MRI Exercise Device

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Abstract

Old age, obesity, and other disease states can cause a person to experience loss of breath, loss of consciousness, and even a stroke during seemingly normal activity (Clinic, 2003). In order to analyze what is causing these events, it is important to assess the cerebral blood flow in subjects during exercise. Currently, the best available technology for assessing cerebral blood flow is magnetic resonance imaging (MRI). Implementing a device that allows researchers to observe cerebral blood flow on a subject during constant, dynamic exercise would allow them to assess the problems that may occur in elderly patients, and those with disease states such as obesity. The primary consideration for making such a device is its MRI compatibility. Specifically, the device cannot contain ferrous materials, it must fit on an MRI bed, and it must minimize upper body movement because the subject must be still to acquire an accurate image (Schrage, 2010). The device also must allow the test subject to maintain constant exercise, while achieving a constant elevated heart rate. Through research and evaluation of the design ideas, a pivoting-lever device that creates a constant resistance to vertical motion in the legs was chosen to provide an exercise mechanism, with a strap around the subject's waist to maintain stabilization. Two other designs, ferrous boots and a cycle, were analyzed as well. The ferrous boots were deemed to be too much of a safety risk as well as potentially creating an image disturbance and the cycle created excessive forces along the axis from head to feet.

Problem Statement

This Project is designed to develop a device to allow researchers to observe blood vessel diameter, along with middle cerebral arterial velocity, of a patient during steady-state exercise. In order to observe these conditions, Magnetic Resonance Imaging (MRI) must be used, which limits the materials and mechanics of the device. In particular, we plan to construct a device that allows a patient to maintain upper body stabilization during continuous exercise while inside the MRI machine.

Background

General Purpose

The purpose of this project is to design an exercise device to be used in an MRI so that researchers can view blood vessel diameter and cerebral blood flow during exercise. The motivation behind this is that many elderly, obese, and diseased people are prone to loss of consciousness and stroke during activities such as walking up stairs, and other forms of mild exercise. During exercise the velocity of blood flow, blood pressure, and heart all increase significantly (Hellstrom and Wahlgren 1993). By observing the cerebral blood flow during a period of exercise and increased heart rate, it could be possible to pinpoint some direct causes of fatalities and injuries in patients with these attributes (Schrage, 2010). Although there are many possible methods of provoking an increased heart rate in test subjects, the most effective method for maintaining an elevated heart rate is dynamic exercise (Franklin, 2004). Currently, MRI is the best technology for obtaining real-time images of cerebral blood flow and vein diameter, and it is ideal that test subjects are able to exercise while inside an MRI. In order to accomplish this, a device must be made that causes some form of exercise-inducing resistance, while keeping the patient's upper body and head (the area being imaged) stable.

Previous Prototypes and Current Technology

There have been two BME Design projects dedicated to making an exercise device for use in an MRI. The first design, from the BME Design group in Fall 2009, used a cycle motion to create the necessary resistance for elevating heart rate (**Fig. 1**).

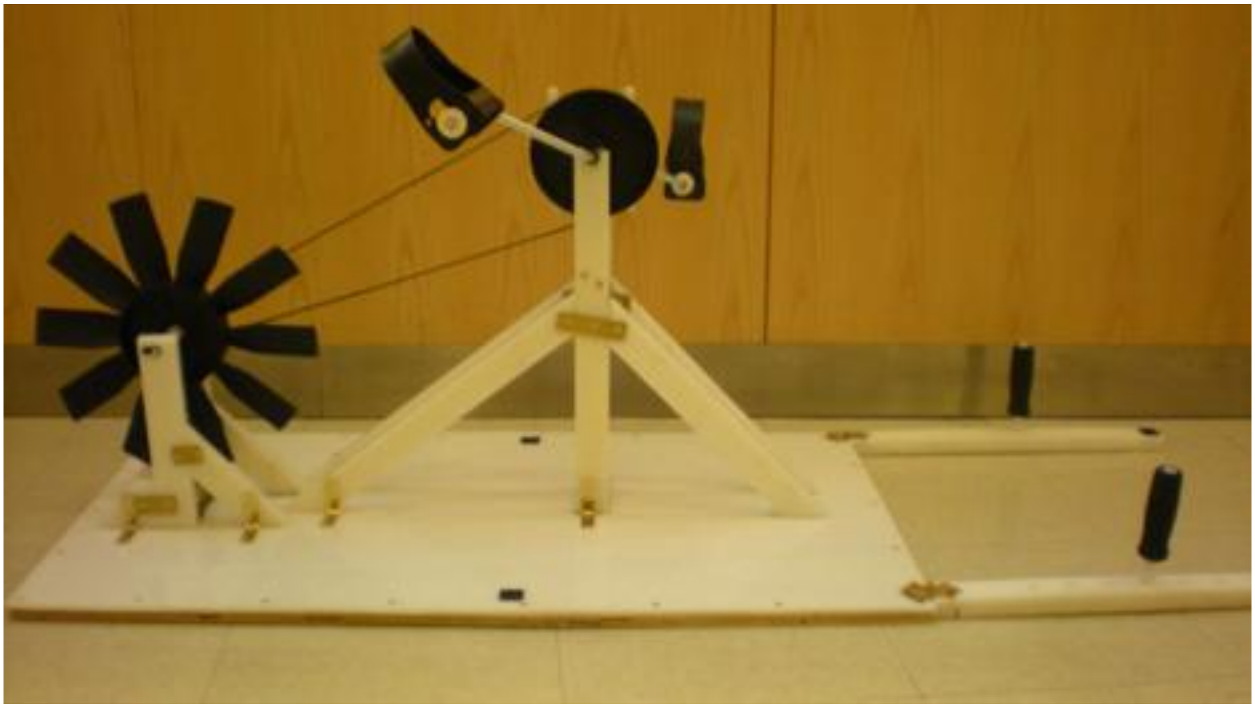

Figure 1: Cycle device from BME Design, 2009 (BME Design, 2009).

