University of Wisconsin - Madison
Department of Biomedical Engineering

MRI-Compatible Cardiac Exercise Device

Nick Thate, Evan Flink, Tongkeun Lee, Andrew Hanske

Abstract

Background

Many cardiovascular diseases could benefit from assessment during exercise. Currently, the optimal way of non-invasively measuring cardiac function is through the use of magnetic resonance imaging (MRI); however, literature on imaging a non-pharmacologically induced state of stress is very limited.

Methods

We developed a device that utilizes a stepping motion with adjustable weight resistance and power output measurement system that is compatible with the MRI bore. We tested the device using MRI and echocardiography to determine its effectiveness at generating a state of exercise.

Results

The device functioned well in the MRI environment and proved able to successfully increase the heart rate and cardiac output on average by 98.5% and 53.2% respectively. The echocardiography testing showed similar trends.

Conclusions

The MRI-compatible exercise device demonstrated the ability to generate a state of exercise while allowing for simultaneous MR imaging. Although the device was only used to examine cardiac function, it has the potential for use in a variety of other research applications involving the effects of exercise.

Background

The assessment of cardiac function during exercise can be used as a tool in the investigation of a wide range of cardiovascular diseases. Several diseases are only apparent during a state of stress [1]. The "gold standard" for non-invasive measurement of cardiac function is the use of magnetic resonance imaging (MRI) [1]. However, echocardiography can also be used, as well as invasive techniques, such as heart catheterizations. The traditional way of measuring cardiac function with MRI is to pharmacologically induce a state of exercise, characterized by increased cardiac output and heart rate. Then, the change in flow, ventricular volume, and ventricular mass is measured throughout the cardiac cycle [1]. This type of test is called a stress test. Pharmacological stress tests can be dangerous for diseased patients, and may have slight variations compared to normal exercise [1]. Therefore, it is desirable for the patient to obtain a state of exercise through physical activity. The main limitation of this method is that the exercise must be performed outside of the MRI bore, allowing for the patient to recover before scanning occurs. Therefore, it would be advantageous to have an exercise device that could be used during the imaging process.

Currently, there are no commercially available devices that allow a patient to exercise during a cardiac MR scan. The Lode BV MRI Ergometer is an exercise device that is MRI-compatible; however, its range of motion requires more leg room and knee clearance than is possible during a chest scan [2]. Also, this device is very expensive, with a minimum price of $28,000 [2]. Another exercise device that can be used for stress testing is the MRI-compatible treadmill developed at Ohio State University [3]. This device is ineffective because the patient exercises outside of the scanner, allowing their vitals to return to baseline before images can be taken [3]. Finally, a group at the University of Auckland has recently developed an MRI-compatible cycle ergometer [1]. This device has a much smaller crank length than the Lode BV MRI Ergometer, allowing patients to perform the cycling motion during cardiac MRI scans [1]. However, the limited crank length may hinder the level of exercise the patient is able to achieve. Additionally, they allowed for the heart to be located up to 10 cm away from MRI isocenter, which may suggest patient height limitations [1].

The goal of this project was to create an MRI-compatible exercise device that could be used while a patient undergoes cardiac MR scans. The device should provide adjustable workloads with enough resistance to maintain a state of exercise for the duration of the scan. The following sections will discuss our product design specifications, custom-made prototype, scanning protocol, and testing results we acquired over the past year.

Methods

MRI Exercise Device

The goal of this project was to develop an exercise device that could be used by patients while they lie within the confines of an MRI bore. In order to be MRI-compatible, all materials used must be non-magnetic so as not to endanger the patient or damage the equipment. The exercise motion must be comfortable and safe for the patient while eliminating unwanted chest movement and body translation. It should

accommodate for a wide range of patient sizes and fitness levels. Most importantly, the device must be successful at inducing a sufficient state of exercise to observe physiological changes in cardiac function.

