MRI Exercise Device

October 20, 2010

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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. 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. 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 lever device that creates a constant resistance to vertical motion in the legs was chosen to provide an exercise mechanism, with straps on the subject's upper body to maintain stabilization. Testing will be conducted to ensure MRI compatibility, as well as the prototype's ability to provide a means of constant exercise for the test subjects.

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. By observing the cerebral blood flow during a period of increased heart rate, it could be possible to pinpoint some direct causes of fatalities and injuries in patients with these attributes. 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. 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**).

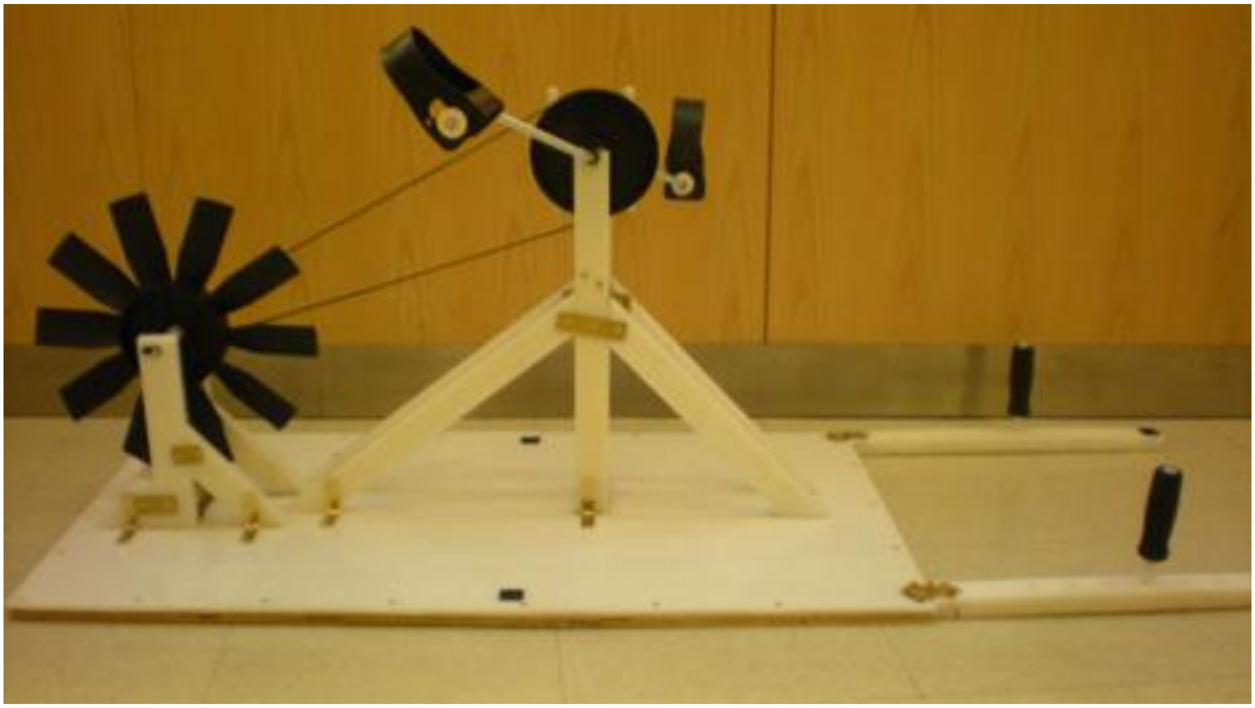

Figure 1: Cycle device from BME Design, 2009 (BME Design, 2010).

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 the client from this project was 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. 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. 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 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.

