

# Development of an Adaptive Rowing Machine for use by Individuals in Wheelchairs

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**Abstract**

Exercise is essential for maintaining a healthy lifestyle. Fitness centers offer a wide variety of workout equipment to strengthen and exercise various muscle groups within the body. However, most exercise machines are not accessible to individuals in wheelchairs and require external modifications for accommodation. To address this problem, an existing Matrix rower was modified to create the Adaptive Rowing Machine. The Adaptive Rowing Machine is convertible and allows for rowing on both the standard and adaptive sides of the rower. Individuals in wheelchairs can row on the side of the rower opposite that of the standard side, termed the adaptive side, via the use of a second pulley and two supporting plates. Safety mechanisms, such as a stabilization frame and lap pad, were integrated to ensure a safe adaptive exercise experience. The console was relocated and implemented with automatic rotation for ease of use. The resistance dial mechanism was modified with the help of a stepper motor to enable adjustment from either the standard or adaptive sides. Recruited user testing of the hybrid device revealed \_\_\_\_\_. This unique and convertible design increases gym inclusivity and improves quality of life through exercise.

**Keywords**

*Rowing machine, adaptive rowing, adaptive exercise equipment, wheelchair accessible equipment, exercise, wheelchair*

## **Purpose**

To present the details of the Adaptive Rowing Machine for use by individuals in wheelchairs for the development of upper body strength with possible applications related to rehabilitation.

## **Introduction**

Individuals with injuries or disabilities, particularly those that necessitate the use of a wheelchair, experience difficulty utilizing typical workout machines due to a lack of accessibility. Wheelchair users form a significant portion of the world's population; in the United States alone, 5.5 million people require a wheelchair to perform daily tasks [1]. Currently, there is a lack of wheelchair-accessible workout equipment in fitness centers. A reported 81% of individuals with physical disabilities that go to fitness centers stated that they felt uncomfortable in gym settings due to this lack of accommodating exercise equipment [2]. Common complaints among people that require wheelchairs include a lack of space between equipment for wheelchair access and concerns about needing or requesting external assistance. Current adaptive rowing equipment permanently alters the functionality of the rowing machine such that only individuals in wheelchairs can use the machine. To overcome this limitation, a standard Matrix rowing machine (**Figure 1**) was adapted to create the Adaptive Rowing Machine, which accommodates users in wheelchairs while still retaining the machine's original functionality [3]. This modified design allowed users in wheelchairs to complete a modified rowing exercise on the adaptive side of the machine without external assistance. Additionally, the Adaptive Rowing Machine promoted proper rowing form and ultimately helped to improve the overall well-being of the user.



**Figure 1. Standard Matrix Rower.** This figure illustrates the standard rower fabricated by Johnson Health Tech [3].

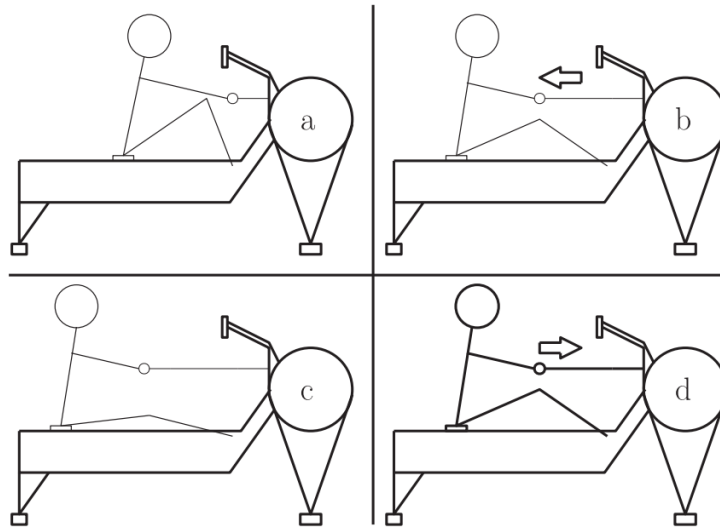
### **Relevant Physiology**

Individuals who use wheelchairs commonly experience shoulder pain [4]. Factors that affect shoulder pain include age, weight, and BMI. While a lack of proper training and implementation of graduate increases in workout regime may contribute to shoulder pain, proper increases in resistance and form can actually reduce shoulder pain [4]. The rowing motion allows an individual to actively exercise many of the essential muscle groups needed to refine both core and upper body strength. These muscles include the triceps, biceps, abdominals, back muscles, and lower back muscles [5].

The rowing motion consists of four phases: the catch, drive, finish, and recovery (**Figure 2**). The catch phase primarily activates the triceps and flexor muscles in the fingers. The abdominal muscles are engaged to allow the user to flex the torso in a forward motion. The subsequent phase is called the drive. In standard rowing, this phase includes the contraction of the quadriceps to propel the user backwards with simultaneous activation of the biceps to pull the handle of the rower towards the user's chest. However, for an adaptive user, it will only activate the biceps as they pull the handle towards their abdomen. The back muscles will also contract as the torso swings backward. The drive's movement is completed by the finish phase in which the abdominals and lower back stabilize the body. The full rowing motion is completed during the recovery phase, which occurs when the triceps engage to push the arms away from the body



while the abdominals flex the torso forward. Together, the four phases allow for a complete workout that strengthens the shoulder complex and upper body muscles [5].



**Figure 2. Visual Representation of the 4 Phases of Rowing.** The figure labeled *a* corresponds to the Catch phase, *b* is the Drive phase, which is followed by the Finish phase in *c*, and finally the Recovery phase in *d* [6].

## Description of Adaptations

### *2nd Pulley/Pulley Plate*

An additional pulley was integrated into the Adaptive Rowing Machine (**Figure 3**) to guide the rowing rope to the backside of the machine. This additional pulley allows for the Adaptive Rowing Machine to maintain standard functionality while also enabling the handlebar to be pulled from the adaptive side. The pulley plate supports the second pulley and is mounted on the rower using the same connection points as the original pulley.

### *Antlers*

This feature relocates the rowing handlebar to the middle of the machine, equidistant from the standard and adaptive sides. This alteration improves the device's ease of use for individuals utilizing the adaptive side of the machine.

### *Stabilization Frame*

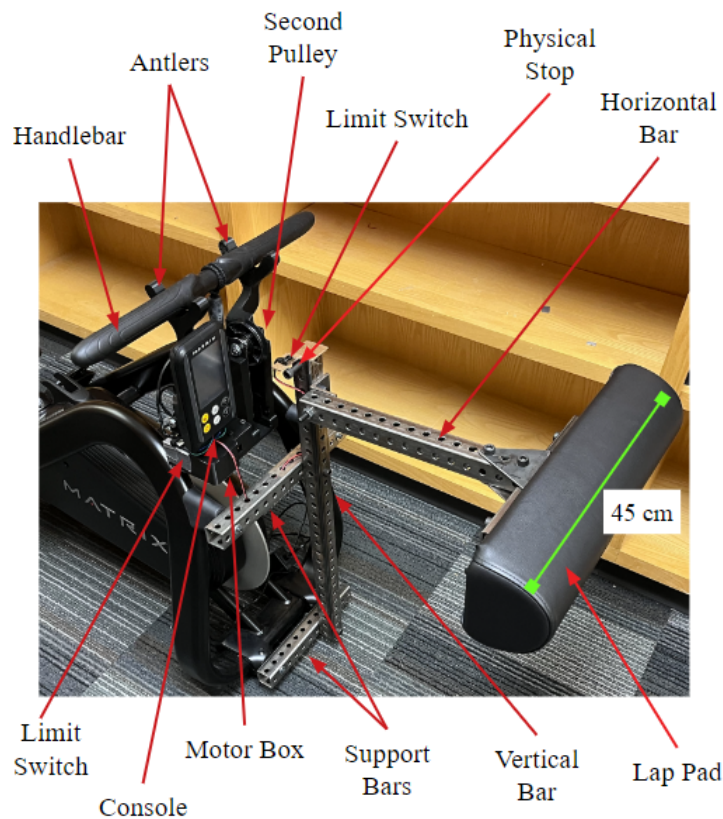
The stabilization frame secures the user on the adaptive side of the Adaptive Rowing Machine while they are completing the rowing exercise. The frame features a lap pad restraint to resist translation and rotation of the individual and their wheelchair while rowing.

### ***Console Motor Rotation***

A stepper motor and associated circuit automatically control the orientation of the console using feedback provided by the position of the lap pad. When the lap pad is stowed, the console will face the standard side of the machine. When the lap pad is lowered, indicating that the adaptive side of the machine is in use, the console will rotate to face the individual secured by the stabilization frame.

### ***Resistance Dial***

A stepper motor was implemented as part of the Adaptive Rowing Machine's resistance dial mechanism, converting the adjustment mechanism from mechanical to electronic. Rowing resistance levels can be altered using up/down buttons on both the standard and adaptive sides. The rowing machine will be equipped with a display to show the resistance level.



**Figure 3. Adaptive Rowing Machine.** The assembly shown includes the pulley support plates with antlers, the console rotation mechanism and electronics box, and the metal adjustable stabilization frame. Taken in the perspective of the adaptive side of the machine. \*This will be updated with a picture of the final assembly that incorporates all updates and new features at the end of the semester.\*

## **Materials and Methods**

To verify the ability of the Adaptive Rowing Machine to keep users safe and comfortable while providing a sufficient workout, subjects were recruited to use and rate the machine. Three participants (\*this will be updated based on study participation\*) who required the use of a wheelchair were recruited to test the adaptive side. To compare the adaptive side to the standard side, three participants (\*this will be updated based on study participation\*) who do not require the use of a wheelchair were recruited. Prior to completing testing, exemption was provided by the IRB (\*this will be updated based on IRB application decision\*). Additionally, all participants signed consent forms and were provided with relevant details regarding the testing protocols, process, and purpose of the study. Two tests were completed on the Adaptive Rowing Machine. The Adaptive Side test examined users who require the use of a wheelchair and their interaction with the machine. The Adaptive and Standard Side Comparison test was completed by users who do not require the use of a wheelchair and compares the adaptive and standard sides of the machine.

Following completion of each test, a survey was given to each user, both individuals in wheelchairs and participants that did not require wheelchair use, to analyze the safety and effectiveness of rowing on the wheelchair accessible portion of the machine. The two surveys (adaptive side survey and comparison survey) were administered to the appropriate groups of participants. Several questions about the safety, ease of use, comfort, and overall design feedback were included on each survey. Participants were asked to provide a rating on a scale from 1 to 5 (1 being the most negative feedback option, and 5 being the most positive). Space for additional comments and short answer questions pertaining to user experience were also included.