The machine that was developed utilizes a stepping motion with adjustable weights as the source of resistance. The final prototype can be seen in Figure 1. It is constructed mainly of high-density polyethylene (HDPE), aluminum, brass, and nylon. This material selection is not to be overlooked, as it is of the utmost importance that the device is entirely non-ferrous. The base of the device is made from a ½-inch (1.27 cm) thick HDPE sheet, with two angled tracks at its bottom. These were cut to fit the contours of the MRI couch, allowing the device to slide with the patient as needed.

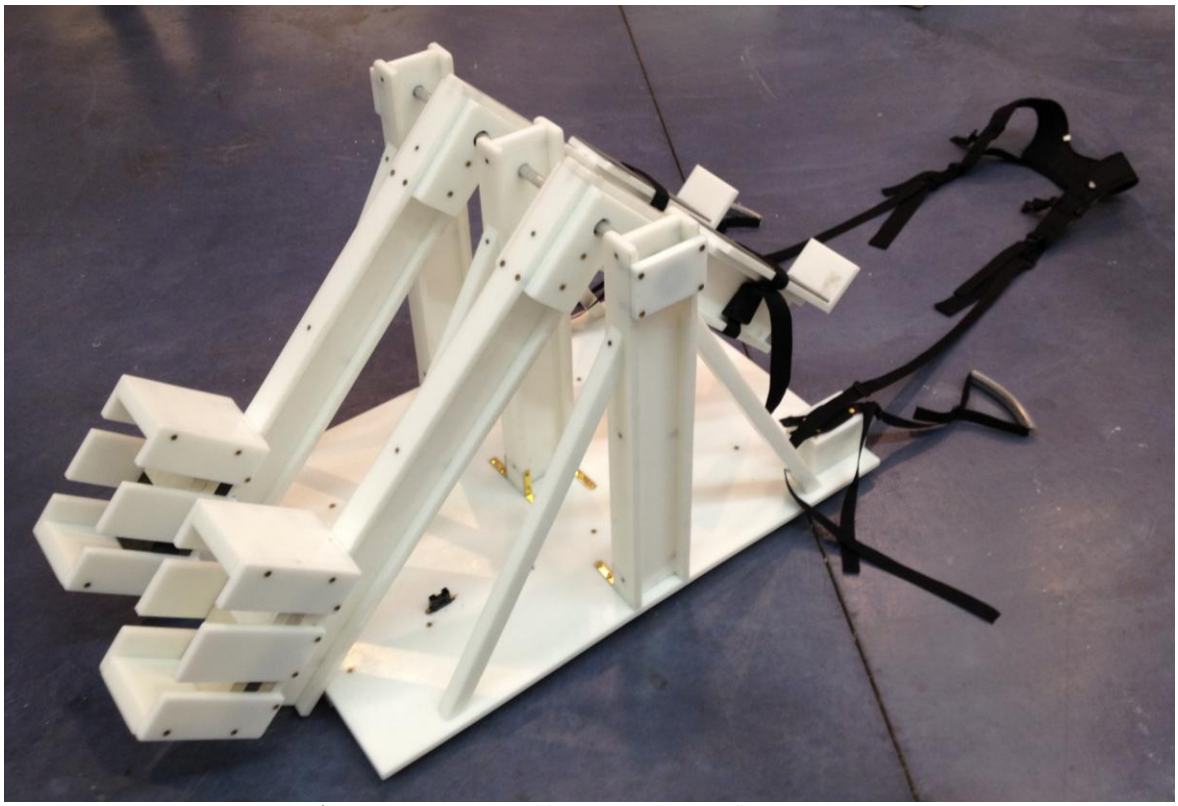

Figure 1: MRI-compatible exercise device – final prototype

The stepping motion is accomplished through the use of two L-shaped lever arms. Within each lever arm, two glass-acetal bearings allow for smooth rotation on an aluminum bar. These components are held up with three vertical supports. Both the lever arms and supports were constructed as I-beams using ½-inch (1.27 cm) thick HDPE. The patient uses foot pedals on one end of the lever arm to push with a stepping motion, allowing them to raise weights on the opposite end. The weights consist of DuPont Zodiaq tiles: a non-ferrous, mainly quartz, material with a fairly high density of 2.4-2.5 g/cm^3. HDPE weight containers, each with a maximum capacity of 16 tiles, are located at the weighted end of the lever arms. Since each tile weighs approximately one pound (0.45 kg), this allows for a variable capacity of 0-16 additional pounds (0-7.27 kg) on each leg. This facilitates an adjustable level of work depending on each patient's

fitness level. Nylon hand and foot straps, along with a shoulder harness, are used to secure the user to the device and ensure minimal patient movement.

Electronic Measurement