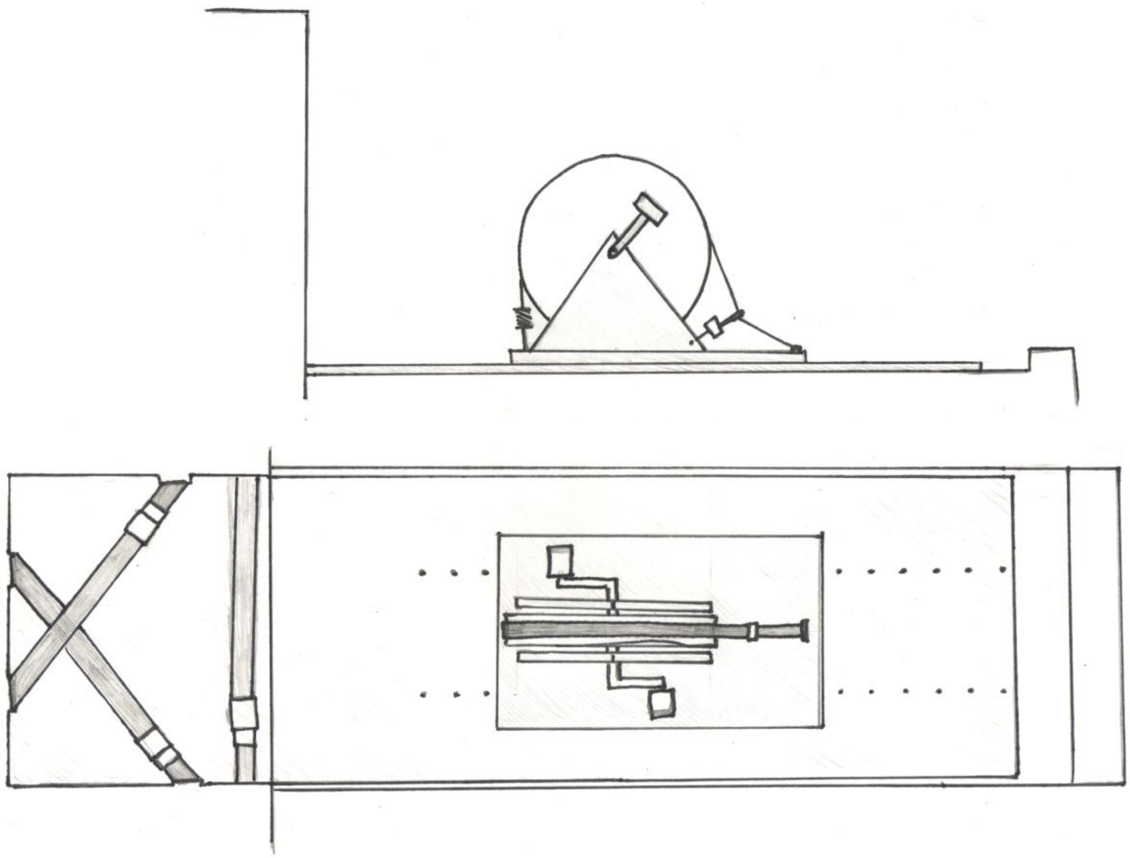

Figure 4: Sketch of Cycle Design

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 run over a fulcrum mounted to the backboard and be allowed to slide along the fulcrum as well as pivot. The subject's feet will be strapped into a track that allows them to slide along the head to foot direction but limits movement in the floor-to-ceiling direction. 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 slide along their fulcrum, and the feet to slide along the track, 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.