### ***Adaptive Side***

Users who required the use of a wheelchair participated in testing by only using the adaptive side of the Adaptive Rowing Machine. These participants were directed to navigate to the adaptive side of the machine, lower the lap pad onto their lap, and grab the handlebar from the antler mechanism. Once they held the handlebar, the participants were directed to complete the rowing motion by pulling the handlebar to their chest, and subsequently push it back out in front of their body. Users were asked to complete this rowing exercise for one minute. This test was completed on resistance levels of 1, 5, and 10. Between each trial, the participants rested for two minutes. After completing the three trials and interacting with the console and adaptive resistance mechanism, the participants were directed to place the handlebar back in the antlers and lift the lap pad back to its resting position. The participants completed a survey rating their experience interacting with the Adaptive Rowing Machine. The survey included questions about the user's level of comfort, perceived safety, and ability to interact with the console, handlebar, lap pad, and resistance mechanism.

### ***Adaptive and Standard Side Comparisons***

To compare the adaptive and standard sides of the Adaptive Rowing Machine, users who do not require the use of a wheelchair tested both the adaptive and standard sides of the machine. On the standard side, the participants positioned themselves in the sliding seat with their feet strapped in. The users were then directed to grab the handlebar and complete one minute rowing trials on the resistance levels of 1, 5, and 10 with two minute breaks between each trial. Afterward, the participants placed the handlebar back in the handlebar holder, unlocked their feet from the straps, and got out of the sliding seat.

After completing the trials on the standard side, participants were provided with a wheelchair and asked to wheel to the adaptive side of the rowing machine. The users followed a protocol very similar to that mentioned in the *Adaptive Side* test. After pulling the lap pad down onto their lap, the participants were directed to complete one minute rowing trials on resistance levels of 1, 5, and 10. However, for the Adaptive and Standard Side Comparison test, users were directed to not use their legs while rowing on the adaptive side. Between each trial, the participants rested for two minutes. After completing the testing on the adaptive side, the participants placed the handlebar back in the handlebar holder and completed a survey rating their experience. Similar to the Adaptive Side survey, participants rated their comfort, safety, and interactions with various components of the Adaptive Rowing Machine. The Adaptive and Standard Side Comparison survey also asked the user to rate their perceived difference in workouts between the adaptive and standard sides.

### **Results**

Testing is not yet complete; no results are currently available.

### ***Adaptive Side***

Outline of things to touch on in this section:

- Number of participants which had previously used a rowing machine (mention type of rowing machine used if applicable and relevant to data analysis)
- Rower handlebar ease of manipulation ratings and comments
- Interaction with console and comments
- Resistance level changing (ease of use and comments)
- Overall ease of use
- Safety evaluation and comments
- Comfort ratings
- Additional comments
- Graphs of distributions of survey ratings

### ***Adaptive and Standard Side Comparison***

Outline of things to touch on in this section:

- Number of participants with rowing experience
- Rower handlebar ease of manipulation ratings and comments
- Interaction with console and comments
- Resistance level changing ease of use and comments
- Overall ease of use
- Safety evaluation and comments
- Comfort ratings
- Additional comments
- Graphs of distributions of survey ratings

### **Discussion**

Testing data is not yet available. The discussion will be written upon completion of testing.

Outline of things to touch on in this section:

- Connections and main takeaways from testing data collected
- Potential sources of testing errors / influences
  - Users with little to no experience rowing and with varying fitness levels (impacts survey feedback)
  - Use of legs on the adaptive side by users not requiring wheelchairs
  - Difficulty in rating ease of use, etc. if no previous experience with rowing
  - Inconsistent rowing during trials
- Analysis of test results in terms of overall user experience and impact on society and different demographics
  - How will this benefit the general population?
  - Discuss design size (compact), fitness inclusivity, and health benefits for individuals in wheelchairs
  - Comparison between sides of the rowing machine

### **Acknowledgements**

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## Declaration of Interest

This project was funded by Johnson Health Tech.

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## Appendices

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**Appendix A: PDS****Johnson Health Tech: Adaptive Indoor Rower for  
Wheelchair Users***Product Design Specifications*

Feb 28th, 2023

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Individuals with injuries or disabilities have trouble utilizing typical workout machines due to a lack of exercise equipment that is accessible to them. One of these affected groups are individuals who require the use of a wheelchair. People require wheelchairs for a multitude of physical disabilities or injuries to the brain, spinal cord, or lower extremities. The majority of exercise machines are not designed for wheelchair use, and thus exercise options for wheelchair users are limited. In order to solve this issue, modifications need to be made to current manufactured machines. A standard Matrix rowing machine will be adapted to accommodate individuals who require the use of a wheelchair [1], but will retain the ability for someone not in a wheelchair to easily use the machine. The Adaptive Rower will secure the wheelchair/user to the rowing machine, preventing the user from both tipping backwards and falling forwards out of the wheelchair during the workout. This modified design will increase the accessibility and ease of use of a rowing machine by individuals in wheelchairs while allowing the user to maintain proper rowing form, and will help to improve their overall well-being through exercise.

**Client Requirements:**

- A magnetic rowing machine will be built to better understand how the overall assembly fits together. This will aid in the design of optimized adaptations to the current assembly process.
- The adapted rowing machine should allow individuals in wheelchairs to easily fit into the machine and use it properly. The machine should be accessible to both wheelchair and non-wheelchair users.



- Users with varying sized wheelchairs should be able to adjust the equipment to still be able to use the rower comfortably.
- Individuals in wheelchairs will be able to lock themselves into a stabilization frame without assistance. Individuals will also be able to change the resistance, view the display console, and grab the handlebar without external assistance.
- The rowing machine will be user-friendly and alterations to the rower will not hinder the rowing motion.
- The rowing machine will be used several times in a day, and components will not degrade over a short period of time.
- The rowing machine will have a mechanism to reduce excessive recoil force to prevent users from tipping backwards in the wheelchair.
- The user will remain in their wheelchair for the duration of the exercise.
- The added components to the current rower will be made out of metal to ensure a professional finish.

## **Design Requirements:**

### **1. Physical and Operational Characteristics**

#### *a. Performance Requirements:*

- i. The modified rower will enable people in wheelchairs to use the machine. The user will be able to easily secure/unsecure themselves to/from the modified rower. The attachment to the rowing machine should keep the wheelchair from tipping over backwards and will prevent unnecessary chair movement during the rowing motion.
- ii. The modifications made, to allow for attachment of the user/wheelchair, should remain intact and not break with repeated use of the rowing machine.
  1. The modifications used for the attachment should be able to resist and endure stresses caused by a pulling force within the range of 100 N to 400 N. This range was determined based on the preliminary data collected in BME 301.
  2. The modifications made to the machine should be able to endure the fatigue due to the repetitive rowing cycle.
- iii. The user will grip the handlebars to complete rowing movements. The wheelchair and the adaptive rower machine will remain stationary during rowing.
- iv. The device will be used daily.
- v. The transition of the handle and rope from the original configuration to the adapted side should be easily carried out by all users, including those in wheelchairs.

b. *Safety:*

- i. The modifications made to the rowing machine will not pose any biological hazards to the user.
- ii. Any modifications made to the rower will be filed and made smooth in order to prevent sharp points that could harm the user. Additionally, all modifications will be reviewed to make sure that no pinching/excess pressure is felt by the user during exercise.
- iii. The modifications made to the rower will ensure that the user is securely stabilized to the rower and will not be ejected from their wheelchair during use of the rower.
- iv. Electrical components incorporated into the design will be covered to prevent harm to the circuit and/or user (i.e. water damage or electrocution).

c. *Accuracy and Reliability:*

- i. The adapted rowing machine should accurately simulate the feeling of a traditional rowing machine for the user's upper body by producing a force per pull between 100-400 N. This range accommodates for the different resistance settings.
- ii. The loading and recoil motions should accommodate pulling the handle bars back to approximately one arm's length and should be smooth and absent of excessive friction.
- iii. In order to prevent backwards tipping, a mechanism should be included that provides a downward reaction force to counteract the maximum backward force of 400 N with a safety factor of two. The reaction force output by this mechanism should not cause forward tipping. The force output necessary to prevent tipping should be repeatable given a certain force input from the rower.
- iv. Once the adapted fixtures are designed, proper tolerances will be assigned to each of the components to ensure proper assembly and functionality of the adapted rowing machine.

d. *Life in Service:*

- i. The modifications and attachments added to the rowing machine should last for the same duration the rowing machine typically lasts. The lifetime of a rowing machine is categorized a few different ways. The modifications made should last:
  1. At least 10 years [2]
  2. At least 8 million meters [2]
- ii. The product will be able to be used for at least 10 years and withstand normal wear and tear from the user.
  1. Weight placed onto the product from the user

2. Friction applied by the user
- iii. All modifications will provide the user with a stable and safe rowing experience for the 10-year period.
  1. This includes preventing the user from tipping over while using the machine.
  2. A safe locking system that ensures the wheelchair does not move during use.
  3. Support the user's body to ensure security.
- e. *Shelf Life:*
  - i. The product will be stored in an environment that minimizes external loads placed onto the rower. This includes when it is being manufactured overseas, while shipping, and during storage in various facilities. Maximum external loads applied will be limited to 158.76 kg [1].
  - ii. The temperature range for the manufacturing, shipping, and storage process should be maintained within -20°- 45°C (-4°-104°F).
  - iii. When stored at a facility, the product will remain functional for a minimum of 30 years.
- f. *Operating Environment:*
  - i. Ideal temperature range for the machine is 5°-35°C (41°-95°F). Temperatures exceeding 95°F/35°C might lead to the device warming up, causing discomfort for the user.
  - ii. No large water sources should be used near this device. The LCD display relies on a power generator and water could destroy internal components of the rower.
  - iii. The device will allow a wheelchair user to attach the chair to the device.
    1. All forces applied by the wheelchair onto the rower will not hinder the machine's ability to perform at its optimal level.
    2. Forces will be minimized by the use of harnesses and supports.
- g. *Ergonomics:*
  - i. The user will secure themselves to the adaptive rower. This action will utilize only hands and arms and will be possible in an upright sitting position.
  - ii. A locking support system will ensure the user will not move during rowing.
  - iii. External additions to the rower will not inhibit comfort to the user. Stability measures will not inhibit the rowing experience for wheelchair users.
  - iv. After the user is secured into the machine, only the upper body will be used to complete the rowing motion. In addition, the user will be in an upright position.