A Sharp GP2Y0A02YK0F analog distance sensor was incorporated into the design in order to sense the position of one of the lever arms as it moves in space. This sensor emits an infrared (IR) beam of light which is reflected off the lever arm and returned to the sensor. Based on the distance to the lever arm, the angle of reflection changes and allows the sensor to output a varying analog voltage [4]. This information is transmitted to an Arduino Uno microcontroller. The data is then sent via Universal Serial Bus (USB) to a port on a laptop computer equipped with the MATLAB computing environment. A MATLAB code is then used to read the serial port and convert the voltage data to a distance measurement. This conversion was calibrated by manually measuring a variety of lever arm heights, and relating them to the analog voltage readout using a logarithmic line of best fit, the results of which can be seen in Figure 2.

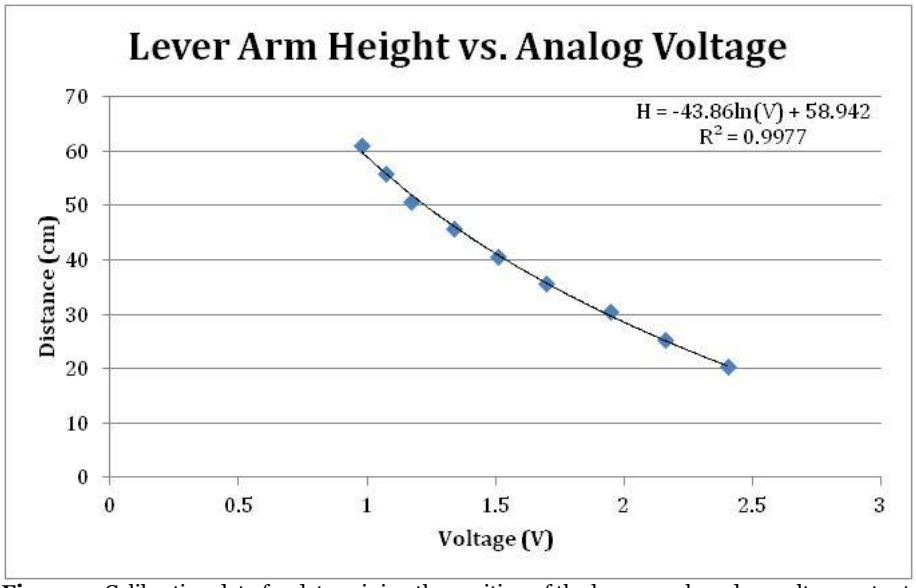

Figure 2: Calibration data for determining the position of the lever arm based on voltage output

As the subject exercises, MATLAB allows for the angular rotation of the lever arm to be consistently calculated for each step based on the distance sensor output. In addition, the time between each peak height was recorded in the MATLAB code and allowed for the calculation of stepping cadence. Using the values for angular rotation and stepping cadence, along with the amount of weight added to the lever arm and the geometry of the device, the power output could be approximated using the work-energy principle. The resulting power equation can be seen in Figure 3. A MATLAB display shows a dynamic plot of the height of the lever arm, as well as the height change per step, cadence, and power output as the patient exercises. A screenshot of this display during patient exercise can be seen in Figure 4. This will allow a technician or doctor in the MRI control room to know more about the patient's exercise load, as well as provide feedback where necessary.

