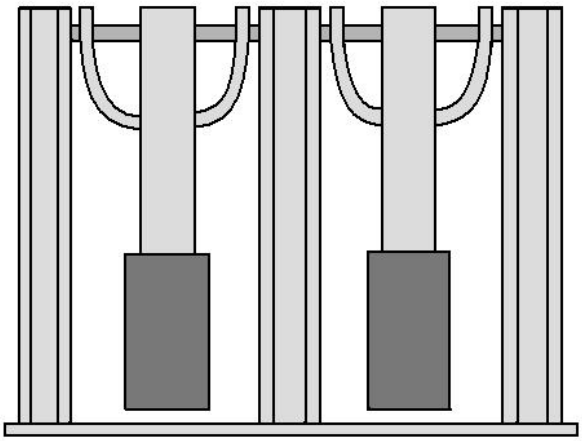


Figure 10: The arc-support design for lateral arm stability

Design Evaluation

Using a design matrix, the three designs mentioned were evaluated on the following four criteria: effectiveness, durability, ease of assembly, and cost **(Table 1)**. Each criterion was weighted with a certain percentage out of 100% based on relative importance, and each design was given a score out of 10 for each individual criteria. These scores were then multiplied by the weight of each category and then added to get the final score of each design. The track-guided design was given lower scores on effectiveness and durability because the track may not completely limit the lateral movement of the lever arms and may wear down due to friction over time, however it received a higher score for cost and ease of assembly due to the little amount of material that needs to be purchased and fabricated. It received a final score of 5.1 out of 10. The block design received higher scores for durability, effectiveness, and ease of assembly because this design limits the lateral lever arm movement, lowers the amount of friction on the interface between the lever arms and aluminum rod, and utilizes simple shapes which would make fabrication easier. However the block design scored lower in the cost category because this design requires the most new materials. It received an overall score of 8.2 out of 10. The arc-support design received high scores in the effectiveness and cost categories because the arcs would effectively limit lateral motion and new materials would only need to be purchased for the arcs. It scored lower however in the durability and ease of assembly categories because the arc supports have the potential to break and fabricating the arcs would be difficult. The arc supports design received an overall score of 7.4 out of 10. Therefore, the block design alternative was chosen to be pursued.

Table 1: Design matrix comparing the lateral lever arm stability designs. Criteria were weighted out of 100% based on relative importance; each design was given a score out of 10 for each criteria. Scores were multiplied by weight and added to get the final score of each design.

Weight	Criteria	Track-Guided	Block	Arc-Support
0.4	Effectiveness	4	8	9
0.4	Durability	5	9	6
0.1	Ease of Assembly	7	8	6
0.1	Cost	8	6	8
	Weighted Total:	**5.1**	**8.2**	**7.4**

VI. Securing Patient to Device Designs

Extended Base

The second major area for improvement was securing the patient to the device. The extended base design would address this issue by lengthening the HDPE base so that the patient's whole body rests on top of it **(Figure 11)**. The user would be held in place by two shoulder pads. The base of the shoulder pads would have four pegs that fit into holes on the HDPE base. This would allow the shoulder pads to be adjustable and accommodate for users of varying heights. This design would be very effective at securing the patient in place relative to the device. It would also be very easy for the patient to exit the device quickly in an emergency situation. One downfall of this design was the fact that extending the base would almost double the size of the device, making transportation and use even more difficult, something that was already a concern. The cost of the HDPE needed to construct the base would also make this a relatively expensive design option.

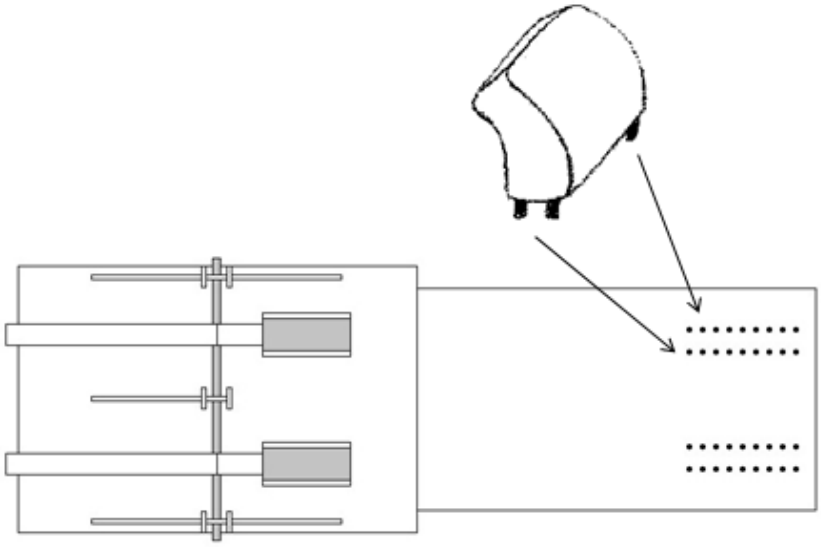


Figure 11: The extended base design for securing the patient to the device

Backpack Straps

This design utilizes straps, similar to those found on a backpack, to hold the patient to the device **(Figure 12)**. The connecting straps would be adjustable so that users of various heights can be held at the appropriate distance from the device. In comparison with the extended base design, this solution would be lightweight and allow for easier transportation. Additionally, with the appropriate choice of backpack straps, this design would be very comfortable for the patient and relatively affordable. However, it was speculated that the straps might prove to be slightly restrictive if the patient needed to be removed quickly from the device.