1. No leg movements will be required during the use of the machine.
- v. Users will not need to reach more than 70 cm (1.8 ft) from the front of the wheelchair to grab the handlebar [3].
- h. *Size*
  - i. Additions will extend from the device by a maximum amount of 1.6067 m (3.5 feet). This will be measured by taking the distance perpendicular from the points of addition. The current dimension of the device is 223 cm x 55 cm x 97 cm [1].
- i. *Weight*
  - i. The current weight of the design is 158.76 kg/350 lbs [1].
  - ii. A maximum of 40 kg (approximately a fourth of the rower's weight) of mass will be added to the existing rower. This is to ensure the rower can still easily be moved via its transportation wheels if necessary.
- j. *Materials:*
  - i. When possible, adaptations will be fabricated out of clean, polished, or painted metal for support and durability.
    1. Common materials used for exercise equipment include steel and aluminum due to high durability and strength [4].
      - a. The Pulley Plate and Antler will be made out of Plain Carbon Steel.
  - ii. Materials that have a high degree of flexibility should not be used for the stabilization structure. However, cushioning materials may be used where this structure contacts the user for added comfort.
  - iii. Plastics used will have a high degree of strength and durability.
    1. 3D Printed Components will be printed out of 100% Infill Tough PLA.
  - iv. After application of 400 N (safety factor of 2) onto the plates supporting the additional pulley is applied, a maximum deformation of 2.0 mm will be allowed. The pulley plate material will be able to withstand these typical operating conditions.
- k. *Aesthetics, Appearance, and Finish:*
  - i. Adaptations made to the machine will have a smooth finish to prevent abrasions or lacerations to the user.
  - ii. Welds will be smooth.
  - iii. If time permits, adaptations will be painted black to match the rower.

## 2. Production Characteristics

- a. *Quantity:*
  - i. One rowing machine will be constructed and modified to accommodate the inclusion of a wheelchair during use.

- b. *Target Product Cost:*
  - i. A budget of \$500 will be used for development of the fixtures to the rowing machine structure for both the Fall and Spring semesters.

### 3. Miscellaneous

- a. *Standards and Specifications:*
  - i. The International Organization for Standardization (ISO) entry 20957-7:2020 stipulates the safety requirements for rowing machines, specifically rowing machines within classes H, S, and I and classes A, B, and C for accuracy. Entry 20957-1 describes the general safety requirements for stationary workout equipment. Entry 20957-1 covers the safety requirements for any additionally provided accessories to be used in conjunction with the rowing machine [5].
  - ii. This product does not require FDA approval as it does not fall under any of the FDA regulated products such as pharmaceuticals, medical devices, medical biologics, food, products that contain tobacco, supplements, cosmetics or electronic products that emit radiation [6].
- b. *Customer:*
  - i. The adapted rowing machine should be functional for individuals in wheelchairs, but ideally should be able to function as a standard rowing machine as well.
  - ii. The client prefers to have the rowing machine fully built into one assembly rather than broken up into several components that need to be attached each time the rowing machine is used.
- c. *Patient Related Concerns:*
  - i. The rowing machine will need to be sterilized between uses to remove debris and sweat from previous users.
  - ii. The added adaptations to the rowing machine should be able to accommodate a range of wheel thicknesses and wheelchair widths up to 3 inches wide.
  - iii. The added adaptations to the rowing machine should not cause overuse injury to other parts of the users body, such as hands and arms.
    - 1. The user should be thoroughly taught how to properly use the machine to reduce risk of misuse or injury.
  - iv. If the use of patient data is deemed necessary to construct specific adaptations to the rowing machine, it should be kept secure and confidential.
- d. *Competition:*
  - i. There are currently a plethora of adapted rowing options for wheelchair users available on the market. One of these options is an adapted rowing

machine seat that is easily switched with a standard seat and is more accessible to get in and out of for paralyzed users [7].

- ii. Adapted rowing machines such as the AROW (Adapted Rowing Machine) by BCIT REDLab [8] utilize an adapter and a stabilizer to isolate the rowing motion to the upper body of the user while keeping their chair in place.
  1. These adaptations were designed specifically for the Concept 2 rowing machine.
- iii. There are also existing patents for adapted rowing machines, including patents specific to wheelchair users. One such patent describes a machine that includes a unit for fixing the upper half of a user's body to the machine, straps to keep the user's legs stabilized, and a pulley system to create the rowing motion for the upper body [9]. Many of these patents appear to require an additional person to assist the user onto the machine or the user to move themselves from their chair to the machine - both scenarios that have been deemed undesirable for this project by the client.
- iv. There appears to be a gap in the market for a rower that can be converted between an adapted and standard model. This interconvertibility is something that the client expressed interest in and is a unique deliverable for this project.

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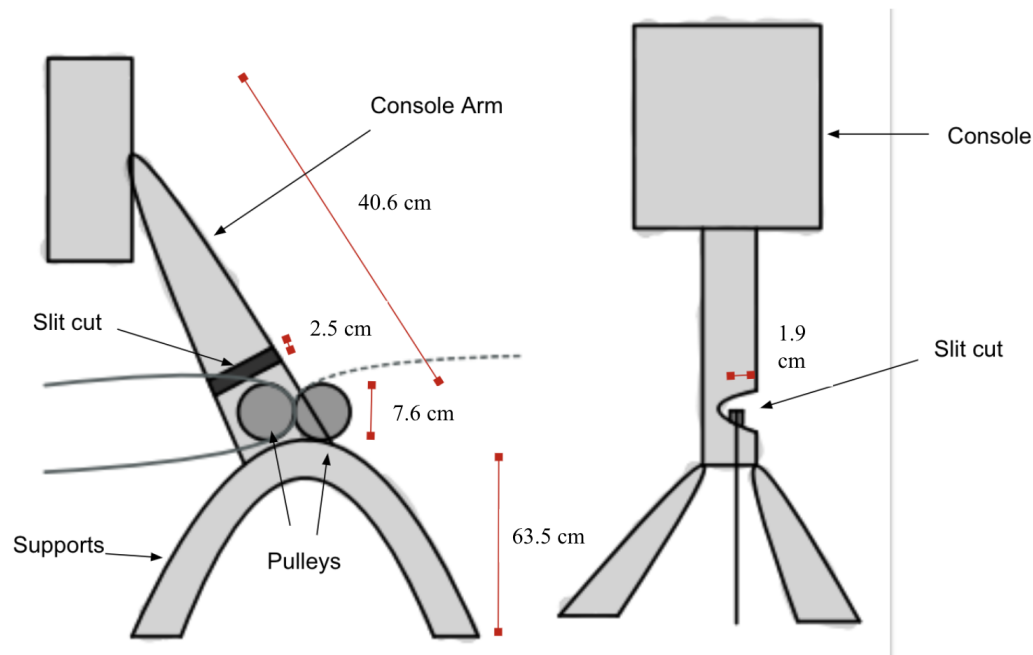
<https://adaptederg.commons.bcit.ca/rowing-solutions/> (accessed Feb. 09, 2022).  
 [9] 박대성, 김민, 정다운, and 이범석, "Rowing machine for paraplegic patient," WO2012008664A1, Jan. 19, 2012 Accessed: Feb. 09, 2022. [Online]. Available: <https://patents.google.com/patent/WO2012008664A1/en>

## Appendix B: BME 301 Designs & Design Matrices

### I. Preliminary Designs

#### A. Pulley Design 1: 2 Pulleys with Slit

The 2 Pulleys with Slit design (**Figure 1**) includes using two pulleys that are located at the same height on the rowing machine. The purpose of adding the second pulley is to allow for the rope and handle to be repositioned on the adaptive side of the rower, opposite to the sliding seat bar. This is where the wheelchair user will be located during use of the adaptive rower. This design concept uses the original rope and handle of the standard rower. However, the 2 Pulleys with Slit requires a cut to be made on the console arm in order to allow for the rope and handle to be transitioned from the standard to the adaptive side of the machine.

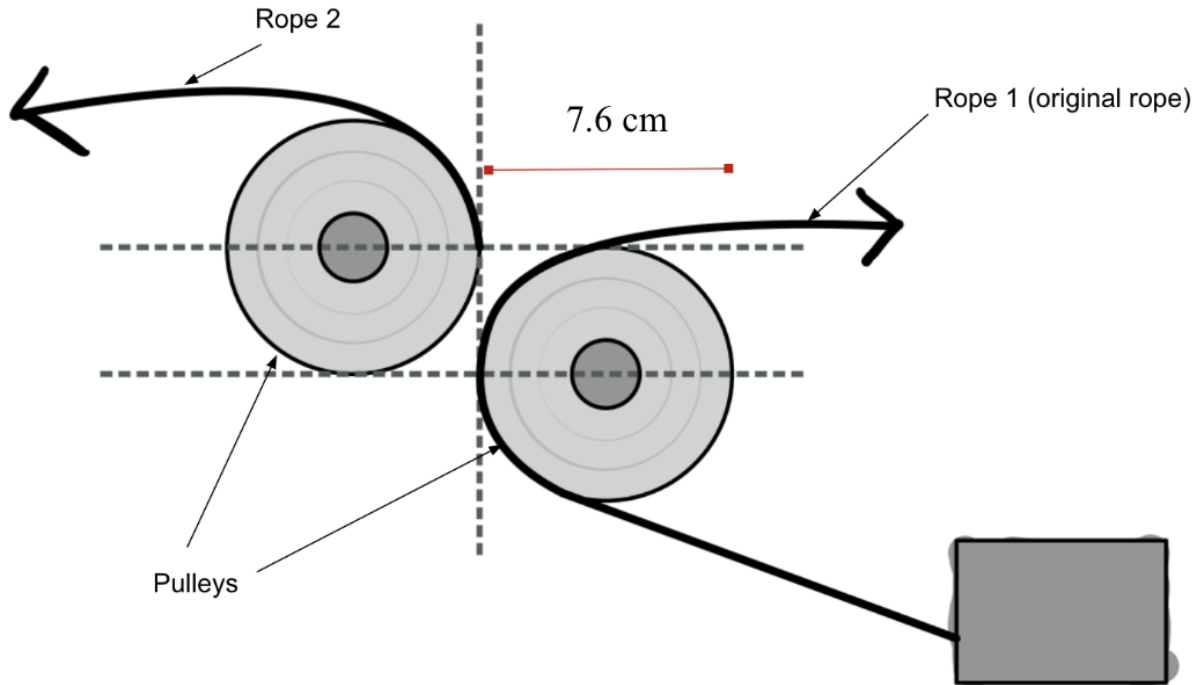


**Figure 1. Visual Representation of 2 Pulleys with Slit Design.** The 2 Pulleys with Slit design consists of two pulleys that are at the same height. The rope can be transferred from one pulley to the other to switch from standard to adaptive rowing. A slit cut will be made in the console arm to allow for this to happen.