$$\boldsymbol{P} = 0.1635 \frac{\text{min}}{\text{sec}} \cdot \frac{\text{m}}{\text{sec}^2} \; \boldsymbol{R} * \left[\sin(\boldsymbol{\theta})\left(1.7928\ \text{kg} \cdot \text{m} + 0.2828 \frac{\text{kg}}{\text{lb}} \cdot \text{m}\ \boldsymbol{N}\right) + (\cos(\boldsymbol{\theta}) - 1)(0.2276\ \text{kg} \cdot \text{m})\right]$$

$$\boldsymbol{\theta} = \tan^{-1}\left(\frac{\boldsymbol{H}}{25.72\ \text{cm}}\right)$$

Where:
$\boldsymbol{P}$ = Power (Watts)
$\boldsymbol{R}$ = Cadence (steps/min)
$\boldsymbol{N}$ = Added weight to lever arm (lbs)
$\boldsymbol{\Theta}$ = Angle of lever arm rotation
$\boldsymbol{H}$ = Height change of lever arm (cm)

Figure 3: Formula used in MATLAB code to compute power produced by the patient during exercise

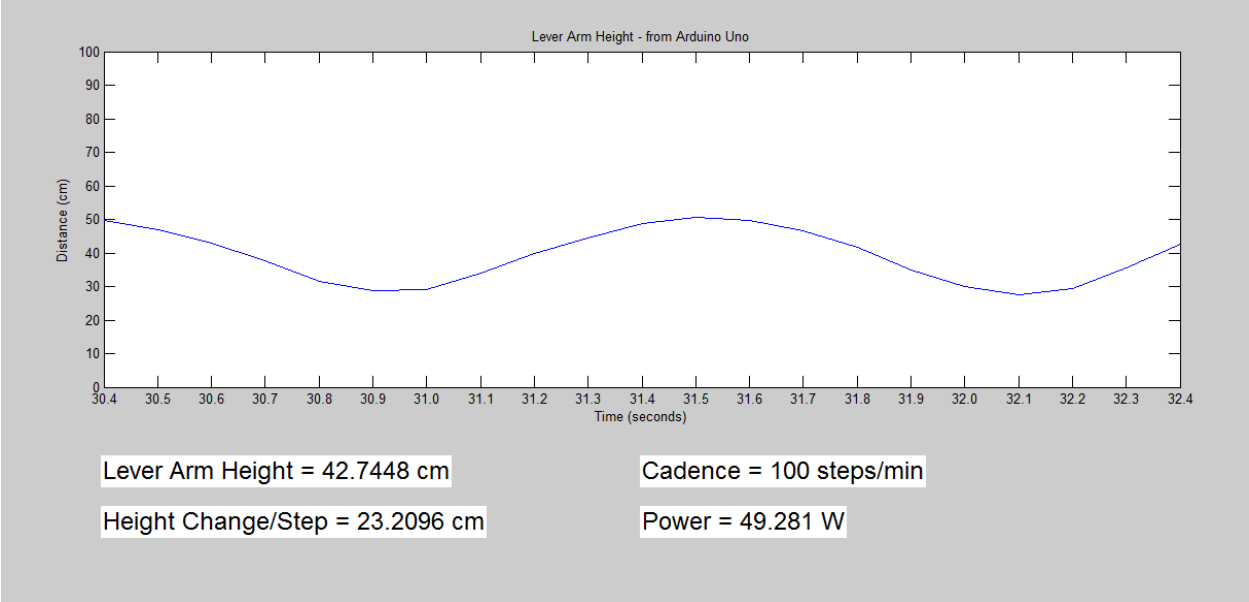

Figure 4: Screenshot of MATLAB display on a laptop computer during patient exercise

It should be noted that, as it currently exists, the electronic measurement system has not been outfitted for total MRI-compatibility. Given time and budget constraints, it was deemed more important to develop a working measurement system for the exercise device and then later adjust it to ensure compatibility. An aluminum Faraday cage will be used to shield the sensor and Arduino Uno from electromagnetic and radiofrequency (RF) interference. In addition, the USB output from the microcontroller will be converted to fiber-optic signals so that they can be safely transmitted to the computer in the control room.