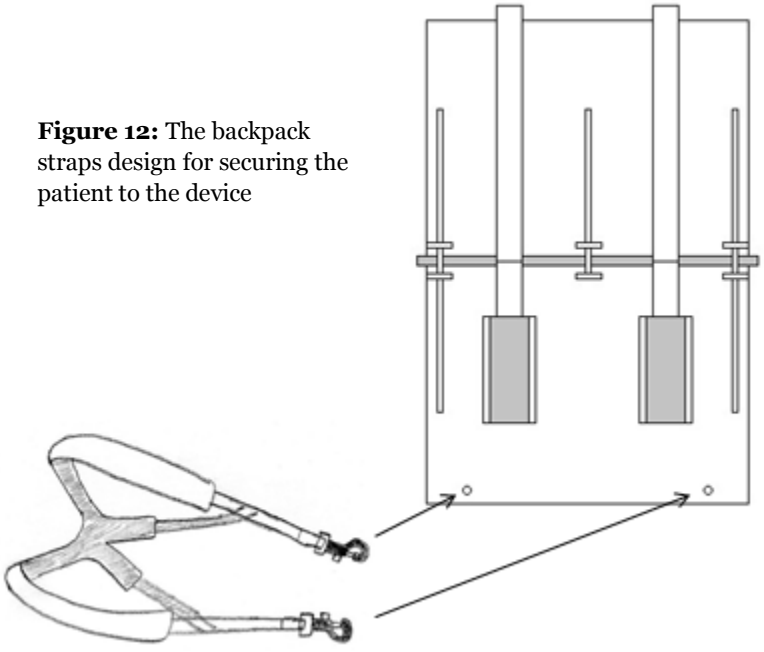


Figure 12: The backpack straps design for securing the patient to the device

Velcro Yoga Mat

The Velcro yoga mat design incorporates the yoga mat of the previous prototype with a Velcro interface to better secure the patient to the device **(Figure 13)**. In the previous prototype, the patient's weight alone was not sufficient to generate the static friction needed to hold the user to the device. Another problem encountered with the yoga mat in the previous prototype was that the epoxy used to attach the mat to the base wore out over time. This could be overcome by screwing the yoga mat to the base. In the improved design the patient would wear a large belt with a Velcro patch that matched a complimentary Velcro surface on the yoga mat. This would effectively hold the patient to the device and allow for a wide range of patients with varying heights to use the device. Additionally this design would be light weight, permitting for easy storage and transportation. Despite these benefits, it was thought that this design might be a fairly uncomfortable setup for the patient and the Velcro interface might wear out over time.

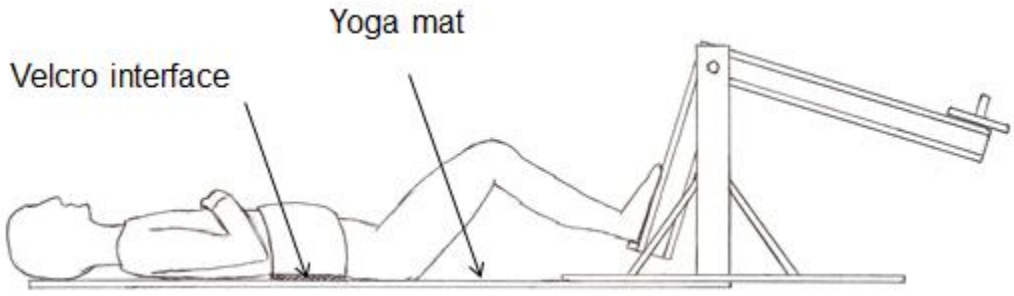


Figure 13: The Velcro yoga mat design for securing the patient to the device

Design Evaluation

A design matrix comparing the three previously mentioned designs was created in order to determine the best solution to the problem of securing the patient to the device **(Table 2)**. The three designs were evaluated based on a range of criteria including: effectiveness, patient comfort, size/weight, durability, safety, and cost. These six criteria were then given a weight based on their importance. Patient comfort and effectiveness were given the highest weight because they are the most critical to the success of the prototype. 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. Therefore, the exercise device should not add to that by being uncomfortable or strenuous to use. Also, if the design is not effective at attaching the patient to the device, the patient will move away from the device during use. This would take the patient out of the optimal range of leg movement, in turn making it more difficult for the patient to increase their heart rate. Additionally, if the patient's body moves during the scanning, the images taken would not correspond to the same spot in

the body. Finally, safety is the top priority for our design team; however, it was given an average rating because all of the designs are considered to be relatively safe.

Table 2: Design matrix comparing the designs for securing the patient to the device. Criteria were weighted out of 100% based on relative importance; each design was given a score out of 10 for each criteria. Scores were multiplied by weight and added to get the final score of each design.