#### B. Pulley Design 2: 2 Pulleys with 2 Ropes

The second pulley concept is called the 2 Pulleys with 2 Ropes design (**Figure 2**). This design also involves adding an additional pulley to the rowing machine. However, the 2 Pulleys with 2 Ropes design differs from the 2 Pulleys with Slit concept because this design adds an

additional rope and handle to the rowing machine so that one rope and handle can be located at both the standard and adaptive sides permanently. This eliminates having to transition the rope and handle from one side to the other while switching from standard to adaptive use. A downside to the 2 Pulleys with 2 Ropes design is that it would require adding an additional coiling mechanism to the flywheel for the second rope. The internal workings of the rowing machine and flywheel are quite complex, so adding this coiling mechanism would add another degree of difficulty to the project.



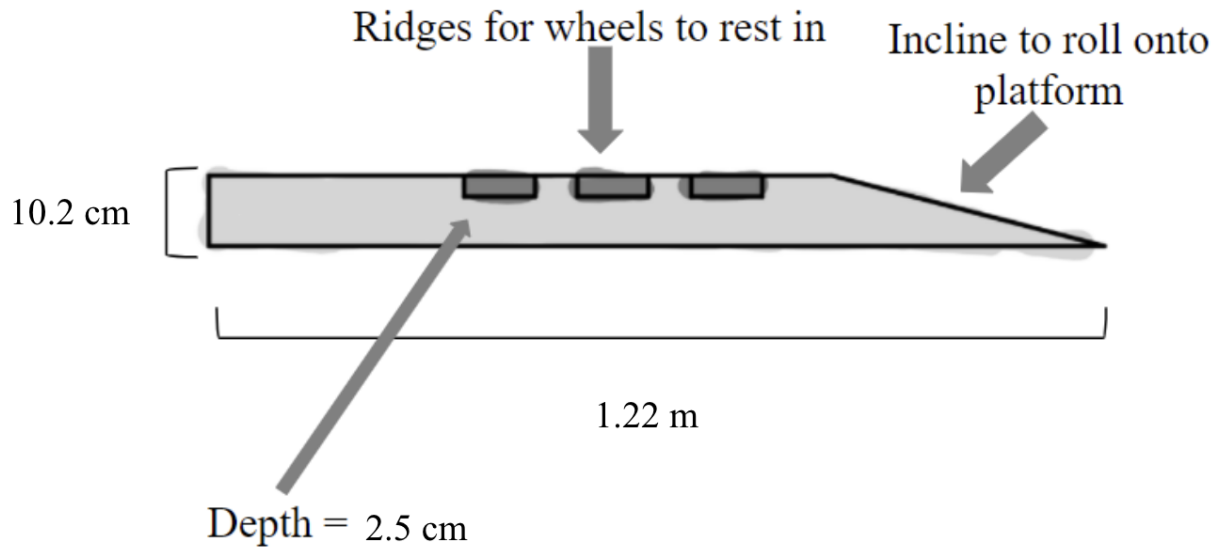
**Figure 2. Visual Representation of 2 Pulleys with 2 Ropes.** The 2 Pulleys with 2 Ropes design involves adding an additional pulley, handle, and rope to the existing rowing machine. The transitioning of the handle and rope from the standard side to the adaptive side would not be required since there would be a rope permanently positioned on both sides of the rowing machine.

### C. Stability Design 1: Highway Ridges

The Highway Ridges design (**Figure 3**) incorporates a platform that rests flat on the ground with an incline down to the floor. This incline allows the user to roll up onto the flat portion of the platform. On this flat portion, there will be 3-4 ridges cut into the face of the platform that act as resting places for the wheels of the wheelchair to rest in during the action of rowing. Thus, as the user pulls the handlebar toward their chest during the rowing motion, they will not roll backwards because the wheels are resting within the ridges. One downside of this design is that with an excessive amount of force applied to the handlebar, the user may



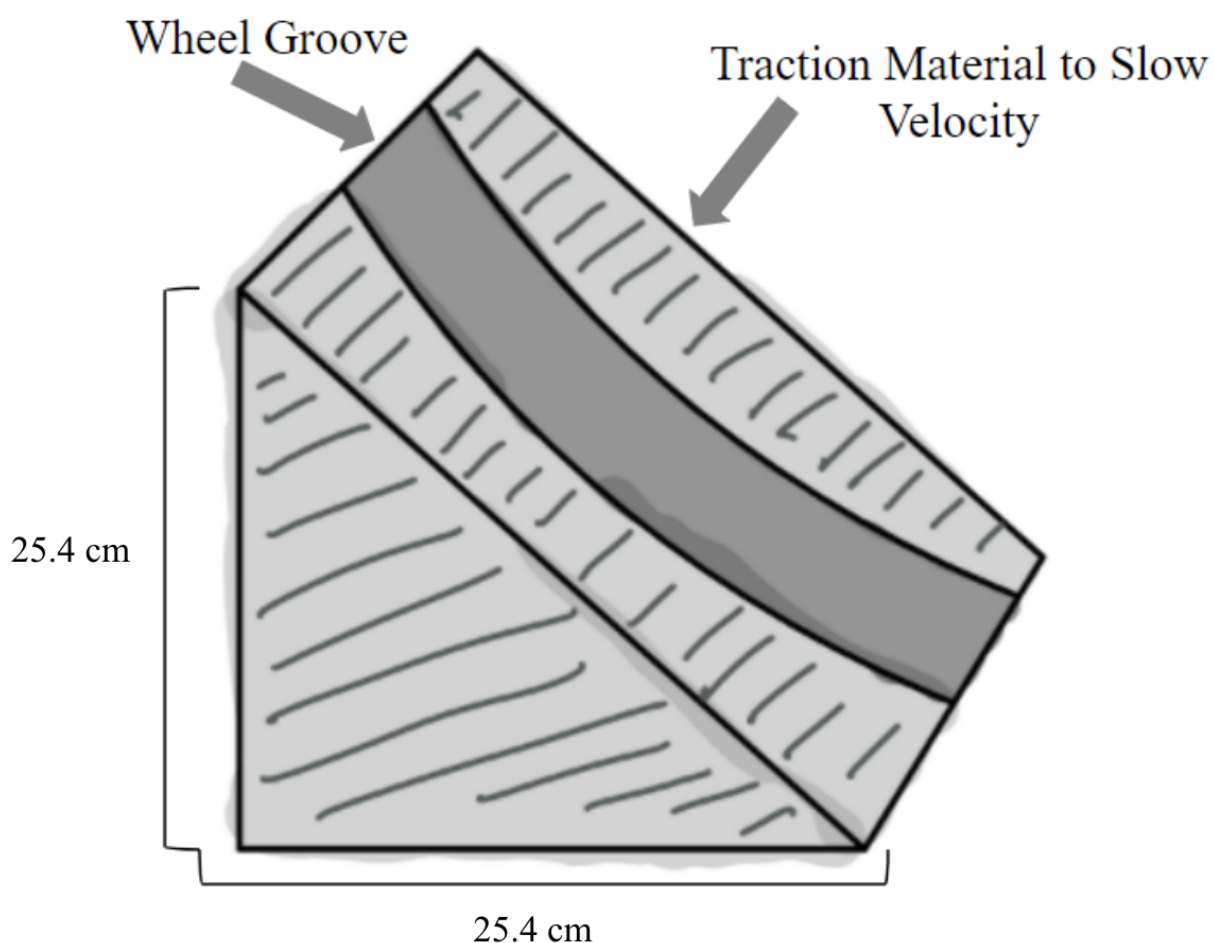
provide enough force to actually roll up and out of the ridges, which would lead to backwards translation / rotation.



**Figure 3. Visual Representation of the Highway Ridges Design.** The platform has an incline down to the floor so that the user can roll up and into place on top of the platform. The base will have ridges cut into it for the wheels to rest in during the action of rowing to stabilize the wheelchair.