This design was effective in creating resistance for the subject, and a cycle motion was an efficient mode of dynamic exercise. The reason why this design was not put into continued use was the fact that the subject's range of motion was very limited while in the MRI tube. It should be noted that this project had a different client who required using the MRI to view blood flow in the chest, meaning that the subject was farther into the tube than subjects in our test, whose head will be imaged to view cerebral blood flow. Although the overall design of the cycle was not ideal for this project, the principles of constant dynamic exercise were taken into account.

The BME Design team then changed their design in Spring 2010 to implement a stepper to create resistance against the motion of the test subject's legs (**Fig. 2**).

Figure 2: Stepper design (BME Design, 2010).

Rubber bands were used to create the resistance, and were attached to pedals, which the subject pushed back and forth to induce exercise, and an elevated heart rate. This design was compatible with the MRI and required a smaller range of motion to create exercise, making it beneficial for tests in which the subject is deep in the MRI tube. Although this design used a smaller range of motion, the motion was hardly constant, and it was difficult to maintain dynamic exercise due to the fact that the resistance of the bands increased as the legs extended. In addition, the force acting against the motion of the legs is oriented in the head-to-toe direction, making it difficult to stabilize the upper body and obtain a clear image.

Currently, there is an exercise device in commercial production that is designed to induce exercise in an MRI. The Lode BV MRI Ergometer (**Fig. 3**) uses a cyclical motion to create resistance for the test subject, and has been used in MRI tests in many applications (Lode, 2010).

Figure 3: Lode BV MRI Ergonometer (Lode, 2010)

This device is MRI compatible, and applies constant dynamic resistance, making it ideal for cardiology readings. Another appealing element to this design is that the resistance can be adjusted, as well as measured and recorded, during the test. Although this design is able to accomplish all the goals of this project, the cost of the Lode Ergometer is around $50,000, which is much higher than the budget allows.

Design Motivation

Our client would like to investigate the affects age, obesity, and various illnesses have on cerebral blood flow during exercise. Currently transcranial Doppler ultrasound is used to measure cerebral blood flow but this gives limited information in that it cannot measure blood vessel diameter (Schrage, 2010). For this reason our client would like to do this research with MRI which can both measure the blood flow and blood vessel diameter. However, there are currently very few exercise devices that can be used while in an MRI machine and the few that do exist are very expensive. Therefore, our main motivation is to create an affordable, MRI compatible machine that can adequately raise a test subject's heart rate.

Requirements and Design Constraints

There are a number of specifications and requirements the design must meet. First and foremost is that the design must be MRI compatible. Nothing on the device can contain ferrous materials as they are magnetic and cause both a safety issue and disruption with the imaging. Also the device must be sized to fit on the MRI bed. There is a total area of 162 cm by 39 cm within which it needs to be contained. Furthermore it must be able to fit inside the tube which is 45 cm above the bed itself.

The design must also limit upper body movement. It is very common to move the torso and head while exercising. However, it is essential for a clean image that there be very little to no movement of the area being scanned (Zaitsev, 2006). As our client will be scanning subject's the head, it is imperative the head remain as stationary as possible.

This exercise device needs to adequately raise a test subject's heart rate. The goal is to raise a resting heart rate of 60 to 70 beats per minute to a working heart rate of 120 to 130 beats per minute. This elevated heart rate is needed to show a sharp contrast between resting cerebral blood flow and cerebral blood flow during exercise.

The test subjects using this device are going to be of varying heights, weights, and levels of physical fitness. For this reason the apparatus must be robust enough to handle the largest subjects yet adjustable in order to accommodate the smallest. In order to provide an appropriate stimulus to the varying levels of physical fitness, the level of resistance and work will need to be adjustable.

The client would like this device to last a minimum of three years with frequent use so it also needs to be durable. Along with overall durability it would be optimum to have parts that could be easily replaced. This would ensure the best opportunity for it to remain operational for the maximum period of time.

Aside from these primary requirements there are several secondary requirements that will be addressed given adequate time and funds. The first of these secondary points to address is aesthetics. This device will be used by test subjects and seen by colleagues and therefore needs to look professional. This device should also have a certain level of comfort built into it. Subjects will be using this device for ten minute periods and a higher level of comfort will make this much more easily done. This device should also be easily transportable from the client's laboratory to an MRI room. Lastly, there should be a means of measuring the work done by a test subject during the exercise in order to directly compare one test to another. All of this must be done within a budget of $1000.

Design

We came up with three design options to meet our client's needs. They are a cycle design, a lever system, and ferrous boots. We analyzed each of them, details can be seen in the following sections and in the design matrix, and finally decided to pursue the lever system design. Our reasoning for this follows.