MRI Protocol

The device was tested using a 1.5 Tesla MR scanner (Signa HDx, GE Healthcare) with an eight-element phased array cardiac coil (GE Healthcare). Cardiac function was assessed by acquiring images of the ascending and descending aorta. The slice location and a resulting image are shown in Figure 5. Scans were performed before exercise as a baseline and then immediately after 10 minute intervals of exercise. The amount of weight used depended on subject fitness levels. Subject heart rate and O_2 saturation

were monitored using a pulse oximeter. Two members of our design team participated in the MRI testing using an institutional review board (IRB) approved protocol. Written informed consent was obtained from both subjects.

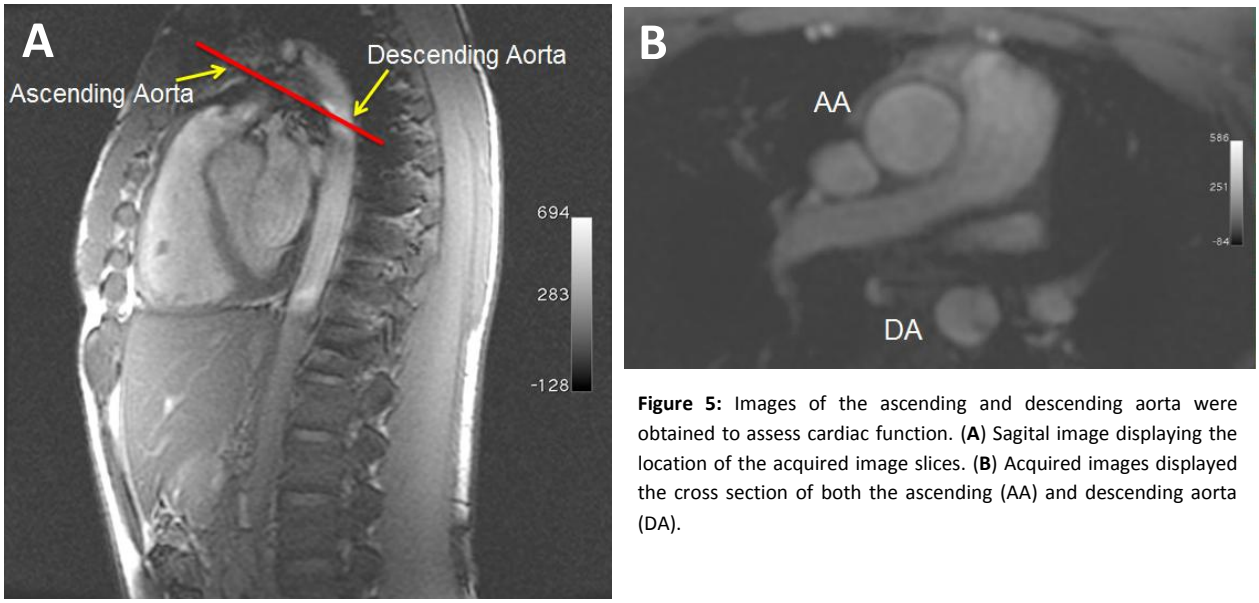

Figure 5: Images of the ascending and descending aorta were obtained to assess cardiac function. (**A**) Sagital image displaying the location of the acquired image slices. (**B**) Acquired images displayed the cross section of both the ascending (AA) and descending aorta (DA).