#### D. Stability Design 2: Traction Blocks

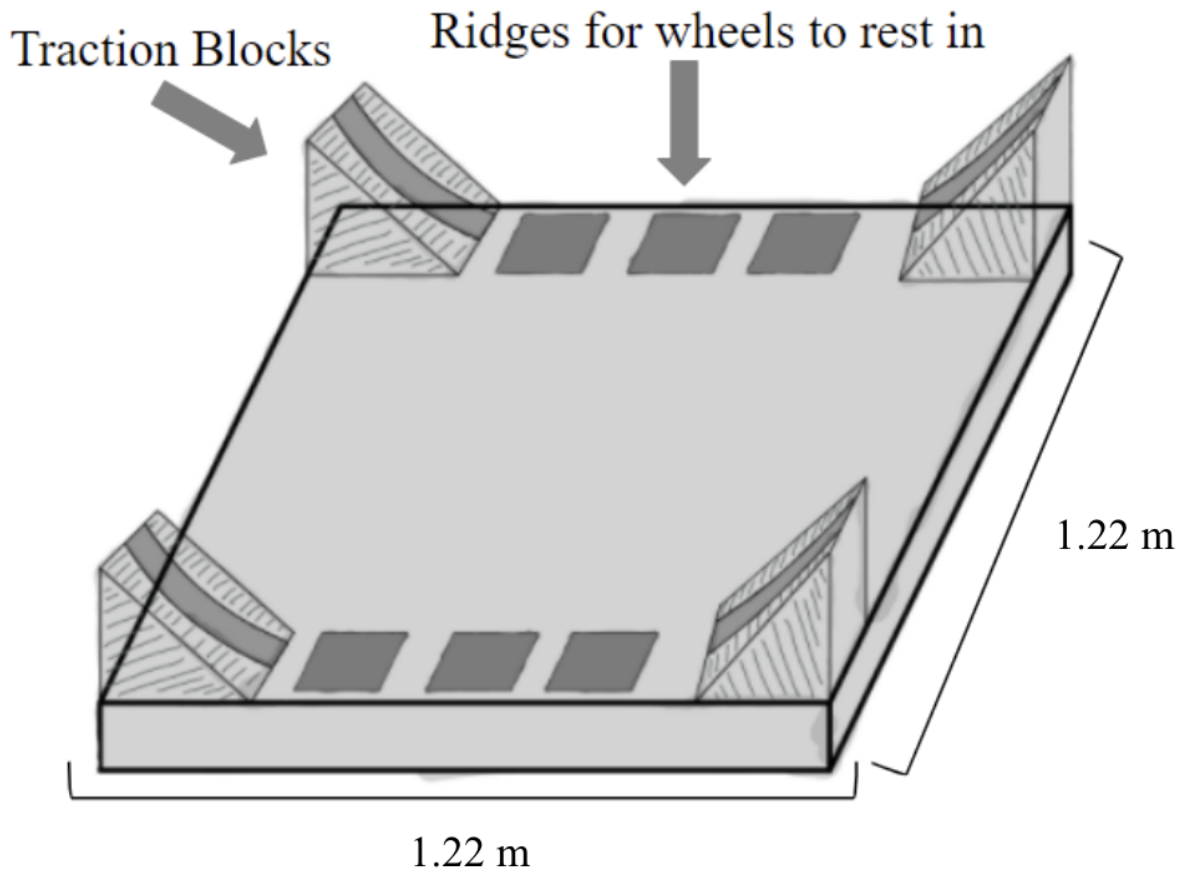
The Traction Blocks design (**Figure 4**) includes two triangular prism shaped blocks that are placed in front of the wheels, and two that are placed behind the wheels. Each block has a semicircle groove cut down the middle which is wider than the wheelchair wheel width, to accommodate different sized wheels. As the user rolls slightly forward or backward, they would roll into the groove and the force of gravity, along with the reaction force provided by the block, would reduce their velocity and prevent forward or backward tipping. The surfaces of the block would also be covered in a traction-like material to further reduce the user's velocity. One downside to this design is that it would require external assistance to place the blocks in front of and behind the wheels once the user has rolled into place on the adaptive side of the rowing machine.



**Figure 4. Visual Representation of the Traction Blocks Design.** The block has a semicircle groove down the middle which allows for the user to experience slight recoil during the action of rowing. The user will roll up and into the block, which is covered in a traction-like material to reduce velocity, to prevent forward / backward tipping.

### E. Stability Design 3: Combined Design

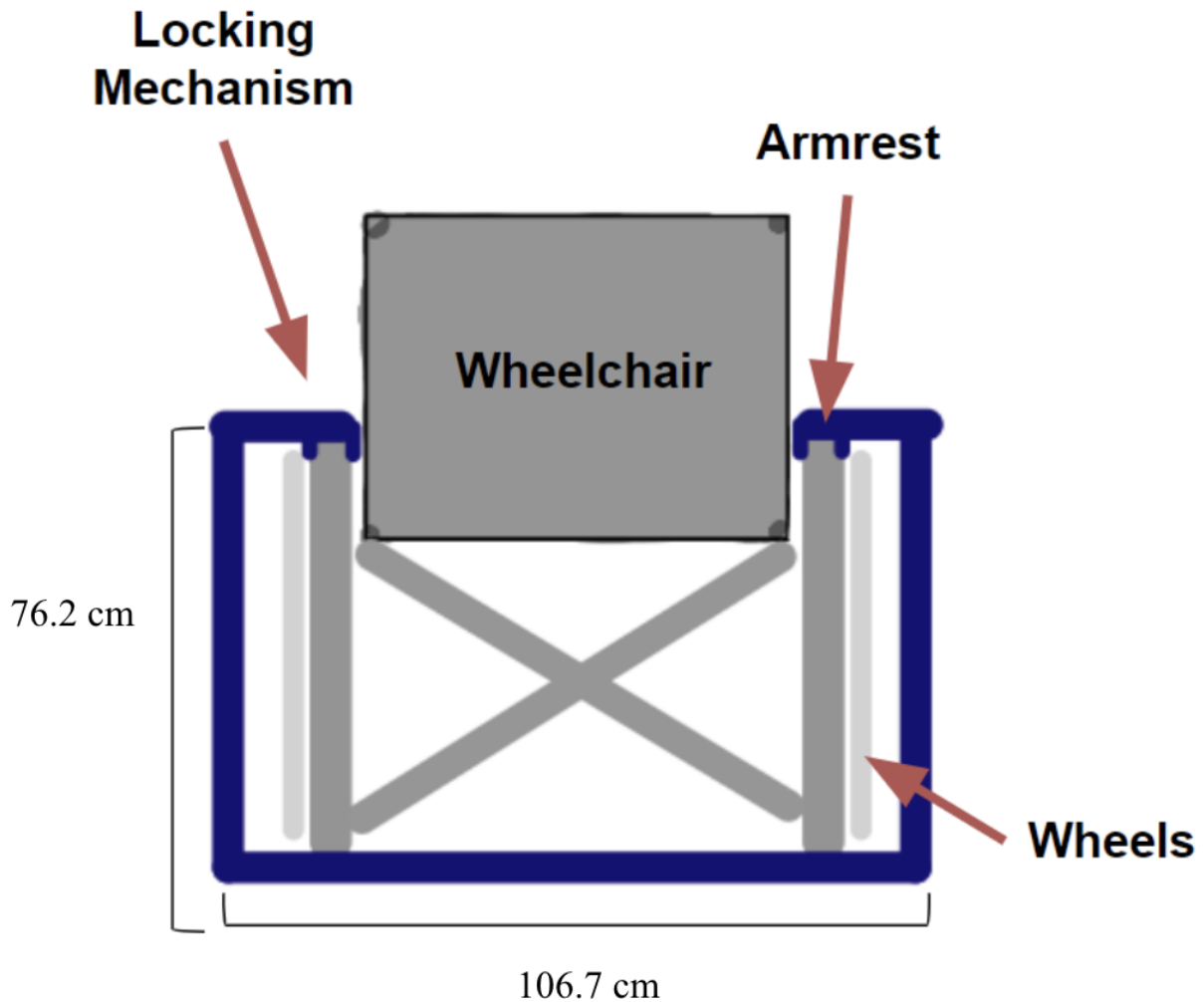
The Combined Design (**Figure 5**) is a combination of the Highway Ridges and Traction Blocks designs. Thus, this design utilizes an inclined platform with ridges for the wheels of the wheelchair to rest in, and includes four traction blocks that would allow for recoil motion and reduce the users velocity if they were to roll out of the ridges on the platform. This design provides the most stabilization to the wheelchair, but requires the most complex fabrication process. One downside to this design is that it would require external assistance to place the blocks in front of and behind the wheels once the user has rolled into place on the adaptive side of the rowing machine.



**Figure 5. Visual Representation of the Combined Design.** The inclined platform with ridges is combined with 4 traction blocks to prevent translation / rotation of the wheelchair during the action of rowing.

#### **F. Common Design: Armrest Hooks**

The Armrest Hooks design (**Figure 6**) will be utilized across all designs, and thus was not considered in any design matrix. The above stability designs focus solely on preventing forward or backward rotation of the wheelchair during use. However, the Armrest Hooks design prevents both forward / backward and lateral rotation of the wheelchair. This design incorporates side plates that are connected to the base platform that the wheelchair rests on via a hinge. When erect, the side plates will be parallel with the wheels of the wheelchair. Extendable arms with hooks will come off the top of each side plate and grasp the armrests of the wheelchair. This will essentially secure the wheelchair from tipping over side-ways, as the arms will make a rigid connection between the thin wheels of the wheelchair and the flat base plate it rests on. Additionally, two angled pieces will connect the vertical support arms with the base piece to improve the strength and rigidity of the entire frame.



**Figure 6. Visual Representation of the Armrest Hooks Design.** The base platform will have two sideboards connected via a hinge that can swing up to be parallel with the wheels. Extendable hooks will reach out and grasp the armrests of the wheelchair to prevent side-to-side rotation during the action of rowing.

## II. Preliminary Design Evaluation

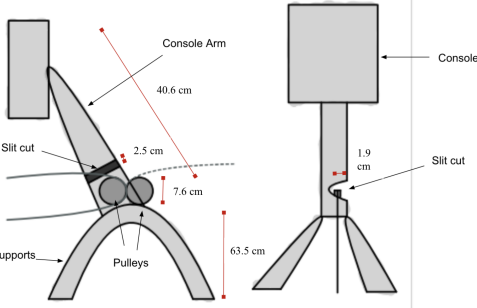
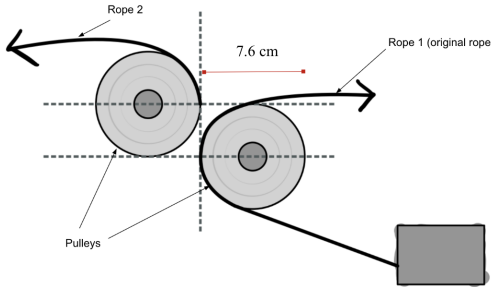
### A. Pulley and Stability Design Matrices Criteria

In order to adequately compare the designs against one another, several criteria were chosen that captured the most important aspects of the Product Design Specifications. The designs were then scored in each category, and their scores totaled to choose a preliminary design. The most important criteria is user stability / safety. For pulley designs, this refers to the safety of the user while changing the direction of the rope / handle to the other pulley, and the stability of the rope in the new pulley during use. For designs stabilizing the wheelchair, this refers to the ability to secure the user so that they do not tip over or translate forward / backward during the course of the repetitive rowing motion. Additionally, no parts of the design should

cause harm to the user during use of the rowing machine. Another equally important criteria is the ease of fabrication. Designs that do not involve drastic disassembly of the current rowing machine will score higher in this category. Designs were also scored based on their ease of use and ergonomics. The overall device should be easily accessible for individuals in a wheelchair, and not require extensive outside assistance to use the rowing machine properly. Pulley designs were scored in versatility of the pulley mechanisms as well. The incorporated pulley mechanism should minimize the complexity to convert the standard rowing machine into an adaptive state. Each design's potential materials were scored using the durability criteria, which takes into account the potential wear and tear of the device. The materials used should not affect the overall functionality of the device. Finally, each design's estimated cost of the materials needed was considered; components should not be unreasonably priced and cheaper components are preferable.