Weight	Criteria	Extended Base	Backpack Straps	Velcro Yoga Mat
0.25	Effectiveness	9	9	6
0.2	Patient Comfort	7	8	6
0.15	Size/Weight	3	9	8
0.15	Durability	7	7	5
0.15	Safety	10	8	7
0.1	Cost	5	7	6
	Weighted Total:	**7.15**	**8.15**	**6.3**

As seen in the design matrix above, the backpack straps design scored the highest, with a score of 8.15/10. It was followed by the extended base (7.15/10) and the Velcro yoga mat (7.05/10). It managed relatively high scores in almost every category and therefore was chosen to be pursued in the fabrication of our final prototype.

VII. Final Design

The final prototype produced this semester **(Figure 14)** uses the same stepping motion as the previous prototype. The subject alternates pushing against the shorter ends of L-shaped lever arms while in the supine position. Non-ferrous weights at the other end provide the resistance for the motion. When the subject pushes on the lever, it rotates around a central axis, raising the weights. The two lever arms rotate about a 1.59 cm (5/8”) diameter aluminum rod. The cross-section of each lever arm is an I-beam structure made of 1.27 cm (½”) thick HDPE, which is 10.16 cm (4”) tall in total with 5.08 cm (2”) flanges. The foot pedal sides of the L-shaped lever arms have a length of 0.53 m (1’, 9”). The length of the weighted side of the lever arms was decreased from the previous prototype by 25% to a length of 0.8 m (2’, 7.5”) to reduce the overall size of the device while still affording a mechanical advantage to increase the resistance. The

aluminum rod and lever arms are held up by three 0.61 m (2') tall HDPE supports that were also made into I-beams in order to add structural integrity and strength. These are supported with 1.27 cm (½") by 2.54 cm (1") HDPE diagonal braces on either side. The base of the device is 60.96 cm by 91.44 cm (2' x 3') and is again made of 1.27 cm (½") thick HDPE. The total cost of manufacturing the device was $177.69, which was within our allotted budget of $200. A detailed summary of all costs can be found in **Appendix D**.