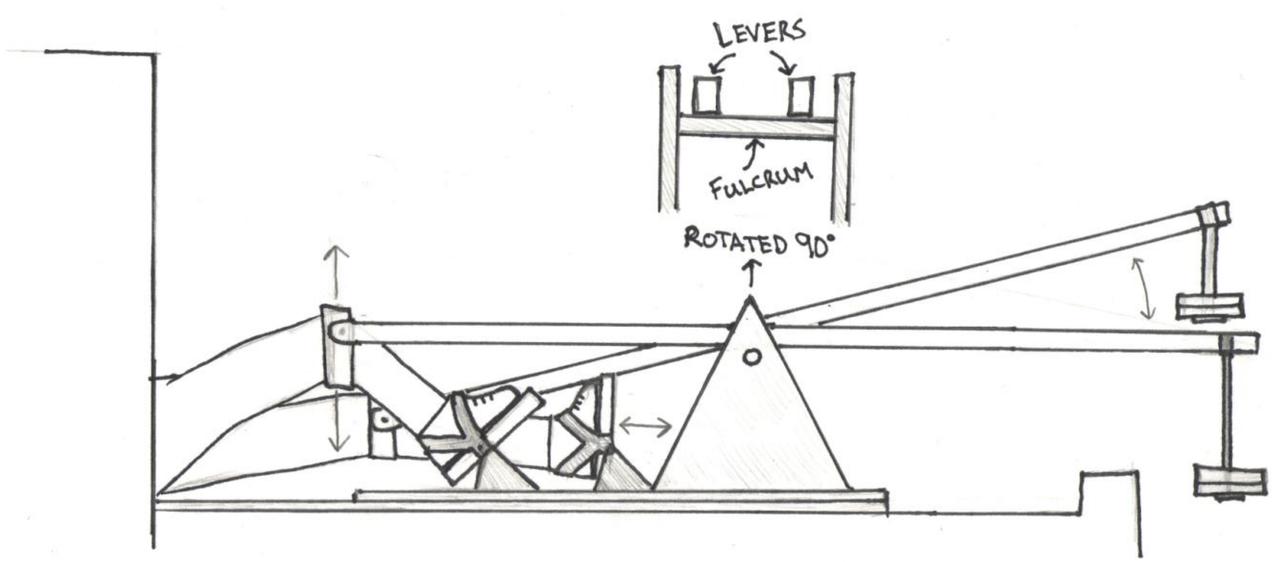

Figure 5: Sketch of Lever System

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. Because of these two downfalls, the ferrous boots were not chosen as our final design.

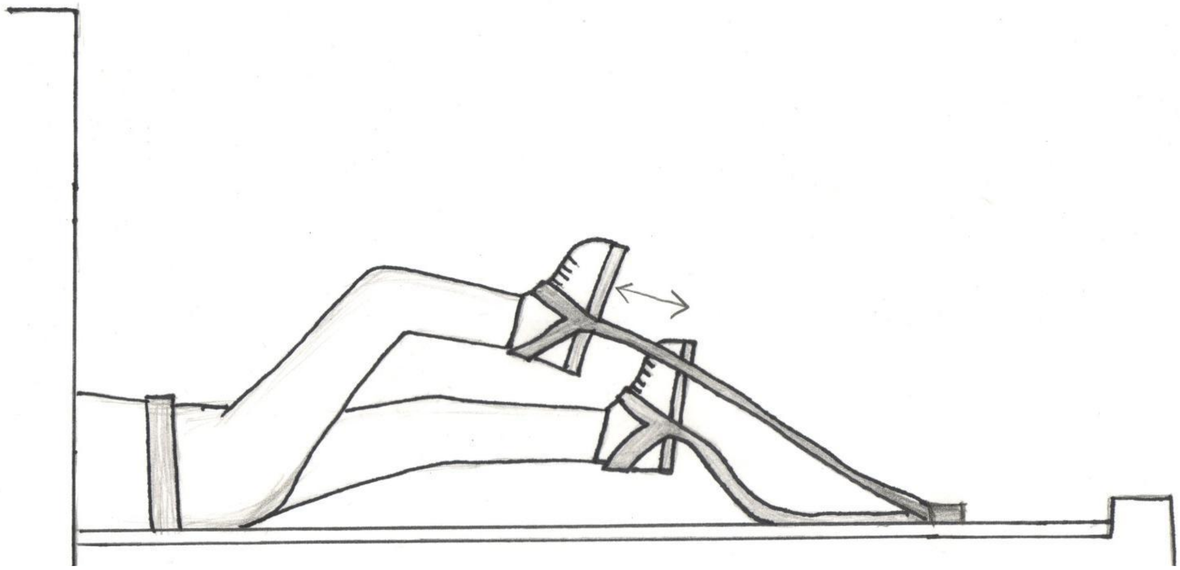

Figure 6: Sketch of Ferrous Boots Design

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.

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 which we have decided to pursue. We believe this design will best satisfy all of the design requirements provided by our client.

Future work

In the very near future, we hope to make major progress on our project. We already have a good idea of what parts we will need to purchase, but these selections will have to be finalized. Once we have a solid list of the components necessary for our design, we will purchase them. In order to make sure that they are in fact non-ferrous, we will test each part after receiving it. Immediately after all of our components pass the test, they will be assembled to make our first prototype. This will then be tested to make sure that it satisfies all of our design requirements. If we find that it lacks in certain areas, we will troubleshoot and attempt to fix any problems with the device with the remaining time that we have. The next step will be to make sure the design is aesthetically pleasing. Afterwards, we will deliver our final product to our client, Dr. Bill Schrage.

References

Farrell, Lenz, Maharaj, Yagow. (2010) *An MRI-compatible lower-leg exercising device for assessing pulmonary arterial pressure.* Presented as a final report for BME Design 400, UW-Madison.

Lode BV. "MRI Ergometer Pedal." *http://www.lode.nl/en/products/mri_ergometer_pedal* Last Accessed October 18, 2010.

Product Design Specifications

MRI Exercise Device

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September 17, 2010

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
- 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.