Echocardiography Protocol

In addition to MRI testing, the performance of the device was evaluated using echocardiography, or cardiac ultrasound. Although the aim for the device is to be used in the MR environment, echocardiography testing was used as a comparison for MRI results. During this testing, cardiac function was assessed by monitoring the pulmonary artery. The artery diameter, velocity time integral (VTI), and tricuspid regurgitation were measured at different levels of exercise. Further analysis provided the flow rate through the pulmonary artery.

Echocardiography testing was performed using a volunteer from our design team. Subject heart rate was continuously monitored using electrocardiography (ECG). Two-dimensional ultrasound images were collected at incremental heart rates during exercise. The testing began with imaging at rest, followed by exercise with the device. When a desired heart rate was reached, the subject briefly stopped exercising so that images could be acquired. These images were then assessed to calculate all relevant data.

Results

MRI Results

During testing, subject A exhibited an increase in heart rate of 110%, from a baseline of 50 beats per minute (bpm) to 105 bpm. Subject B displayed an 87% increase in heart rate from 75 bpm to 140 bpm. The relatively lower heart rate of subject A was a result of his increased level of physical fitness; however both subjects were able to approximately double their resting heart rate. The flow through the descending aorta of

subject A during one cardiac cycle for both pre- and post-exercise is displayed in Figure 6. A summary of the flow data and resulting stroke volume and cardiac output is shown in Table 1. Exercise was shown to increase the peak and mean flow, as well as the stroke volume. The cardiac output increased from 5.4 L/min to 8.7 L/min, which suggests a significant physiological change. Subject B's cardiac output also increased: from 5.3L/min to 7.7 L/min. The increase in cardiac output is both significant and relatively consistent for both subjects.

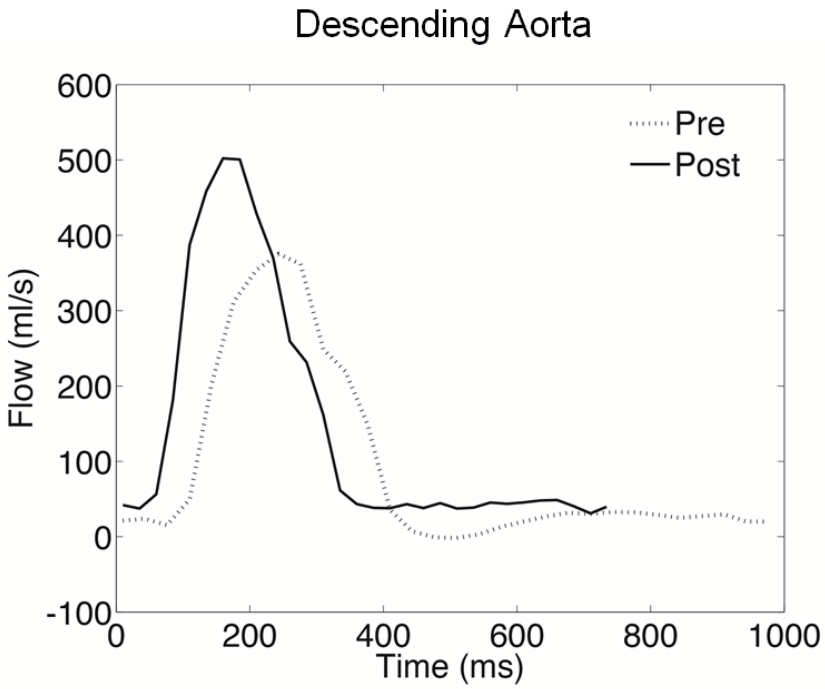

Figure 6: Flow diagram of the descending aorta of subject A during one cardiac cycle, showing both the pre- and post-exercise data.

Table 1: Flow data obtained from the descending aorta of subject A.