Design Alternative 1: Cycle

The first design we came up with was a cycle system. In our initial meeting with our client it was clearly expressed that a design based on a bicycle motion would be preferred. The advantages to the cycling motion are numerous. The main reason our client liked it was the characteristic of a cycle to provide a constant, easily adjusted resistance. It is a familiar concept and simple to conceive. We were able to study several models of exercise bike and using the merits of each along with the requirements of our client we were able to come up with a design quite easily. It consists of two pedals pushing a heavy flywheel, cement coated in plastic is our plan, with a nylon belt going around it. The belt will attach to the baseboard upon which the apparatus is mounted. Along the rear side of the belt there will be a hook wrapped around the belt with which the tension of the belt can be adjusted. This will provide an easily adjustable resistance to meet the demands of any fitness level. The flywheel assembly will be mounted on a backboard that will rest on the existing MRI bed. The test subject will lie on the backboard and turn the pedals while being scanned. Restraining belts around the subject's waist and crossing the torso will minimize movement. We feel this design has a lot of potential and are encouraged by the fact that it would be similar to the commercially available model that has obviously already been proven.

However, as we continued to look into the design some unavoidable disadvantages came to light. The largest of these is the direction of the force being applied by the test subject. The thrust the subject applies to the pedals will cause all the force and resultant motion to occur along the axis from head to foot. This will provide the largest potential for head movement since it is quite difficult to restrain a lying person along this axis. The second difficulty we ran into is the cycling motion itself. Although optimum in many ways, the fact that the pedals have to make a complete turn in order to operate limits the available motion. If a subject's legs are too long and cannot complete a turn without hitting the MRI tube, or if the subject is too short and required being too far into the MRI tube, that subject will not be able to use the cycle. This could limit research diversity. The third disadvantage was making the cycle assembly non-ferrous. With all the rotating parts durability may be sacrificed with plastic or wooden parts.

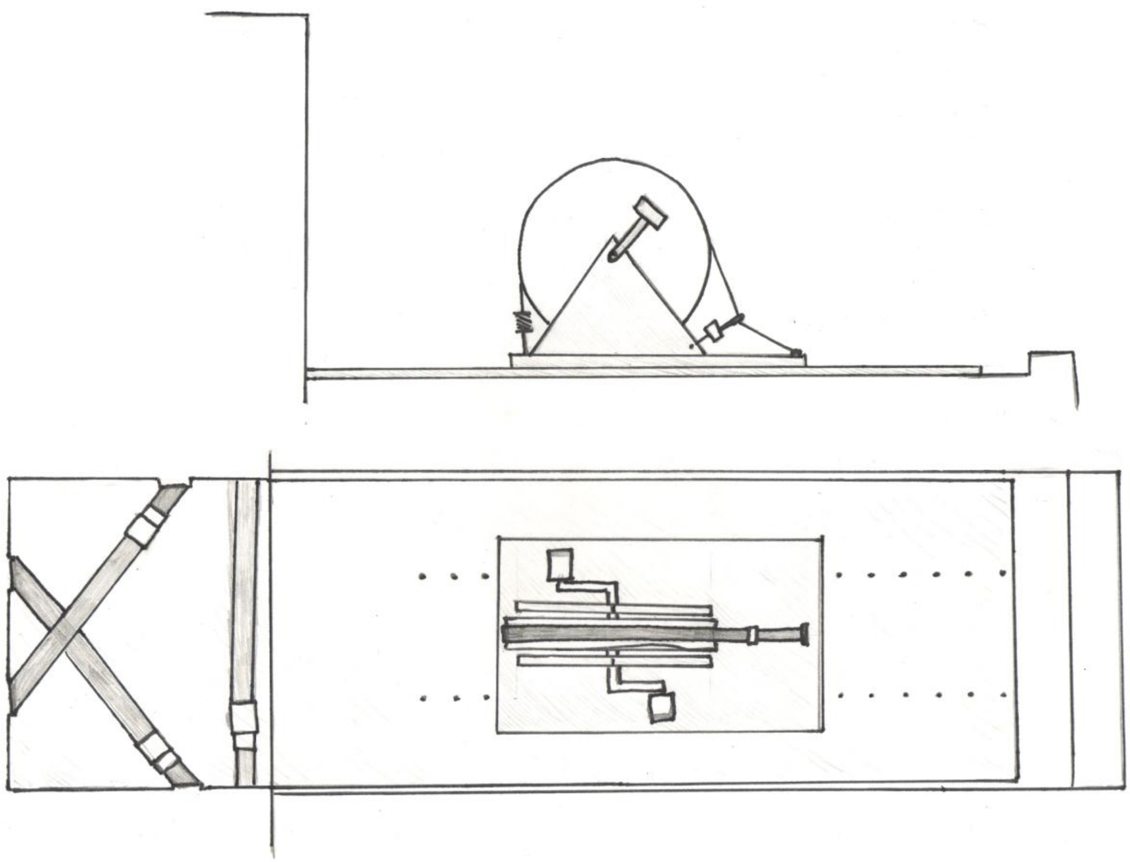

Figure 4: Sketch of Cycle Design

List of the decision factors:

<u>Advantages</u>	<u>Disadvantages</u>
Constant, easily adjusted resistance	Forces along head-feet axis
Familiar, simple to conceive	Limited space for knee movement
Proven effective for HR increase	Non-ferrous construction difficult

Design Alternative 2: Lever System

The second design we came up with is a lever system. This design was inspired by a meeting with Dr. Gruben of the physiology department at UW Madison. He has done some previous analysis of an exercise device similar to the one we are building. His design consisted of ropes that attached to a board running under the subjects knees, then ran up over a series of pulleys suspended above, and to a motor that provided a constant cycling force. This design proved more complicated than we felt was necessary and some aspects of it were not compatible with the MRI. However, using the concepts he pointed out, namely force in a floor-to-ceiling motion applied to the knees, we came up with our own design.