## B. Pulley Design Matrix

**Table 1. Design Matrix for Pulley Designs.** The two design ideas were compared against each other to determine which pulley design to proceed forward with.

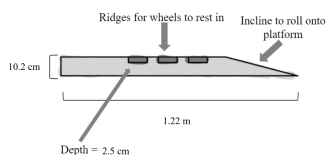
Design	<b>2 Pulleys with Slit</b> 		<b>2 Pulleys with 2 Ropes</b> 	
User Stability / Safety (25%)	4/5	20	5/5	25
Ease of Fabrication (25%)	4/5	20	2/5	10
Ease of Use / Ergonomics (20%)	4/5	16	5/5	20
Versatility (10%)	5/5	10	5/5	10
Durability (10%)	5/5	10	5/5	10
Cost (10%)	5/5	10	3/5	6
<b>Total for each design:</b>	<b>86</b>		<b>81</b>	

### C. Stability Design Matrix

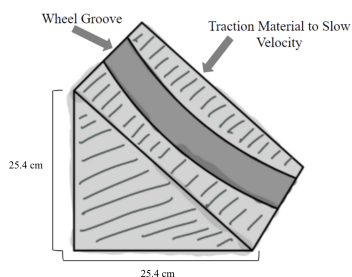
**Table 2. Design Matrix for Wheelchair Stabilization.** The three design ideas were compared against each other to determine a winning stabilization design.

Design	Highway Ridges		Traction Blocks		Combined Design	
	4/5	20	4/5	20	5/5	25
User Stability / Safety (25%)	4/5	20	4/5	20	5/5	25
Ease of Fabrication (25%)	5/5	25	4/5	20	3/5	15
Ease of Use / Ergonomics (20%)	5/5	20	3/5	12	3/5	12
Durability (15%)	5/5	15	4/5	12	4/5	12
Cost (15%)	5/5	15	4/5	12	3/5	9
<b>Total for each design:</b>	<b>95</b>		<b>76</b>		<b>73</b>	

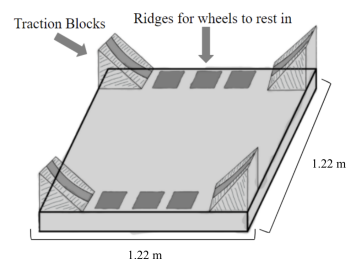
#### Highway Ridges



#### Traction Blocks



#### Combined Design



#### **D. Pulleys: Design Matrix Discussion and Proposed Final Design**

The two pulley designs were compared to each other using the design criteria, as can be seen in **Table 1**. Although both pulley designs ended up scoring very similarly, the 2 Pulleys with Slit concept was determined to be the best option to move forward with. This design requires the addition of a second pulley to the rowing machine to allow for the rope and handle to be used from the adaptive side of the rower. In order to allow the rope to pass from one side to the other, a slit cut will be made along the console arm to allow for this transition.

Both pulley designs ended up scoring highly in terms of user stability / safety. However, the 2 Pulleys with Slit design scored a 4/5 instead of a 5/5 due to the fact that it would be slightly less safe for a person in a wheelchair to transition the handle and rope from the standard side to the adaptive side as opposed to there being a rope and handle on each side with the 2 Pulleys with 2 Ropes design. The ease of fabrication design criteria was the differentiator for both pulley designs. The 2 Pulleys with Slit design scored a 4/5 on this criteria since fabrication would only require adding an additional pulley to the rower and cutting a slit in the console arm. The 2 Pulleys with 2 Ropes design scored a 2/5 for ease of fabrication due to the difficulty that would be involved with adding an additional coiling mechanism within the rower for the second rope.

For ease of use / ergonomics, the 2 Pulleys with Slit design scored a 4/5 due to the minimal external assistance required to move the handle and rope from one side to the other. The 2 Pulleys with 2 Ropes design scored a 5/5 here due to there being a rope on each side of the rower. Therefore, no outside assistance is required for aligning the handle and rope on the adaptive side. In terms of versatility, both designs scored a 5/5 since they both allow for the transitioning of the machine from standard to adaptive use and vice versa. Both designs also earned 5/5 scores for durability since the pulleys / rope / handle used for each design will be sourced directly from JHT, and therefore be as durable as the existing rowing machine materials. Lastly, in terms of cost, the 2 Pulleys with Slit design scored a 5/5 since this design would only require purchasing materials to secure the second pulley to the rowing machine. The 2 Pulleys with 2 Ropes design would require the same cost to secure the pulley, but would also require additional materials to create a second coiling mechanism for the second rope. Since these additional materials would create additional purchasing costs, the 2 Pulleys and 2 Ropes design scored lower with a 3/5 for the cost criteria. Overall, the 2 Pulleys with Slit design most closely adhered to the design criteria outlined in the design matrix and scored the highest at 86/100. Thus, it is the best option for solving the problem outlined by the client.

#### **E. Stability: Design Matrix Discussion and Proposed Final Design**

After comparing the three stability designs against each other (**Table 2**), the Highway Ridges design proved to be the design that will most closely accomplish the project goals outlined in the PDS. This design utilizes a platform with built in ridges that the wheels of the



wheelchair rest in during the action of rowing. The wheels sit in these ridges so that the wheelchair does not translate or rotate backward during rowing. However, this design is not capable of preventing all backwards rotation, and thus received a 4/5 in the user stability / safety category. The Traction Blocks design received a 4/5 for user stability / safety because it is capable of preventing backwards rotation, but if the user applies an excessive amount of force, the wheelchair could still tip over. The Combined Design received a 5/5 due to containing both mechanisms from the Highway Ridges and Traction Blocks designs, which gives it the best ability to prevent backwards tipping or rotation.

The three designs were then scored according to their ease of fabrication. The Highway Ridges design received a 5/5 because it only involves minimal external changes to the platform for cutting the ridges out and inserting an incline down to the floor. The Traction Blocks design received a 4/5 due to the challenges presented by covering the entire block in a traction material and cutting out semicircular grooves in each of the traction blocks. The Combined Design received the lowest score of a 3/5 because it involves the most complex fabrication process, since it would require the fabrication of both the Highway Ridges and Traction Blocks design at once. With regard to ease of use / ergonomics, the Highway Ridges design received a 5/5 because this design only requires the user to roll up the incline onto the platform and rest in one of the built in ridges. Since no external assistance is required to use this design, it received the highest score. Contrastingly, the Traction Blocks and Combined Design both require external assistance to insert the blocks behind the wheels of the wheelchair. Since the client would like for minimal outside assistance to be required, these two designs both received a 3/5.

In terms of durability, the Highway Ridges design received the highest score of 5/5. This design only involves the wheelchair resting in the built in ridges of the platform. This platform will likely be made out of metal, and thus will be a strong and durable material that will not wear down quickly during successive uses. The Traction Blocks design and Combined Design each received a 4/5 due to the possibility of the traction material wearing down over time. If this material degrades, it will be less effective at reducing the users velocity to prevent rotation, which then reduces the users safety. Thus, these designs received a lower score. Finally, the three designs were compared against the cost to fabricate. The Highway Ridges design received a 5/5 due to the reasonable cost to purchase a platform and build in the ridges. The Traction Blocks design received 4/5 due to the higher cost of buying a sufficient traction material and rigidly attaching it to the blocks. The Combined Design received the lowest score of a 3/5 due to summing the costs of fabricating both the Highway Ridges and Traction Blocks designs. Overall, the Highway Ridges design most closely follows the design criteria outlined in the design matrix and scored the highest at 95/100. Thus, it is the best option for solving the problem outlined by the client.

After further discussion of the stability mechanism for the final design, the platform on which the wheelchair would rest was deemed not necessary. The arm rest support mechanism was determined to be sufficient enough to prevent any excess, unwanted movement of the wheelchair during use. Thus, the Highway Ridges design was not considered during fabrication, as only the Armrest Hooks design was pursued. For future references in this report, the Armrest Hooks design will be referred to as the Wooden Base. In addition to the 2 Pulleys with Slit and Armrest Hooks designs, a swivel component was also added to the final design assembly to allow for the console to be rotated to the adaptive side of the rowing machine.

## **Appendix C: BME 301 Final Design & Fabrication**

### **I. Fabrication and Development Process**

#### **A. Materials**

Various materials were used to develop the final stability and adaptive components of the design. A standard magnetic Matrix Rowing machine was used as the basis for which adaptations and attachments were built [1]. Careful selection of materials was essential to fabricate a model that withstood the forces developed during rowing while also providing sufficient stability to the user. The 2 Pulleys with Slit design required a strong rigid plastic that could withstand forces from the rope during the driving phase. In addition, the chosen material should not deform more than 2.0 mm in the smaller cavity region when a load of 1050 N is applied. After consulting the Makerspace team, it was advised to use Tough PLA, with a 0.2 mm layer thickness and 90% infill. The Makerspace ensured that this was the strongest material that could be printed at their facility. Therefore, this material was used to print the two pulley plates to make the 2 Pulley with Slit design. An additional pulley and washers were also sourced from Johnson Health Tech for the 2 Pulleys with Slit design.

A swivel design was fabricated to rotate the display on the standard Matrix Rower. This part used Tough PLA with a 80% infill and a 0.2 mm layer height. The infill is less than the pulley plates due to minimal forces being placed onto this component. These forces include the following: pressure applied by the user when changing the orientation of the display, and the normal forces that are applied onto the model from the various rower components. All 3D printed components were printed out of Tough PLA due to its high Elastic Modulus (1820 MPa) and Yield Strength (37 MPa) [2].

The stability component of the design used standard wood, nails, and straps (**Figure 1**). Wooden boards of sizes 2" x 4"-8' and 2" x 6"-8' were purchased along with #8x3" nails and 2.54 cm (1 in) width straps. Once combined in the final fabricated stabilizing device, these materials offer a stabilizing system to the user. The specific dimensions for the wood were chosen to maximize stability, but to also provide a sleek design. Larger dimensions would have

increased the bulkiness of the system. The length of the nails allowed for proper connections to be made when taking into account the dimensions of the wood components. Lastly, the chosen straps are strong enough to withstand the typical forces of rowing. A free body diagram of the final design was developed to analyze the placement and value of the reaction forces in the straps so that the wheelchair does not tip.