Summary of Descending Aorta Pre- to Post-Exercise			
	Pre	**Post**	**% Change**
Peak flow [ml/s]	375.2	502.0	33.8
Mean flow [ml/s]	90.5	144.8	59.9
Stroke volume [mL]	88.4	106.3	20.3
Cardiac output [L/min]	5.4	8.7	59.9

Echocardiography Results

During exercise, subject C obtained a maximum heart rate of 130 bpm during exercise after recording a resting heart rate of 68 bpm. However, the heart rate quickly recovered when the subject stopped exercising; thus, acquired data shows the maximum heart rate as 113 bpm. As Table 2 shows, the pulmonary artery (PA) velocity time integral (VTI) increased from 20.7 cm to 25.0 cm as the heart rate increased.

Additionally, the calculated PA cardiac output increased from 7.75 L/min to 13.86 L/min. These values are likely inflated, however there is still a relative increase with exercise. Some values are absent in the table due to shortcomings of ultrasound measurement with exercise. Figure 7 shows ultrasound images at rest and at 100 bpm, demonstrating the difference in PA VTI.

Table 2: Results from echocardiography testing of subject C

Heart rate (bpm)	PA systolic diameter (cm)	PA VTI (cm)	TRJV (m/s)	PA diastolic diameter (cm)	PA Cardiac Output (l/min)	PA Cardiac Index (l/min/ m2)	PA systolic pressure (mmHg)	PA % change in diameter
68	2.61	20.70	2.36	2.16	7.75	3.79	111.39	21.11
93	2.58	-	2.73	2.25	-	-	149.06	14.67
100	2.50	24.00	-	2.14	11.78	5.77	-	16.82
104	-	24.30	-	-	12.40	6.08	-	-
113	-	25.00	-	-	13.86	6.79	-	-

Body surface area=2.04 meters squared, TRJV = tricuspid regurgitant jet velocity

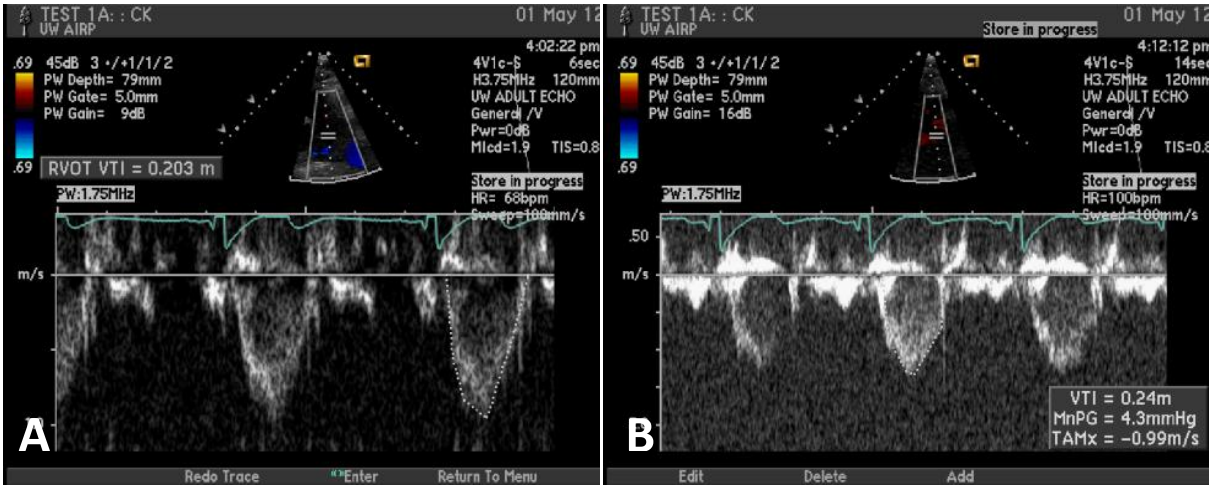

Figure7: Ultrasound images at rest (A) and at 100 bpm (B), VTI increased from 20.3 cm to 24.0 cm.