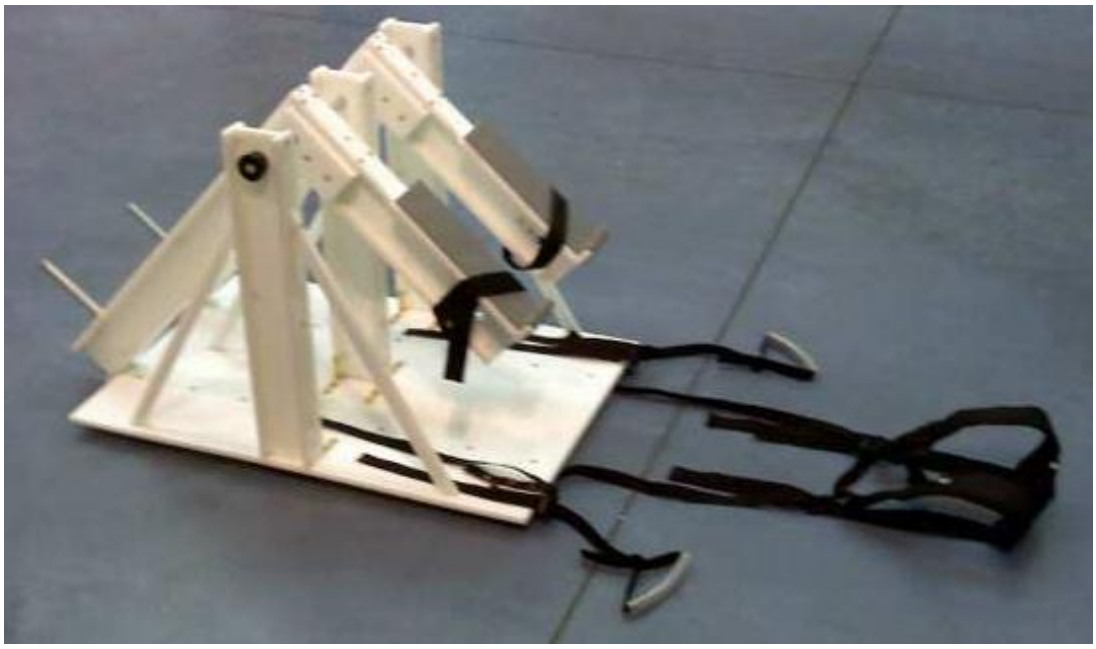


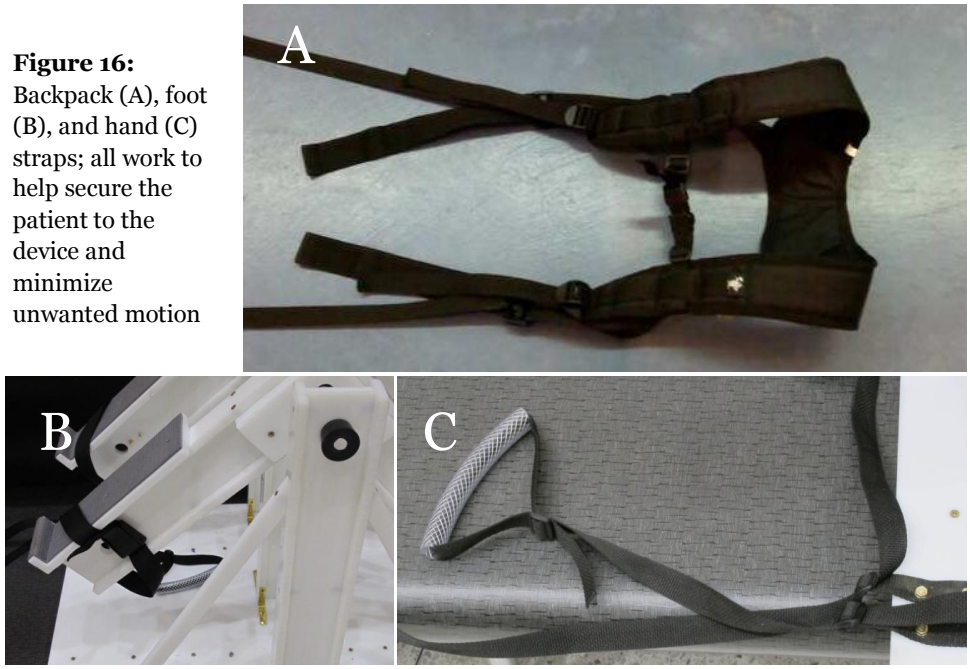
Figure 14: The final prototype with all major modifications

In order to address the problems of the previous device a variety of improvements were made. First the problem of side to side lever arm motion was corrected by implementing the block design mentioned earlier. 2.54 cm (1") thick HDPE blocks have been placed on each side of the web of the I-beam, filling the entire area within the I-beam at the interface with the aluminum rod **(Figure 15)**. Each block has a pocket that was CNC milled on the outer surface just deep enough to fit the bearings, which are press fit into the holes. 1.27 cm (½") HDPE sheets are used to cap the blocks and secure the bearings in place. By using two bearings, there are two points of articulation with the aluminum rod that provide even support. Since the bearings are 5.40 cm (2.125") apart, the moment arms of the reaction forces on the rod are increased, thereby better counteracting the moments generated by lateral movement. Also, the use of bearings reduces the friction and wear on the interface between the lever arm and aluminum rod. Upon testing, this new interface proved to be extremely successful at eliminating side to side lever arm movement and drastically increased the durability of the lever arms.

Figure 15: Block interface between the bearings and lever arms

Another major modification involved the use of a shoulder harness, similar to that of a backpack, to secure the patient to the device and prevent the patient and device from moving apart during testing (**Figure 16, A)**. The shoulder straps are Innova BackSaver straps that were originally marketed as straps to hold a disc golf bag. All ferrous components have been removed and the harness is attached to the device with adjustable nylon straps. The variable length of the straps allows for patients of different heights to be held a comfortable distance from the device. Adjustable nylon foot and hand straps (**Figure 16, B & C)** have also been added to the device to help secure the patient. Improved handles on the hand straps are made of flexible plastic tubing for patient comfort. The foot straps secure the distal ends of the subject's feet to the foot pedals. This allows for some plantar flexion which increases patient comfort during use.

Figure 16: Backpack (A), foot (B), and hand (C) straps; all work to help secure the patient to the device and minimize unwanted motion



Additionally, a method to hold the lever arms in place has been implemented to help the patient more comfortably enter and exit the device. This stopping mechanism utilizes a 1.59 cm (5/8") diameter aluminum rod that can be inserted through a 2.54 cm (1") diameter hole in each of the lever arms behind the foot pedals. Once in place the rod catches on the back of the supports, holding the lever arms in place. This stopping mechanism can be seen in **Figure 17**. During MRI testing, it was found that this stopping mechanism is also extremely beneficial during initial resting scans. It allows for the patients legs to rest comfortably and weight free while the baseline images are taken.

A final improvement made to the prototype involves the inclusion of a tracking structure to the bottom of the base to improve compatibility with the sliding MRI couch **(Figure 18)**. This system consists of two 91.44 cm (3') long HDPE tracks, with an original cross-section of 2.54 cm x 2.54 cm (1" x 1"), which have been cut to an angle of about 11.6^{o} to fit the contours of the sliding MRI couch. The tracks are covered in yoga mat padding to improve the fit and add friction. These base tracks place the whole weight of the device on the sliding part of the MRI couch, which allows it to move smoothly with the patient during imaging. The implementation of all of these modifications has helped to greatly improve the ease and efficiency of using the device.

Figure 17: Stopping mechanism for the lever arms

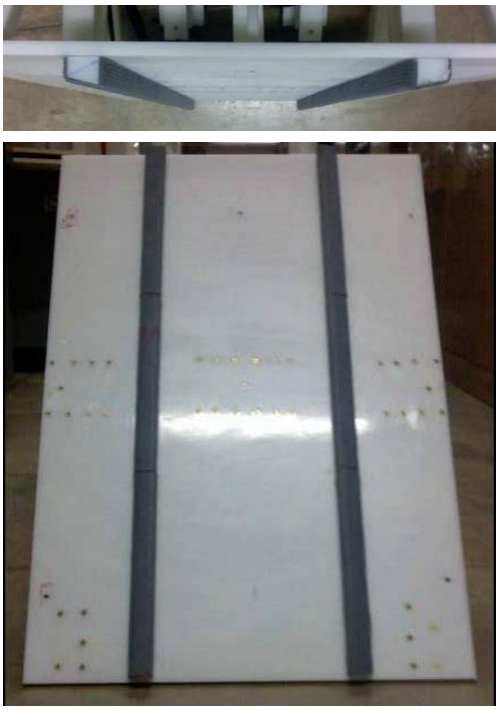


Figure 18: Base tracking made of HDPE cut at an 11.6^{o} angle with added yoga mat padding

