MRI-Compatible Exercise Device

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Abstract

In order to better understand the effects of exercise on patients with pulmonary hypertension, 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. This device utilizes a stepping motion with adjustable weight resistance, and allows for the patient to exercise inside the MRI bore. An electronic measurement system continuously monitors the patient's stepping cadence and power output. The device was shown to be compatible with patients varying in heights from 5'8"-6'3". Real-time MR imaging could be used during exercise, while standard MR images had to be taken post exercise. Using MRI and echocardiography, it was observed that the device increased the patient's heart rate, cardiac output, and arterial flow.

Problem Statement

Design an exercise device to be used in cardiac MRI scans that is able to increase the cardiac output in pulmonary hypertension patients in order to characterize, diagnose, and assess the disease.

Background

Pulmonary Hypertension

- Abnormally high blood pressure in pulmonary arteries
- Chronic decreased systemic blood oxygen concentration
- 2-3 year median survival time if untreated

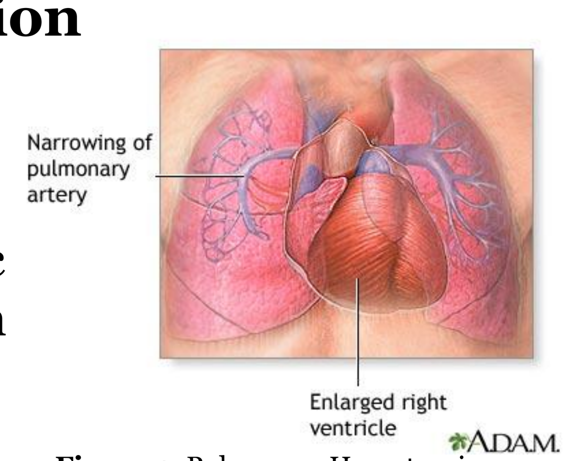

Figure 1: Pulmonary Hypertension [1]

Competition

- Lode BV MRI Ergometer [2]
  - (>$28,000)
- MRI-Compatible Treadmill [3]
- Cycle ergometer by University of Auckland, New Zealand [7]
- Previous UW BME Design Teams [4][5][6]

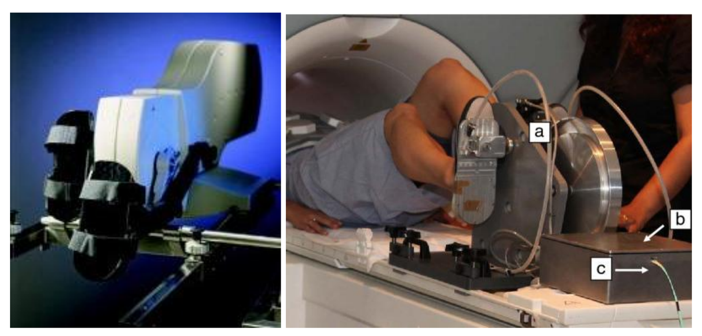

Figure 2: Competing devices: Lode BV [2] (left) and New Zealand cycle ergometer [7] (right)

Design Requirements

- MRI compatible material
- Comfortable supine exercise motion within bore
- No risk for patient injury
- Minimal patient movement
  - Chest movement
  - Body translation
- Accommodate various patient sizes
- Adjustable workloads
- Easy to operate
- Reasonable size and weight
  - Maximum 150 kg (patient + device)
- Sufficient resistance to increase cardiac output
  - Enough to see physiological changes in pulmonary artery through MR imaging