Our design consists of a pair of levers that attach to the subject's knees. Weights will be suspended from the far end of the levers. They will attach to a swing arm handing from a fulcrum mounted to the backboard. The swing arms will pivot around the fulcrum axle on their upper end and the levers will pivot from their lower end. The subject's feet will be strapped onto pedals also swinging from the fulcrum axle. This will keep the feet isolated along a preset path and should make for a much more solid feel. Once again there will be a waist belt to keep the subject as still as possible.

The main advantage to this design is the minimizing of undesired forces. The vast majority of the force will be applied in the floor-to-ceiling direction at the subject's knees. The force applied by the subject will be countered by the waist belt and foot track. By allowing the levers to pivot and swing at the fulcrum, and the feet to swing as well, movement in the head-to-foot direction will be all but eliminated. This will be beneficial to maintaining a stationary head. Other advantages include simple design, adjustable range of motion, and simple adaptability to different sized subjects.

A potential disadvantage will be the force produced. With a weight lifting system there is potential for the weights to create momentum when being lowered which may lead to impulse forces. This would be undesirable for the purposes of constant exercise but we feel it will be negligible. Further testing will be needed to confirm our design.

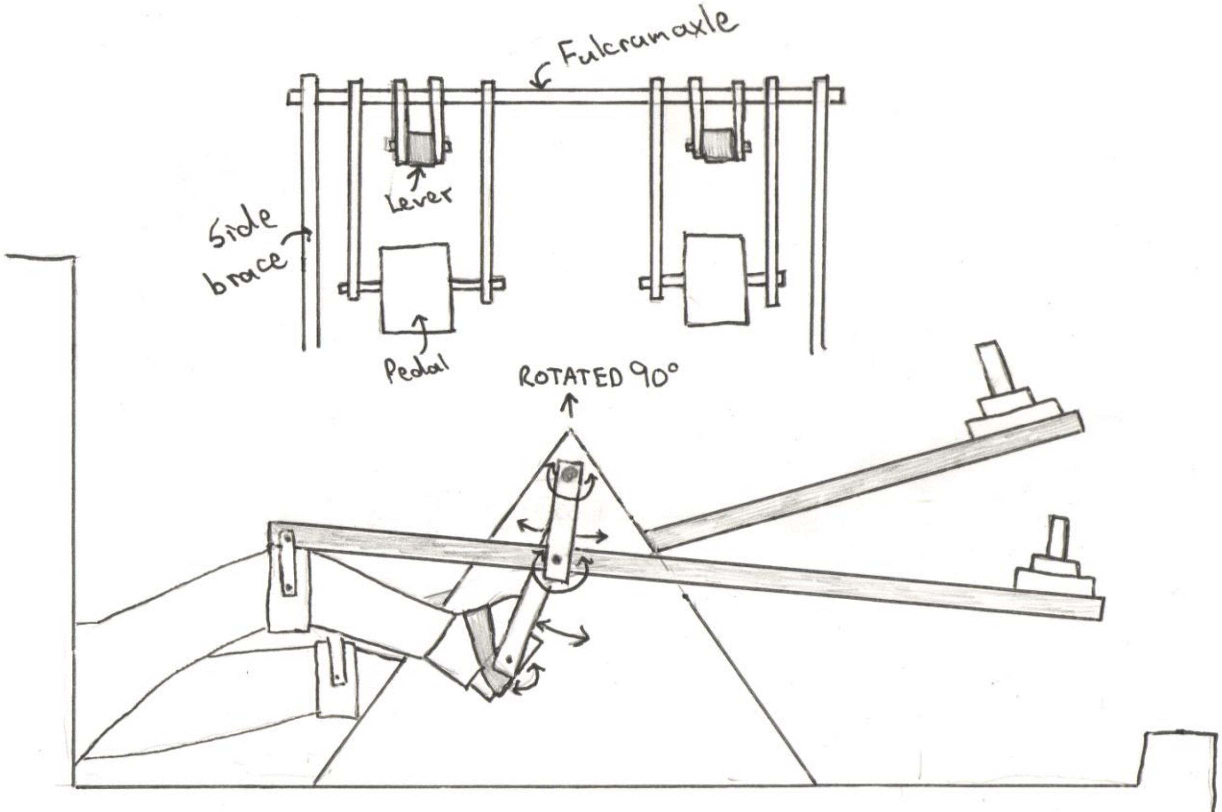

Figure 5: Sketch of Lever System (right leg shown through side brace)

List of decision factors:

Advantages	Disadvantages
Near zero head-feet axis forces	Movement not as natural
Simple resistance adjustment	Larger, less portable
Easily compatible to varying body sizes	Unproven HR effectiveness