Discussion

Through MRI testing, it was determined that our device was successful at inducing a state of exercise while still allowing the patient to be imaged. The observed cardiac output after exercise was significantly greater than the baseline values, 53.2% on average. This is indicative of an induced state of stress. Subjects varying in height from 5'8" (172 cm) to 6'3" (190 cm) were able to use the device in the MRI bore. This range is limited by the heights of our group members, and may prove to be even larger with additional testing. The tracking on the base of the device proved highly effective at facilitating device and subject translation during use. The amount of unwanted device and subject movement during exercise was minimal and did not significantly affect the scans.

In addition to MRI testing, echocardiography was used to verify the performance of the device. While it could be used effectively during scans, some of the limitations of ultrasound became apparent. The pulmonary artery diameter and tricuspid regurgitant jet velocity (TRJV) could not be accurately measured during exercise due to breathing and upper body movement. Additionally, the calculated cardiac output was unreasonably high, which was most likely due to the inaccuracy of the measurements. Although the quantitative values of cardiac output seemed to be skewed, there was still an observed increase with exercise. This helps to confirm the effectiveness of our device at inducing a state of exercise of the subject. In addition, the echocardiography testing demonstrated the versatility of the device with other diagnostic methods.

Both the MRI and echocardiography testing demonstrated the effectiveness of our device in inducing a significant physiological change. It was highly compatible with the MRI environment, and provided for a comfortable and safe exercise experience for the subject. The electronic measurement system was successful at actively measuring the power output and cadence during exercise; however, the system still needs to be modified for MRI-compatibility. All other design specifications set forth for this project were satisfied. The device has great potential for use in a variety of research endeavors studying the effect of exercise on the body.

Abbreviations

AA: Ascending aorta; BPM: Beats per minute; DA: Descending aorta; ECG: Electrocardiography; HDPE: High-density polyethylene; IR: Infrared; IRB: Institutional review board; MRI: Magnetic resonance imaging; PA: Pulmonary artery; RF: Radiofrequency; TRJV: Tricuspid regurgitant jet velocity; USB: Universal Serial Bus; VTI: Velocity-time integral.

Acknowledgements

The authors would like to thank our client Professor Naomi Chesler (Biomedical Engineering, University of Wisconsin-Madison), who proposed this project, as well as our advisor, Professor Willis Tompkins (Biomedical Engineering, University of Wisconsin-Madison). Additionally, a special thanks to Dr. Oliver Wieben, Dr. Alejandro Roldan, Dr. Chris Francois, Dr. Claudia Korcarz, and JoAnne Weber at the University of Wisconsin Hospital and Wisconsin Institutes for Medical Research. We would also like to thank Ken Kriesel at University of Wisconsin Physical Sciences Lab and Alessandro Bellofiore, PhD. Funding for this project was provided by the Department of Biomedical Engineering at the University of Wisconsin-Madison.

Competing Interests

The authors of this paper declare no competing interests.

References

[1] Gusso, S., Salvador, C., Hofman, P., Cutfield, W., Baldi, J. C., Taberner, A., & Nielsen, P. 2012. Design and testing of an MRI-compatible cycle ergometer for non-invasive cardiac assessments during exercise. *BioMedical Engineering Online*, *11*(13), doi: 10.1186/1475-925X-11-13

[2] Lode B.V. 2008. *MRI ergometer*. Lode: the Standard in Ergometry. http://www.lode.nl/en/products/mri_ergometer

[3] Murray, A. 2009. *Ohio state team creates new company based on university invention*. The Ohio State University – News Room. http://www.osu.edu/news/newsitem2425

[4] Acroname Robotics. 2008. *Sharp IR Rangers Information*. Acroname Robotics. http://www.acroname.com/robotics/info/articles/sharp/sharp.html