VIII. Power Calculation

Using the new dimensions of the prototype after all design modifications had been made, the amount of power produced during patient exercise was calculated. It was determined that this is a function of three variables: the mass added to the end of the lever arms, step rate, and the rotation angle of the lever arms during each step. Through experimental testing, it was determined that the MRI bore allows for an average lever arm rotation of 22°. This value was used, along with basic statics and dynamics principles such as center of mass calculation and conservation of energy, to derive the following equation for the user's workload (power):

$$P = R * (0.03986\, J\frac{min}{sec} + 0.03967\frac{m^2}{sec^2}\frac{min}{sec} * M)$$

In this equation, P is power (Watts), R is the exercise cadence (steps/minute), and M is the mass of the weights (kg) added to the end of the lever arms. Some assumptions that were made in the derivation of this equation include that exercise is always characterized by the same 22° arm rotation and the extended leg position leaves the foot pedal perpendicular to the ground. Despite these assumptions, these calculations should give a good estimate of the amount of power produced by the user. A more detailed derivation of this formula can be found in **Appendix B**. Then, using this equation, power was calculated for different combinations of exercise cadence and added mass. These values were calculated using the MATLAB code found in **Appendix C**, and the results can be seen below in **Table 3**.

Table 3: Power produced for different combinations of exercise cadence and added mass

	Exercise Cadence (steps/min)					
Added Mass (kg)		**80**	**90**	**100**	**110**	**120**
	0	3.19	3.59	3.99	4.38	4.78
	3.63	14.71	16.55	18.39	20.22	22.06
	4.54	17.60	19.80	22.00	24.20	26.40
	8.16	29.09	32.72	36.36	40.00	43.63

IX. Testing and Results

Exercise Testing

After the power calculations were made, the device was tested outside of the MRI bore to determine the maximum attainable heart rate. Four subjects exercised with the device for ten minutes at a step cadence of about 110 steps per minute. Subjects chose an amount of weight that was comfortable according to their individual fitness levels. Prior to the start of exercise, the subject's resting heart rate was acquired using a digital pressure monitor. It was measured again immediately after exercise both digitally as well as manually on the carotid artery. This extra measurement was taken because the digital pressure monitor takes about 40 seconds to complete its measurement, so in this time, the heart rate would already have begun to recover. The manual reading could give a more immediate measure of heart rate. If the two numbers differed significantly, the number from the manual reading was used in the data because it is closer to the actual exercising heart rate. The heart rate data for the four test subjects can be seen below in **Table 4**.

Table 4: Exercise testing data for four subjects

Subject	Resting HR (bpm)	Post Exercise HR (bpm)	% Max. HR
1	73	119	59.80
2	74	143	71.86
3	70	122	61.31
4	68	110	55.28
Average	**71.25**	**123.50**	**62.06**

MRI Testing

In addition to heart rate testing, the final prototype was taken to the 3 Tesla MRI scanner at UW Hospital in order to obtain cardiac MR images of a subject using the device. Real-time MRI was used to attain these images. The advantage of this technology is that it provides a continuous image of the heart. This allows for the researcher to see changes in the pulmonary artery in real-time as the patient exercises. Conventional 2-D imaging would require the subject to stop exercising during recalibration and scanning, which would allow the patient's heart rate to decrease and lead to less accurate results. With regards to the assessment of pulmonary hypertension, real-time MRI allows for evaluation of pulmonary artery area, as well as right ventricular function. Still-frames of the real-time MRI images gathered during testing of the prototype can be seen below in **Figure 19.**

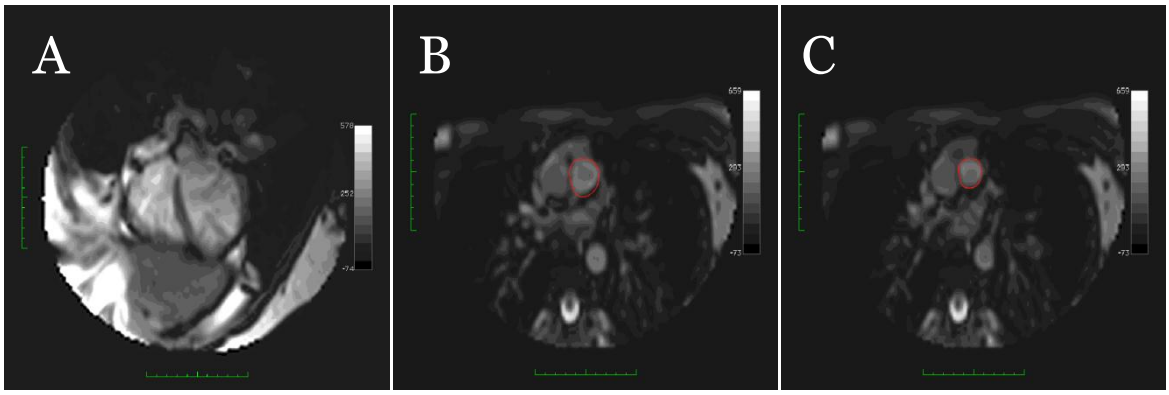


Figure 19: Real time MRI of the subject's heart, including a four-chamber ventral view (A) as well as the pulmonary artery during systole (B) and diastole (C). The pulmonary artery is indicated by the red circle in images B and C.