Design Alternative 3: Ferrous Boots

Our third and final design consists of an idea we call ferrous boots. This design would utilize the magnetic field already present inside of the MRI room to provide resistance, which makes it relatively simple. This idea consists of placing a small ferrous metal plate made of steel inside the sole of several pairs of boots, each a different size. The patients would then wear an appropriately sized pair of boots while being scanned and perform a stepping motion, moving their legs in the horizontal direction. The resistance for this exercise would be provided by the force of the magnetic field acting on the ferrous metal plate. As a safety precaution, the boots would be strapped to a backboard that would be placed on top of the MRI bed. These straps would prevent the boots from being pulled too close to the MRI bore, as the magnetic field increases in strength towards the interior of the MRI tube. Also attached to the bore would be a series of straps that would fasten the patient and prevent movement of the upper body similar to a racing seatbelt, with five points of contact. There would be three straps, one across the waist, the other two coming from each shoulder to the opposite hip. This would prevent the majority of the motion that the upper body experiences, resulting in the most accurate scan possible. One additional feature of this design would be the ability to change resistance by adding or subtracting metal plates from the bottom of the shoe. These plates would be able to be swapped in and out easily, as they would simply rest below the sole of the boot. As stated previously, the largest benefit of this design is the simplicity behind it. Generally speaking, the simpler the design, the easier it is to both build and maintain over time. The ferrous boots would easily accommodate subjects of every height, fitness level, and size.

Despite satisfying the majority of the major and minor design requirements, the ferrous boots fall short in two very important categories which is their ultimate downfall. Any time ferrous metal is brought into a powerful magnetic field, it has the potential to influence that magnetic field. In this circumstance, the change in the magnetic field produced by the MRI would ultimately influence the scanning process, leading to images that are not accurate. This is a serious problem for our project, as the main goal is to obtain clear and accurate images. Additionally, there is a safety concern bringing ferrous metal into such a powerful magnetic field. Such a practice is highly frowned upon because the strength of the magnetic field is powerful enough to send ferrous objects flying, which can result in severe injury (Livestrong, 2010). Because of these two downfalls, the ferrous boots were not chosen as our final design.

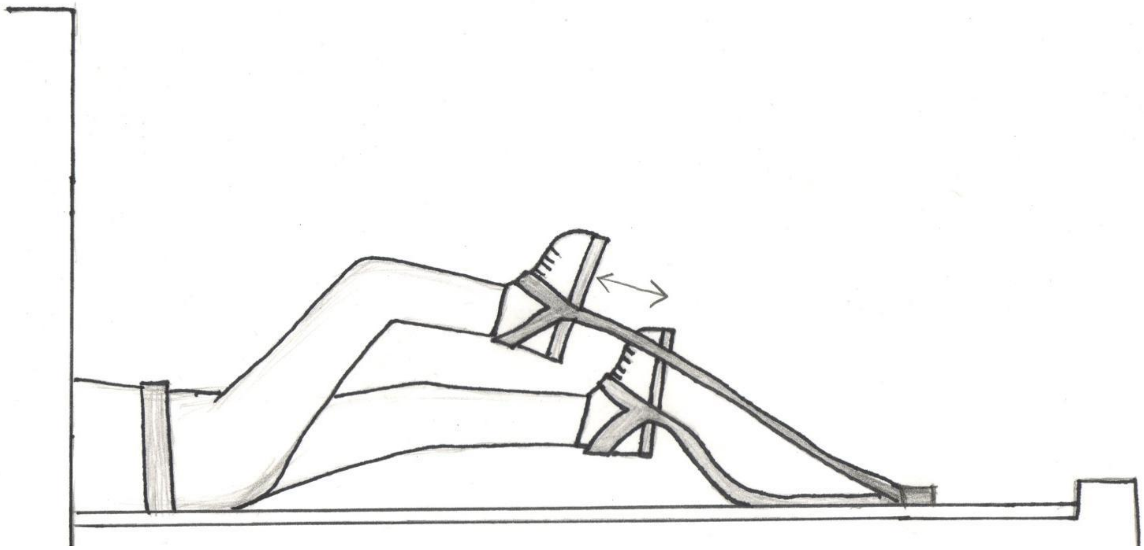

Figure 6: Sketch of Ferrous Boots Design

List of decision factors:

<u>Advantages</u>	<u>Disadvantages</u>
Very simple	Safety concerns
Simple resistance adjustment	Possible image disruption

Final Design

In choosing between our three primary designs, we broke down the design requirements described earlier into categories and rated them based on just how important they are to our project. This can be seen in our design matrix, pictured below (Table 1).

The first design requirement listed in the design matrix is the ability of the designs to provide constant resistance. As previously mentioned, this idea is crucial to the success of the project, which is why we gave it a weight of 20. Our client wants patients to be able to continuously exercise without a large impulse being generated. That being said, all three designs rank high in this category, but the ferrous boots would ultimately provide the most constant resistance, as it would never go away while inside of the MRI room.

The second consideration of the design matrix looked at how easily a particular design could be fabricated. This design aspect was only weighted at 10 because was determined to not be as major as some of the other aspects. The ferrous boots once again had a perfect score, but they were all very close, with the lever having the lowest score of 8/10.

The adjustability of each idea was the next aspect that was looked at. To clarify, this means the ability of the design to change resistance in order to accommodate people of varying levels of fitness. This was also weighted at 10, because ultimately our client is looking for a product that works, and he was willing to deal with the ramifications of not being able to completely adjust the resistance. The lever and the ferrous boots scored well in this category, as they would most likely be able to accommodate people of all fitness levels. Adjusting the resistance for the lever would be especially easy, as it would simply require adding more weight to or taking weight off the end of the lever

The next category that we took into consideration was the range of motion of the exercise. This idea was ranked at 20, because it is important that our design is able to accommodate people of varying heights. The cycle only scored 13/20 in this category because it would likely not be able to fit people under the height of approximately 5’5”. The ferrous boots scored the highest with 18/20 and the lever scored a close second with 16/20. The ferrous boots and the lever ultimately have the same motion; however, the lever scored high in this instance because individuals would be able to limit how far they chose to move their legs very easily.