Final Design

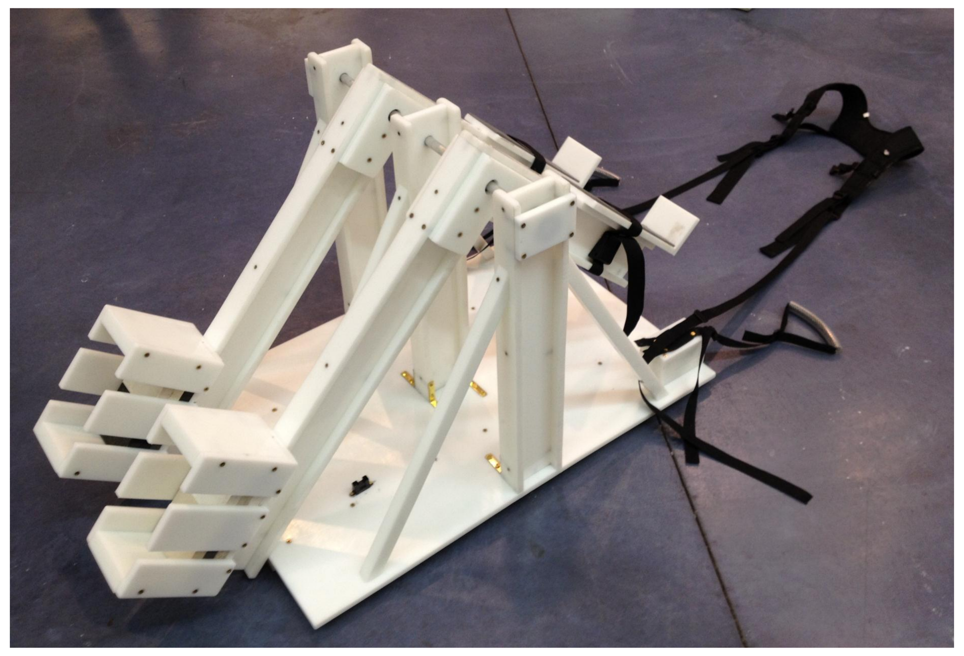

Figure 3: MRI-compatible exercise device – final prototype

Overview of Materials

- HDPE structure
- Brass screws & brackets
- Glass/acetal bearings
- Aluminum rods
- Nylon straps
- Ceramic weights

New Weight System

- DuPont Zodiaq tiles
  - MRI compatible
  - Density 2.4-2.5 g/cm³
  - Free sample tiles ~1 lb each
- HDPE weight containers
  - Holds up to 16 lbs. each

Figure 4: HDPE weight boxes to hold the Zodiaq weights

Device Improvements

- Improved durability
  - Replaced diagonal support with 1" thick HDPE beams
  - Capped both ends of the aluminum rod
- Decreased unwanted device movement
  - Elevated strap connections
  - Moved foot pedals further down lever arms
- Modified foot pedals
  - Extended lip under heel to prevent foot slippage

Electronic Measurement

- Infrared proximity sensor
  - Records dynamic position of one lever arm
  - Range: 20-150 cm (~8"-4'11")
- Arduino Uno microcontroller
- Continuously calculates cadence and power using MATLAB

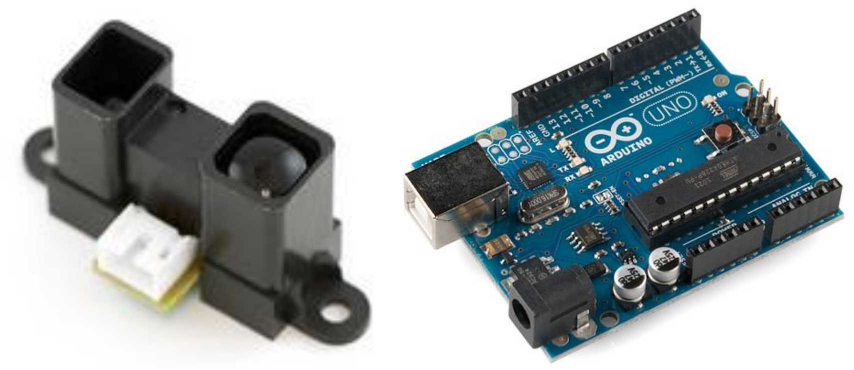

Figure 5: Infrared proximity sensor (left) and Arduino Uno microcontroller (right)

Testing and Results

Power Equation

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

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

Where:
- P = Power (Watts)
- R = Cadence (steps/min)
- N = Added weight to lever arm (lbs)
- Θ = Angle of lever arm rotation
- H = Height change of lever arm (cm)

Real-time MRI

- Continuously images while patient exercises
- Allows for assessment of:
  - Pulmonary artery area
  - Right ventricular function
  - Arterial distensibility (stiffness)
- Shortcomings of real-time MRI:
  - Lower image quality
  - Unable to accurately measure flow

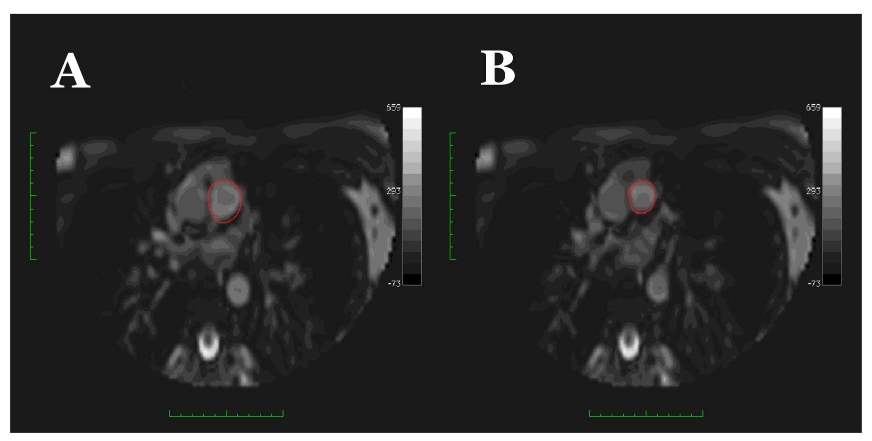

Figure 6: Real-time MRI images of systole(A) and diastole (B) of the subject's heart during exercise; red circles indicate the pulmonary artery