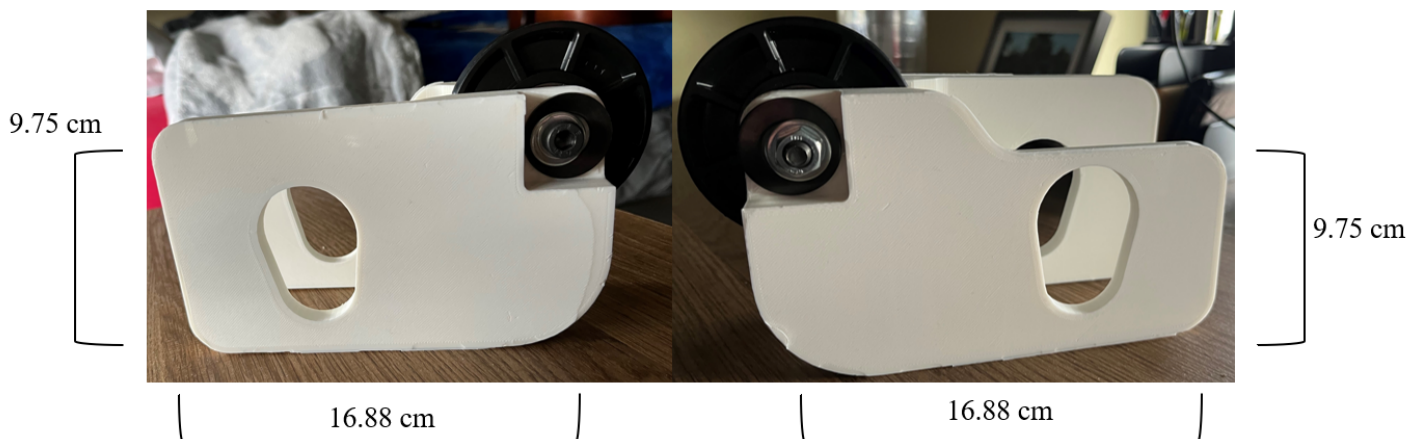
**Figure 1. Straps used in Stability Mechanism.** These straps prevent tipping motion while the user completes the rowing motion [3].

## B. Fabrication Methods

### a. SolidWorks

The pulley support plates (**Figure 2**) are used to stabilize the additional pulley that is added to the rower to allow for rowing from the adaptive side. The sole purpose of these plates is to hold the additional pulley in place under normal loads experienced during typical rowing motions. Each plate has a cavity that allows it to slip onto the outside surface of the two metal support arms that connect to the rower neck. Since these support arms are metal and welded to the bottom frame of the rowing machine, the cavities in the plates were designed to remain fixed around these support arms in order to keep the additional pulley stationary. Each pulley plate also has a circular cavity that fits around the rotational bearing of the additional pulley. This allows the plates to replace the two washers that were previously on the pulley and fit tightly onto the bearing to prevent any unwanted motion of the pulley. Each plate is held rigidly in place by the tight fit around the two metal support arms on the rower. Furthermore, when the neck is reattached and placed in between the plates, it will offer a reaction force outward that prohibits the plates from slipping off inward. The right plate has material removed from the top surface to allow the rope to be transitioned through the slit in the rower neck (on the right side). The plates are otherwise mirror images. Each plate was designed in SolidWorks and 3D printed out of

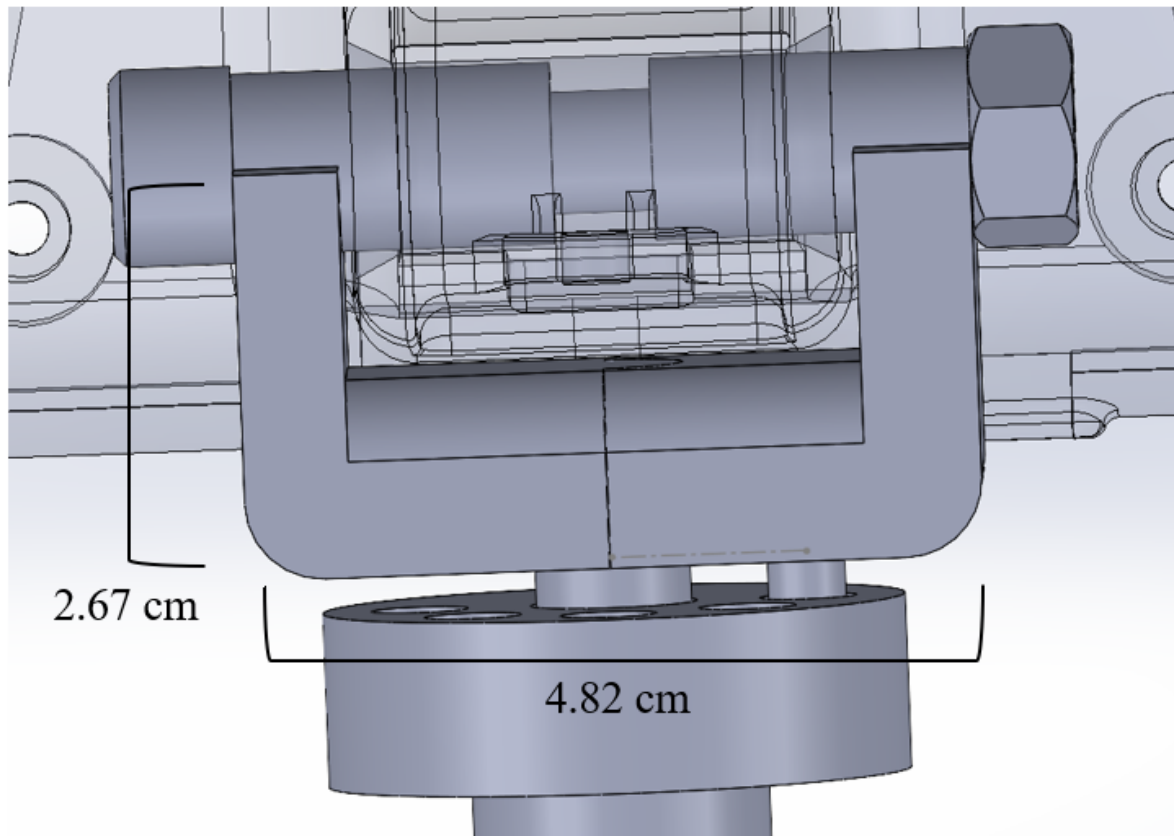
Tough PLA due to its high Elastic Modulus and Yield Strength. Additionally, a layer height of 0.2 mm and a 90% infill were used during printing to increase the strength of the plates.



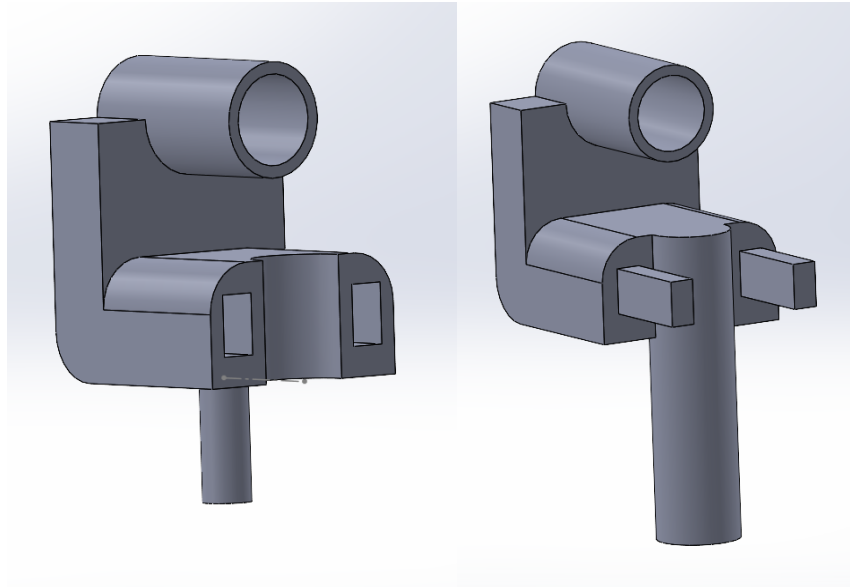
**Figure 2. Left and Right Pulley Support Plates.** The left (left) and right (right) pulley support plates fit tightly around the pulley bearing and have a cavity that fits around the metal support arms for the rower neck. The right pulley support plate has material taken off of the top surface to allow for the rope to pass through the cut made in the right side of the rower neck.

The console display swivel bearing is used to allow the user to rotate the console 180° so that it is visible from both the standard and adaptive sides. The swivel bearing is composed of three separate components: a male and female field goal post, and the receiving bracket. Each of the field goal post components have a cylindrical tube that replaces the metal cylindrical tubes in the back of the console (**Figure 3**). This allows the console to still rotate about its previous axis forwards and backwards to adjust the angle at which the user looks at the display screen. The male field goal post has two extruded rectangle inserts that fit into cavities on the female field goal post. These act as a locking mechanism that secures the pieces tightly together to prevent the console from becoming loose and slipping off. Additionally, the male field goal post has a large peg that extends downward. The female field goal post has a semi-circular cavity that accepts half of that peg so that the two field goal posts sit flush together. The male and female components can be seen in **Figure 4**. The large peg on the male component serves as the bearing that allows for the console to rotate in a plane parallel to the ground. This large peg sits in a cavity in the center of the receiving bracket, to ensure that the console is always centered over the rower neck. The female field goal post has a smaller and shorter peg that acts as a positioning guide. The receiving bracket has five smaller cavities for this guiding peg separated equally around the center cavity by 180° (**Figure 5**). This allows the user to slowly lift the console up so the guiding peg exits its cavity, turn the console in the center rotating cavity, and set it down in one of the other five guiding peg cavities to rotate the console display (**Figure 6**). The receiving bracket also has a through hole for a screw that connects it to the rower neck. This screw can be