One of the most important aspects of our design matrix is whether or not each design is MRI compatible and safe. These two facets of the design are absolutely essential, and the project would not work without the requirements being met in these areas. This category was given a ranking of 20. This is also the ultimate downfall of the ferrous boots. In looking at the table, the ferrous boots perform well in the entire design matrix with the exception of this category. They were given a score of 2/20 because they would not be entirely safe and are not MRI compatible. The lever scored the highest in this category because all parts would be completely nonferrous and the design provides little safety concern.

The final aspect of the design matrix is the ability of each design to stabilize the upper body. The clarity of the scan and the stability of the upper body experience a linear relationship: the more stable the upper body, the better the scan. Since having accurate scans is the ultimate goal of the project, this idea was given a weight of 20. The lever won in this category, with a score of 17/20. The lever does a nice job of making the majority of the force in the vertical direction, which prevents side to side motion of the upper body. The other two designs have the human body subjected to forces in the horizontal direction, which ultimately makes for less stability.

Criteria		Possible Designs		
Considerations	Weight	**Lever**	Cycle	Ferrous Boots
Constant resistance	20	**18**	18	20
Ease of fabrication	10	**8**	9	10
Adjustability	10	**9**	6	10
Range of motion	20	**16**	13	18
MRI Compatibility/Safety	20	**17**	15	2
Upper-body stabilization	20	**17**	15	13
Total	100	**85**	76	73

Table 1: Design Criteria Matrix

It can be seen from our design matrix that the lever is the design idea that we decided to pursue. We believe this design is able to best satisfy all of the design requirements provided by our client. In order to construct the lever device, we decided that we would use aluminum, wood, and brass as the main components of the design. These components were chosen because they are completely nonferrous and the aluminum is relatively strong. The levers and swing arms were all composed of aluminum, the screws were brass and the support system and foot pedals were both composed of wood. Once we decided on our final design idea, we began the process of fabrication.

Fabrication:

Once we decided on our final design, the logical next step was to begin fabrication. As with any project, fabrication often leads to the discovery of various design flaws. Because of this, it is important to begin fabrication as early as possible so that, by discovering many flaws, the design becomes progressively better. Each flaw might be viewed as a failure of an aspect of the design, and the more time spent during fabrication of a prototype the more prone these flaws are to being discovered. The flaws can then be fixed, leading to a better project.

In order to begin fabrication, it was necessary to formulate a plan, get the necessary supplies, and gain access to the student shop. As far as the plan went, it was decided early on that the most basic prototype possible should be created initially. This way, it was possible to test the concept of the design without spending very much time creating it.

Our first crude prototype was created using wood pieces and one aluminum rod. Weight was put at the end of the levers and a vice was used to support the apparatus. Using this prototype, we managed to raise the heart rate to 117 beats per minute in approximately 2.5 minutes. Given this, we decided to pursue the design further.

In order to make the device both more stable and operational, there were several aspects which needed to be greatly improved from the first prototype. Despite being able to raise the heart rate, the main problems with the previous prototype were the knee connections, the overall stability, and weights at the end of the levers. It was by no means a complete prototype, more just a mock up used to see if the basic idea could work.

To fix the stability, the pieces that were previously made of wood were milled out of thinner and stronger aluminum. This made the overall design less bulky and much more stable. In terms of stability, the aluminum used has an ultimate strength of approximately 310 MPa (Aerospace, 2010). In comparison, typical wood has an ultimate strength of approximately 83 MPa (James, 2010). From these numbers, it is clear that aluminum is much stronger. The four swing arms for the levers were created out of thin aluminum stock. Two foot pedals were also added to the design, which each consisted of two swing arms, an 3/8" aluminum rod and a wooden square for the pedal itself. This eliminated the potential source of fatigue from having to hold each foot up for extended periods. The levers, originally made out of 2"x2" wooden rods, were replaced with aluminum stock. This was because the wooden rods were not the most stable, leading to doubts about their ability to continually hold somewhat large amounts of weight. In addition to adding aluminum parts, a solid support system was built (pictured below) so that no external devices, such as the vice, were needed to hold the device. This was built primarily out of wood, with an aluminum rod used as the pivot for the swing arms. With the solid foundation in place, testing could commence and further fabrication of other parts could continue.

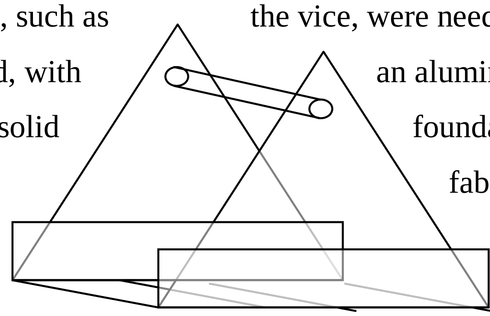

Figure 7: The support system used for the MRI exercise device. The triangles and bottom supports are made of plywood, the rod is made of aluminum.

The knee straps of the previous prototype needed much improvement. In an attempt to alleviate the force on the back of the knee, it was decided that the lever would attach directly above the knee, but in order to strap it to the knee, there would be two straps. Of these two straps, one would attach approximately 8 inches above the knee and the other approximately 8 inches below. The new design also included a knee pad, much like a knee pad used for rollerblading or riding a bicycle. This was to protect the knee from being bruised by the hard lever, placed on top of it. This portion of the design is pictured below, in Figure 7.