Through image processing, a relative area change (RAC) of 39.5% in the main pulmonary artery was observed between diastole (4.6 cm^2) and systole (7.6 cm^2). A comparison between systole and diastole can be used to determine arterial distensibility or stiffness. A stiffer artery is directly correlated to increased blood pressure; thus, this data can be used to characterize and assess the patient's level of pulmonary hypertension. A comparison of this information from the patient at rest and the patient during exercise could be used to show the effect exercise has on pulmonary hypertension. In our trials, the subject was able to raise their heart rate from 70 to 105 beats per minute. Dr. Chris François, the radiologist reviewing the scans, said that he could definitely see evidence of physiological change in the arteries at this heart rate, and that a heart rate of about 100 would be more than enough for these scans. Since previous exercise testing has proven that the prototype is capable of producing an average maximum attainable heart rate of 123.5 beats per minute, this is a proof of concept that it is capable of producing a physiological change in the pulmonary arteries and can be used to study pulmonary hypertension using real-time MRI.

X. Future Work

The prototype provided promising initial results; however, there are still several improvements that can be made. One such improvement is to develop a way to limit the base movement. During testing, when the subject pulled on the back and hand straps, the base of the device would experience forces at an upward angle that resulted in lifting of the patient-side of the device. In the future, the straps will be attached to additional pieces of HDPE to elevate the point of the attachment. This will eliminate any vertical component of the forces, thus preventing lifting of the base.

During testing, it was discovered that the concrete-filled weights were actually slightly magnetic, and therefore could no longer be used during MRI scans. As a result, no weight was added to the device during MRI testing. While the results showed that no

weights were needed to increase the cardiac output, certain amounts of weight are still desired to increase patient comfort by reducing the strain on their abdominal muscles. Therefore, permanently attaching an adequate amount of weight could be considered as an alternative. We plan to create or obtain new, completely non-ferrous weights to be used. A new weight interface will then have to be customized to the dimensions of these new weights.

Since the durability of the lever arms was significantly improved, the stability of the supports became the main source of durability concerns. When the subject used large amounts of added weight, the diagonal braces attached to support I-beams began to bend. These braces will be changed from ½" thick to 1" thick HDPE. This will increase their strength and limit buckling.

A significant goal for next semester will be to improve the device by employing an electronic measurement and feedback system. This will automatically record the cadence and lever arm rotation during exercise. Using these measurements in real-time, it is possible to electronically calculate the power the patient is producing. Visual or auditory feedback can then be given to the user regarding their cadence and power production.

Finally, Institutional Review Board (IRB) approval for human testing is in progress. This will 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.

XI. References

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XII. 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 improved MRI-compatible exercise device for patients undergoing cardiac MRI scans. It should allow the patient to exercise while lying within the MRI bore and be adjustable so patients of varying fitness levels and sizes can generate a sufficient cardiac output and heart rate.

Client Requirements

- MRI-compatible, in both materials and dimensions
- Comfortable exercise motion in supine position
- Sufficient resistance to increase heart rate and cardiac output
- Adjustable workload
- Adjustable for different patient sizes

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 cardiac output enough to see physiological changes in the pulmonary artery using real-time MRI. It needs to be adjustable for various patient fitness levels and heights (155-195 cm). Additionally, only one assistant should be required during set up and testing.
    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 three years with minor maintenance.
    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.

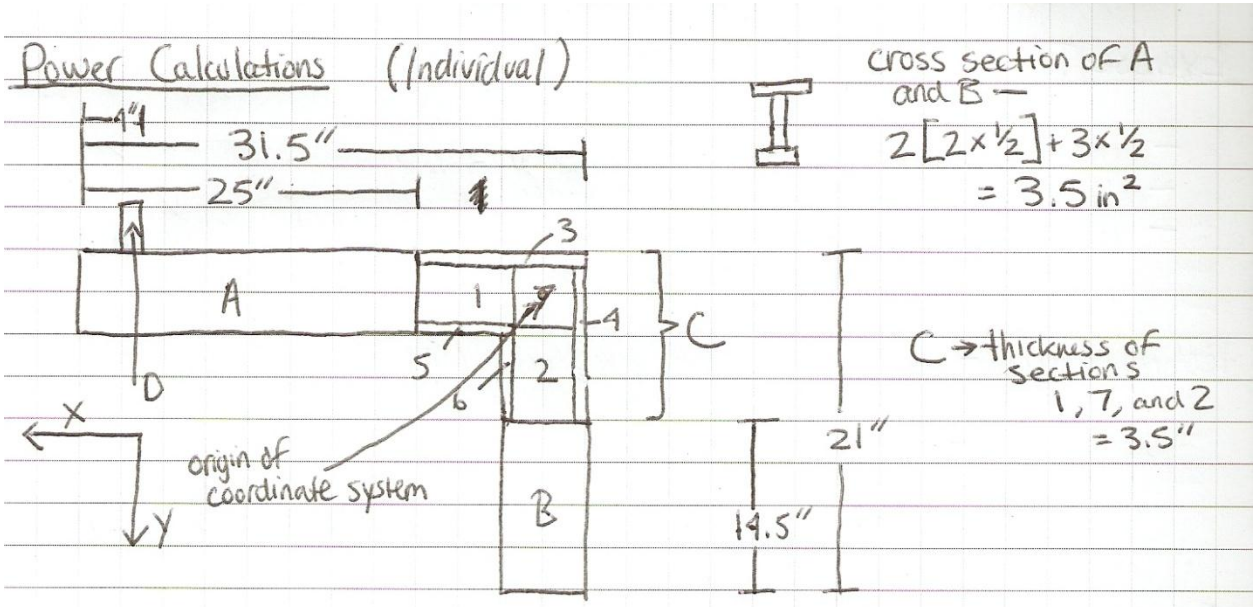
g. *Ergonomics:* The motion should be natural, fluid, and controlled without any undesirable friction.
h. *Size:* The device must allow for exercise within the bore of any MRI scanner. The minimum measurements of the bore are 42 cm from the couch to the top and 60 cm in width.
i. *Weight:* The weight 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