Standard MRI Testing

- MR images were taken before and after exercise
  - Requires breath hold during scan
- Subjects exercised for 10 minutes inside the MRI bore
- Allows for measurement of arterial flow
- Higher image quality

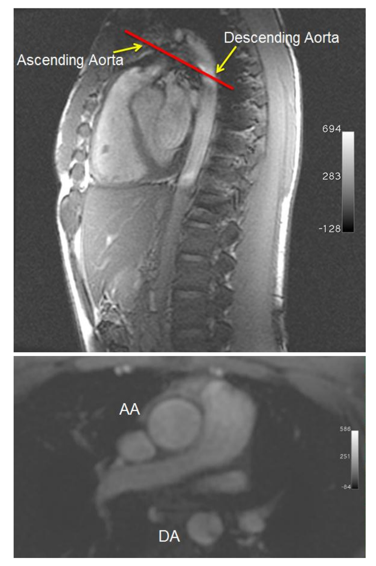

Figure 7 (left): MR images of ascending and descending aorta

Figure 8 (right): Flow data in the descending aorta for one cardiac cycle, pre- and post-exercise

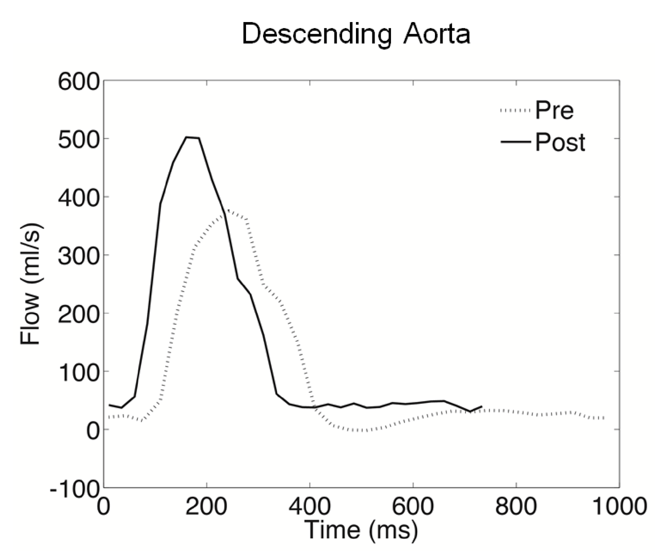

Table 1 – Comparison of descending aorta data, pre- and post-exercise

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

- Used to obtain data on pulmonary artery
- Results and conclusions:
  - Heart rate increased, ~70 to 130bpm
  - Velocity Time Integral (VTI) increased
  - Diameter was relatively constant and was difficult to measure after exercise
  - Cardiac output and flow increased

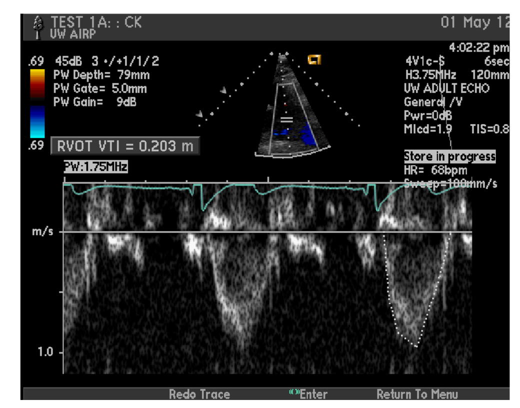

Figure 9: Pre exercise image of pulmonary artery generated by ultrasound. Heart rate = 68 bpm and the measured VTI = 0.203 m

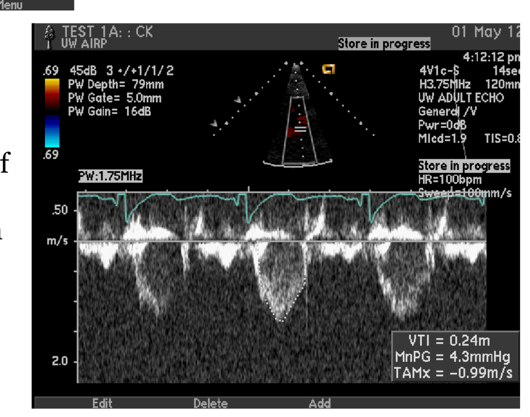

Figure 10: Post exercise image of pulmonary artery generated by ultrasound. Heart rate = 100 bpm and the measured VTI = 0.24 m

Future Work

- Eliminate unwanted strap loosening during exercise
- Make electronics MRI-compatible
  - Aluminum Faraday cage
  - Fiber optic/shielded cables
- Further device testing
  - Larger sample size
  - Pulmonary hypertension patients

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