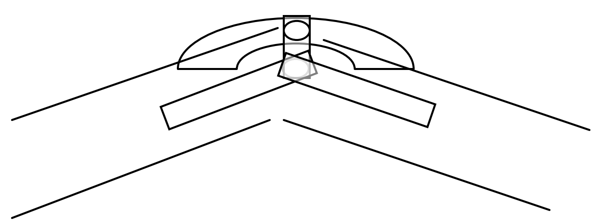

Figure 7: A prototype knee strap which intended to prevent the knee from being exposed to too great of forces

After much testing, however, this knee strap design did not meet the design requirements. It was bulky and uncomfortable, and it took up too much vertical space above the knee. In the end, a simple knee strap that went directly around the back of the knee was used. It consisted of a heavy duty Velcro strap adhered to both a heavy duty ratcheting strap and a pad. The ratcheting strap was included within the knee connection as an extra factor of safety. For further padding, another pad was placed between the strap and the subjects knees. During testing, subjects experienced little discomfort.

The last major problem that was faced with the prototype involved placing the weights on the end of the levers. In order to fabricate this portion of the design, we first needed to obtain weights that were nonferrous. We ended up going with weights that consisted of concrete encased in plastic. These weights are completely nonferrous and suitable for the job. In order to attach them to the levers, a large aluminum rod was placed on top of the end of each lever, facing upward. It was attached by threading an aluminum bolt through both the end of the lever and the rod itself. The weights were then added to the end of the lever by placing their center hole through the aluminum rod.

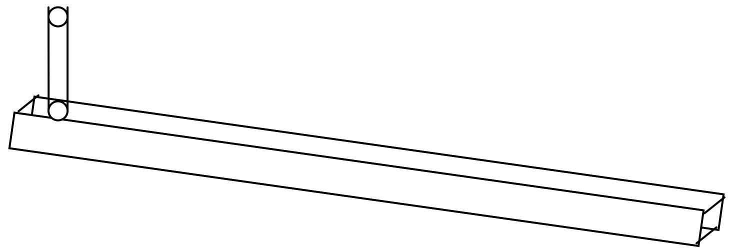

Figure 8: The aluminum lever used with the aluminum rod protruding from it. Weights are placed on the aluminum rod and rest on the aluminum lever.

This support system and stepping device were all made to be put on a backboard which can be placed on the MRI bed. This backboard was made of a single piece of plywood with a yoga mat secured to the top for comfort. Pieces of yoga mat were further used under the backboard to avoid any scratching to the MRI bed. Lastly, this backboard has a strap running around it which the subject can tighten around their waste. This strap is not attached to the backboard to allow for adjustability to height.

It should be noted that during early fabrication, ferrous parts were used simply because they were readily accessible. During the fabrication of the final prototype, aluminum and wood were the primary components used.   There were also a few brass screws which were integrated into the design. At the end of the semester, all of the bolts that were used were still ferrous, which meant that the prototype was not quite ready to be placed inside of an actual MRI. This problem had a simple solution, however, and simply required aluminum or brass bolts to be purchased instead. With fabrication complete, the next aspect that was focused on was testing.

Testing

Two elements needed to be tested for this device. First the team needed to test if the machine could adequately raise a resting heart rate to a working heart rate (110-120 beats per minute). The team then needed to test the device for comfort.

The team first tested the device's ability to raise a subject's heart rate as a proof of concept test on a very rough prototype of the final design. The subject was strapped into the prototype device and the heart rate was initially tested by the subject himself counting the beats per minute. Although the result showed the heart rate was elevated, a consistent heart rate level could not be determined and the team therefore decided a new means of reading the subject's heart rate was necessary. This proof of concept test was done a second time with an electronic heart rate monitor. The team found these results much more consistent. The test showed a heart rate of 117 beats per minute could be obtained after three minutes of activity using the device.

After this initial test, a final device was built and further tests were performed using this new device. The team once again used the electronic heart rate monitor to determine the subject's heart rate. During testing, the subjects in the test worked out for varying periods time the heart rate was recorded at thirty second intervals. The weight used and the pace of exercise were varied during testing. This will be necessary when used during actual tests as each subject will have varying levels of fitness and strength; a stronger person will need more weight and people used to more cardio work will need a higher rate of exercise. With a weight of 22.4 pounds and a rate of 75 pumps per minute, an average heart rate of 119 beats per minute was obtained after 90 seconds of activity. Tests were then done at 60 pumps per minute to see the result of a slower pace. The test only gave a maximum heart rate of 104 beats per minute for the given subject. Finally a test lasting ten minutes was performed. During this test, a heart rate above 110 beats per minute was reached after two minutes of activity and was maintained throughout the remainder of the ten minute test.

The following can be concluded from these tests. First, the device can raise a resting heart rate to a heart rate between 110-120 beats per minute within a reasonable time of 2 minutes of activity. Furthermore, the device can maintain this heart rate for an extended period of time. Finally, the pace and/or the weight must be adjusted per subject to accommodate for varying fitness levels.

A test was done to determine the comfort level of the device. As comfort is different for each person, a more qualitative approach was taken. The subjects were asked to rate the device's comfort on a scale with reference to comfort and how it relates to length of use. The scale consisted of these five levels: extremely comfortable, comfortable and able to use for an extended amount of time, slightly uncomfortable and able to use for an extended amount of time, slightly uncomfortable and unable to use for an extended amount of time, extremely uncomfortable. The results showed that the subjects found the device comfortable and able to use for an extended amount of time. This result shows the device is adequately comfortable for practical purposes. Despite this favorable result the team noted there would still be room for improvement as far as comfort is concerned.