Competition: Lode B.V. MRI Ergometer, prototypes from other universities, and past UW BME design projects

XIII. Appendix B: Power Calculations



Need to calculate mass and COM of segments A, B, and C —

density of HDPE = 0.00095 kg/cm³

A – volume = $25'' \times (3.5\ in^2)\left(\frac{2.54\ cm}{1\ in}\right)^3 = 1433.87\ cm^3$

mass = 1.36 kg @ (17, 0)

B – volume = $14.5'' \times (3.5\ in^2)\left(\frac{2.54\ cm}{1\ in}\right)^3 = 831.64\ cm^3$

mass = 0.79 kg @ (0, 11.75)

C – volume = $3\underbrace{(3''\times 3''\times 3.5'')}_{\text{sec. 1, 2, 7}} + 6.5\underbrace{(2\times 2.5)}_{\text{sec 3}} + 6\underbrace{(2\times 2.5)}_{\text{sec 4}} + 3\underbrace{(2\times 2.5)}_{\text{sec 5}} +$

$+ 2.5\underbrace{(2\times 2.5)}_{\text{sec. 6}} = 112.5\ in^3\left(\frac{2.54\ cm}{1\ in}\right)^3 = 1843.54\ cm^3$

mass = 1.75 kg @ COM of C!

Finding COM of C –

sec 1 – 0.49 kg @ (0,0)
sec 2 – 0.49 kg @ (0,3)
sec 3 – 0.49 kg @ (3,0)
sec 3 – 0.10 kg @ (1.25, 1.75)
sec 4 – 0.09 kg @ (-1.75, 1.5)
sec 5 – 0.05 kg @ (3, 1.75)
sec 6 – 0.04 kg @ (1.75, 3.25)

$\bar{x} = [0.49(0) + 0.49(0) + 0.49(3) + 0.10(1.25) + 0.09(-1.75) + 0.05(3) + 0.04(1.75)] / 1.75\,kg = 0.94$

$\bar{y} = [0.49(0) + 0.49(3) + 0.49(0) + 0.10(-1.75) + 0.09(1.5) + 0.05(1.75) + 0.04(3.25)] / 1.75\,kg = 0.94$

COM of C = (0.94, 0.94)

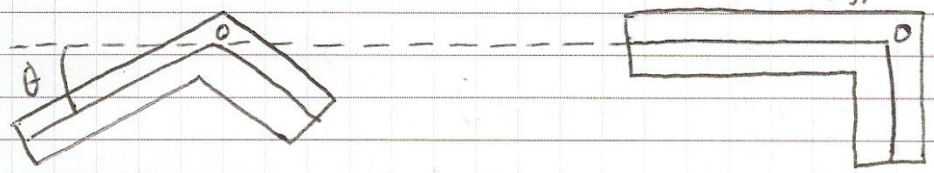
Segment D – (weight fixture)

$\pi\left(\frac{3/4}{2}\right)^2 \times 6 = 2.65\,in^3 \left(\frac{2.54\,cm}{1\,in}\right)^3 \left(\frac{0.0027\,kg}{1\,cm^3}\right) = 0.117\,kg$

Mass = located @ (25.5, 0), 0.117+m kg

added mass (kg)

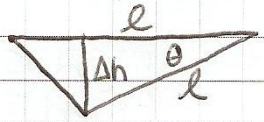
density of 6061 Al



initial condition

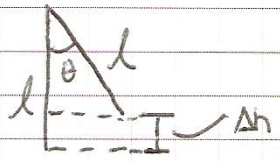
final condition

For the "x" condition –



$\Delta h = l \sin\theta$

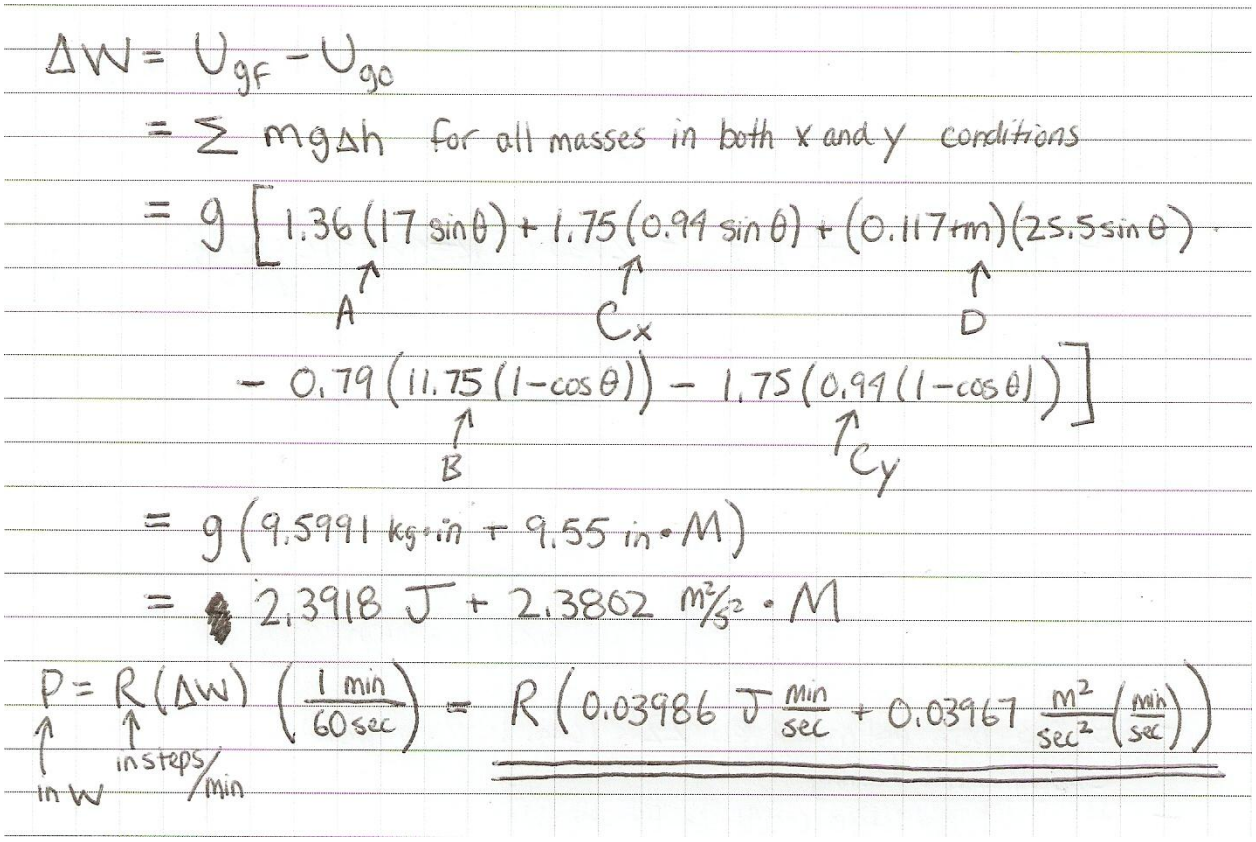
For the "y" condition –



$\Delta h = l(1 - \cos\theta)$

ASSUMPTIONS:

- θ has been estimated @ 22° (avg. lever arm rotation) through experimental testing
- the final condition results in the weighted end of the lever arm being // to the ground



XIV. Appendix C: MATLAB Code Associated with Power Calculations

```
clear
% Custom routine to calculate power produced using the MRI-compatible
% cardiac exercise device for a variety of added masses and exercise
% cadences.
% Nick Thate
% BME 400, UW-Madison, Fall 2011

% Set up the range of values for added mass and exercise cadence
% Added mass = Different combinations possible with the weights we have
% Cadence = 80-120 steps/min, a reasonable range of possible rates
m=[0 3.63 4.54 8.16];
R=[80 90 100 110 120];

% Set up the table for power produced
P=zeros(4,5);

% Fill in the table using the calculated equation for power produced
for X=1:4
for Y=1:5
P(X,Y)=(R(Y))*(0.03967*m(X)+0.03986);
end
end
P
```

XV. Appendix D: Budget

Date	Items		Cost ($)
11/3/11	24”x12” sheet of 1” thick HDPE		30.42
11/3/11	100 1” long, 8/32” diameter brass screws		19.06
11/3/11	2 acetal and glass bearings		19.26
11/3/11	1 5/8” diameter, 3’ long aluminum rod		8.88
11/17/11	Backpack straps		27.38
11/22/11	Ace Hardware	10 Brass nuts	2.00
		2 Rubber Stoppers	4.40
		4 Rubber washers	1.08
		Tubing	2.49
		Nylon straps	12.88
		2 Buckles	5.98
		6 Sliding buckles	2.46
		Tax	1.72
11/23/11	24”x12” sheet of ½” thick HDPE		21.23
12/3/11	Ace Hardware	Brass washers, and epoxy	8.56
		Carpet Tape	4.74
		15 brass screws	4.75
		2 brass nuts	0.40
		Total:	**177.69**