During these tests, the team observed head movement and noted there was very slight head to foot movement. Despite this observation, the team did not measure this movement because the subjects in actual tests would be restrained by an MRI head coil. Any tests done at this time would be irrelevant without this final resistive piece of equipment. The team did mention this movement to an advisor familiar with the use of the MRI and the head coil. He ensured the team that any head movement seen at this stage would be eliminated once the subjects were put into the head coil device.

Work Calculations

In addition to these two tests the team used this opportunity to measure the range of motion allowed by the device. The team used the fact that the distance from the knee to pivot is 22 inches and the distance from the pivot to the weight is 48 inches to convert the weight on the bar to the weight transferred to the knee. The team then used the fact that the range of motion of the knee is 8 inches to calculate the work done by the knee and the power associated with the work. The team used this information to calculate work and power. In these calculations, the following equations were used: $W = mv^2$ where W is work, m is mass, and v is velocity; and $P=W/t$ where P is power, W is work and t is time. With a mass of 22 kilograms of weight on the knee, the following results were found.

Pumps/min	Work/min (J)	Power/min (mW)
30	.44	7.3
45	.99	16.5
60	1.76	29.33
75	2.75	45.8
90	3.96	66

Table 2: Pace during exercise device use, and the work and power associated with each.

Future work

While we feel our project made some significant progress toward finding a solution for our client’s needs, there are still improvements to be made on the design.

The first improvement would be the method of applying resistance. While the weights are effective, the motion of lifting and dropping them is not a natural feeling. The comfort and ease of performing the exercise is not at the level we were aiming. The stopping and starting of the motion also creates more upper body movement than we were hoping. The body tends to jerk a bit when shifting forces from one leg to the other. Ideally the resistance would be a maximum when the leg is in mid-stride, rather than at the lowest and highest points where optimum would be zero force. This would create much less impulse and jerking when switching a leg from an upward motion to a downward one. A solution we feel is worth pursuing would be incorporating a flywheel attached to the end of the levers by straps. This would create a smooth resistance with much more ideal forces.

The second recommendation for improvement is to make the structure a bit sturdier. During testing we found significant deflection in the fulcrum axle when the weights exceeded twenty pounds per lever. A higher amount of weight could very well be necessary in order to raise some subjects' heart rates into the goal range of 110-130 beats per minute. With the lever distances between weight load, fulcrum, and knee connection, the forces on the fulcrum are approximately 3 times greater than at the load point. In order to meet this need the axle should be made of a larger diameter stock. Along with that, the plywood sides could be doubled to ensure their load bearing capacity.

Our third improvement would be the knee straps. While adequately strong and quite comfortable as is, with an increased load or especially sensitive subject, e.g. the elderly, the straps may cause some pain. We experimented with several different designs and found the one in operation to be the best but there could very well be a better solution out there. At the least, in improved padding system could be incorporated.

Finally, the prototype is not yet MRI compatible. This was one of the main design requirements for the project. However, if desired by the client, the conversion of the prototype to full MRI compatibility will be quite simple. We would merely need to order some brass bolts, nuts, and washers to swap out the ferrous ones currently in use.

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Product Design Specifications

MRI Exercise Device

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Function

This Project is designed to develop a device to allow researchers to observe blood vessel diameter, along with middle cerebral arterial velocity, of a patient during steady-state exercise. In order to observe these conditions, Magnetic Resonance Imaging (MRI) must be used, which limits the materials and mechanics of the device. In particular, we plan to construct a device that allows a patient to maintain upper body stabilization during continuous exercise while inside the MRI machine.

Client Requirements

- The device has to be MRI-safe
  - It cannot contain ferromagnetic materials
  - Has to fit on MRI bed
  - Cannot damage MRI machine
- Withstand frequent use
- Provoke a raised heart rate for an extended period of time
- Fit a wide range of patient heights
- Minimize head and upper chest movement

Design Requirements

1. Physical and Operational Characteristics
   a. *Exercise:* The device should allow for steady-state, dynamic exercise for a period no shorter than 8 minutes, generating a heart rate of 120-130 beats per minute.
   b. *Stability:* Device must minimize head and upper body movement, while legs are free for peddling/cycling movement.
   c. *Size:* The device must fit on the MRI bed; Board has to accommodate individuals between 5’4” and 6’4” tall.

d. *Operating Environment*: The device will be used in an MRI machine, so no ferromagnetic materials (containing iron, cobalt or nickel).
e. *Versatility:* Device must accommodate a various patient heights and weights, as well as adjustment for different head coils.
f. *Life in Service*: Ideal for the device to last 3 or more years with frequent use.
g. *Ergonomics:* Device should be comfortable, allowing a wide range of motion for lower body, while minimizing strain on hips and ankles.

2. Production Characteristics

a. *Quantity:* One prototype should be constructed.
b. *Target Production Cost:* Up to $1000.

3. Miscellaneous

a. *Customer:* The primary customers are our clients; their main concern is to observe arterial diameter changes in patients during continuous dynamic exercise.
b. *Competition:* There are current MRI exercise devices; however, the one known brand is very expensive. Our goal is to greatly reduce the production cost, while maintaining function.