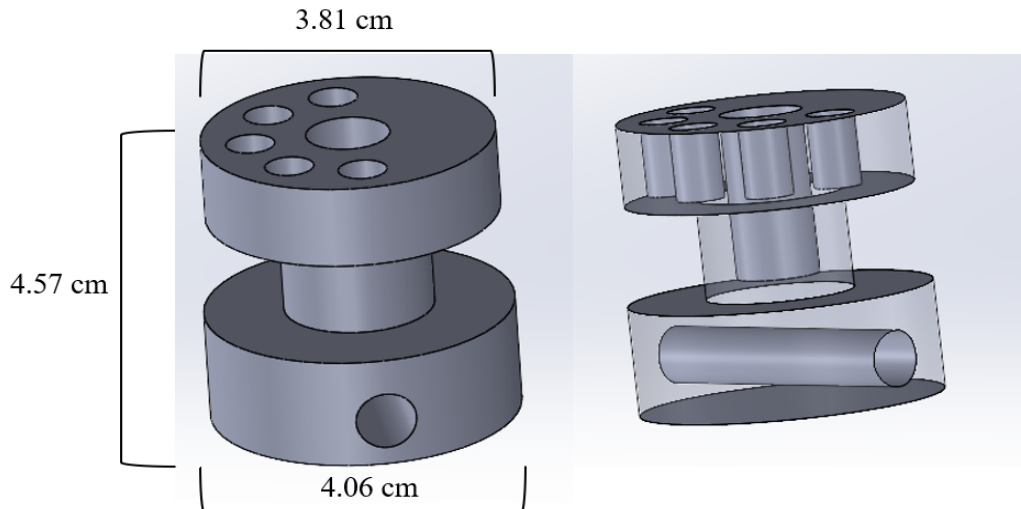
tightened so that the bracket does not rotate about the screw axis, which prevents the console and bracket from tipping forwards or backwards. Each of these three components were printed out of Tough PLA due to its high Elastic Modulus and Yield Strength. Additionally, a layer height of 0.2 mm and a 80% infill were used during printing to increase the strength of the bearing assembly.



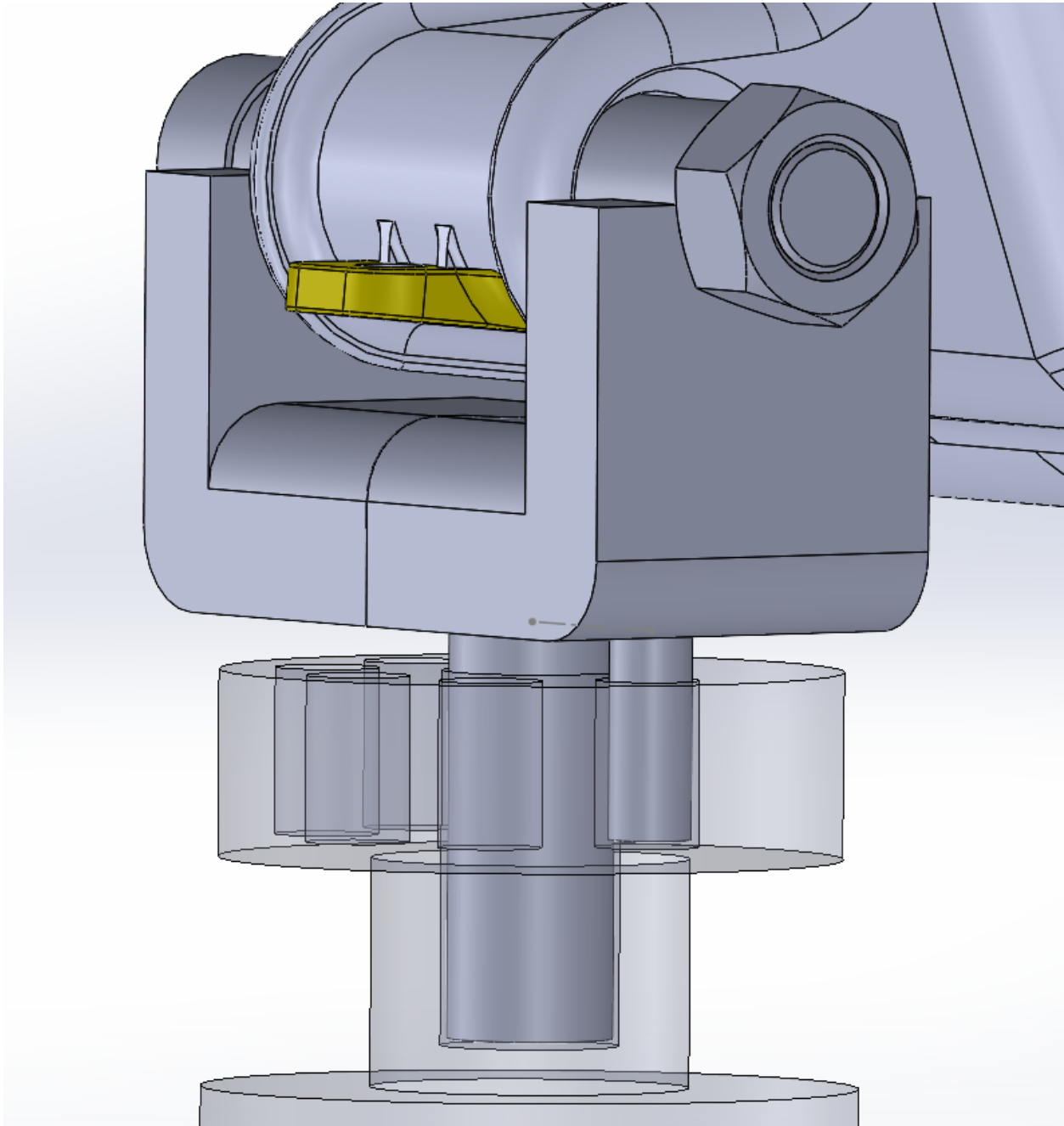
**Figure 3. Field Goal Posts Allow Original Console Rotation.** The field goal posts have cylindrical components that insert into the back of the display console to allow it to rotate about its original axis. This allows the user to adjust the angle at which the console is bent.



**Figure 4. Female and Male Field Goal Posts.** The female (left) and male (right) field goal posts fit together via extending inserts on the male piece and a circular peg on the male piece that fit into corresponding cavities on the female piece. The male piece has a large and longer peg to rotate around the center cavity of the receiving bracket, and the female piece has a smaller and shorter peg that guides the console to different degrees of rotation.



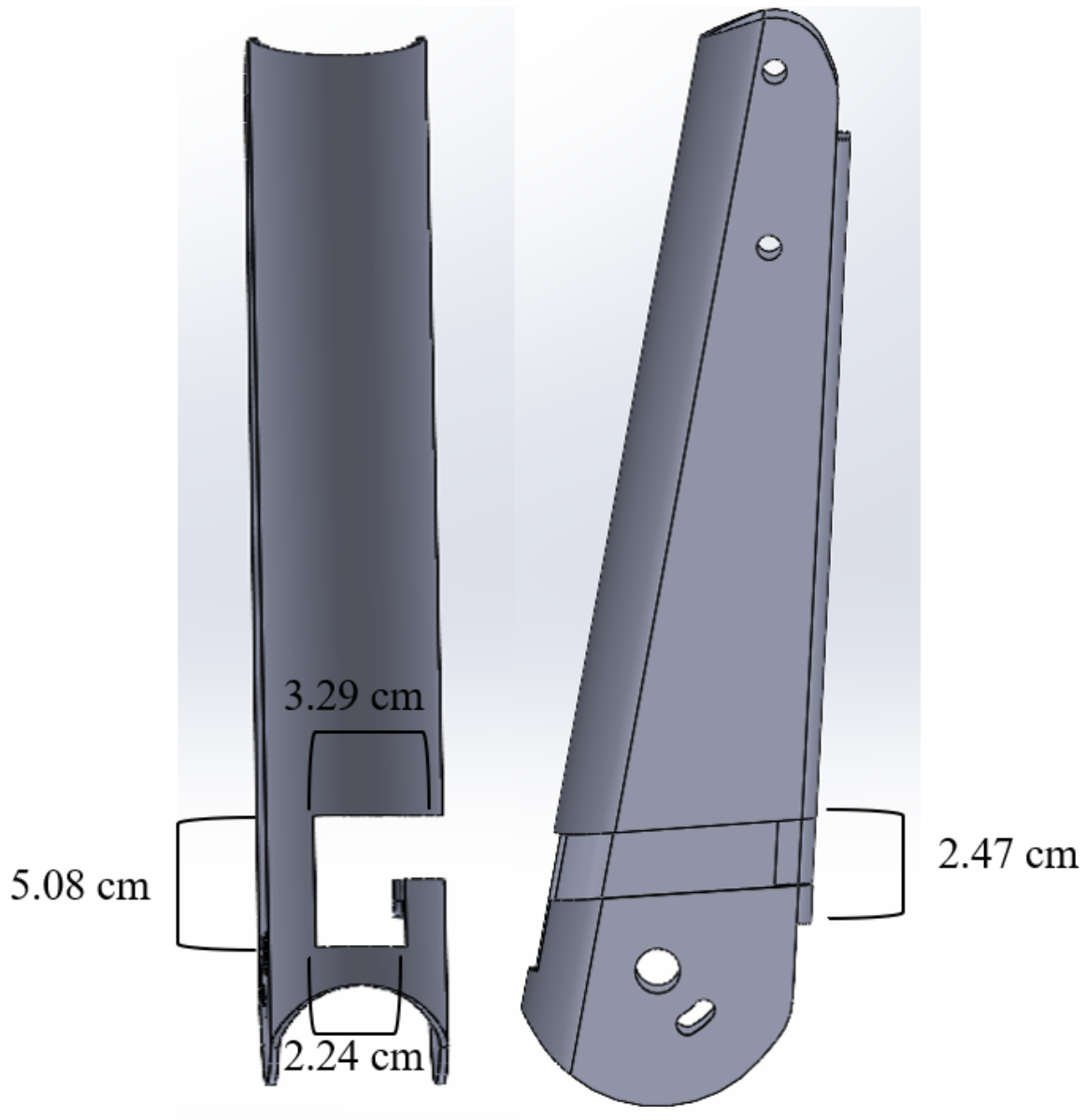
**Figure 5. Swivel Receiving Bracket.** The swivel receiving bracket has a center cavity to allow the large peg on the male field goal post to rotate. It also has five smaller cavities for the guiding peg to insert into to adjust the degree of rotation of the console. A through hole in the bottom allows for a screw to be inserted through the bracket and the rower neck and tightened.



**Figure 6. Rotation of Display Console.** The large peg fits into the center rotating cavity of the receiving bracket, while the guiding peg fits into one of five smaller cavities to adjust the degree of rotation of the console.

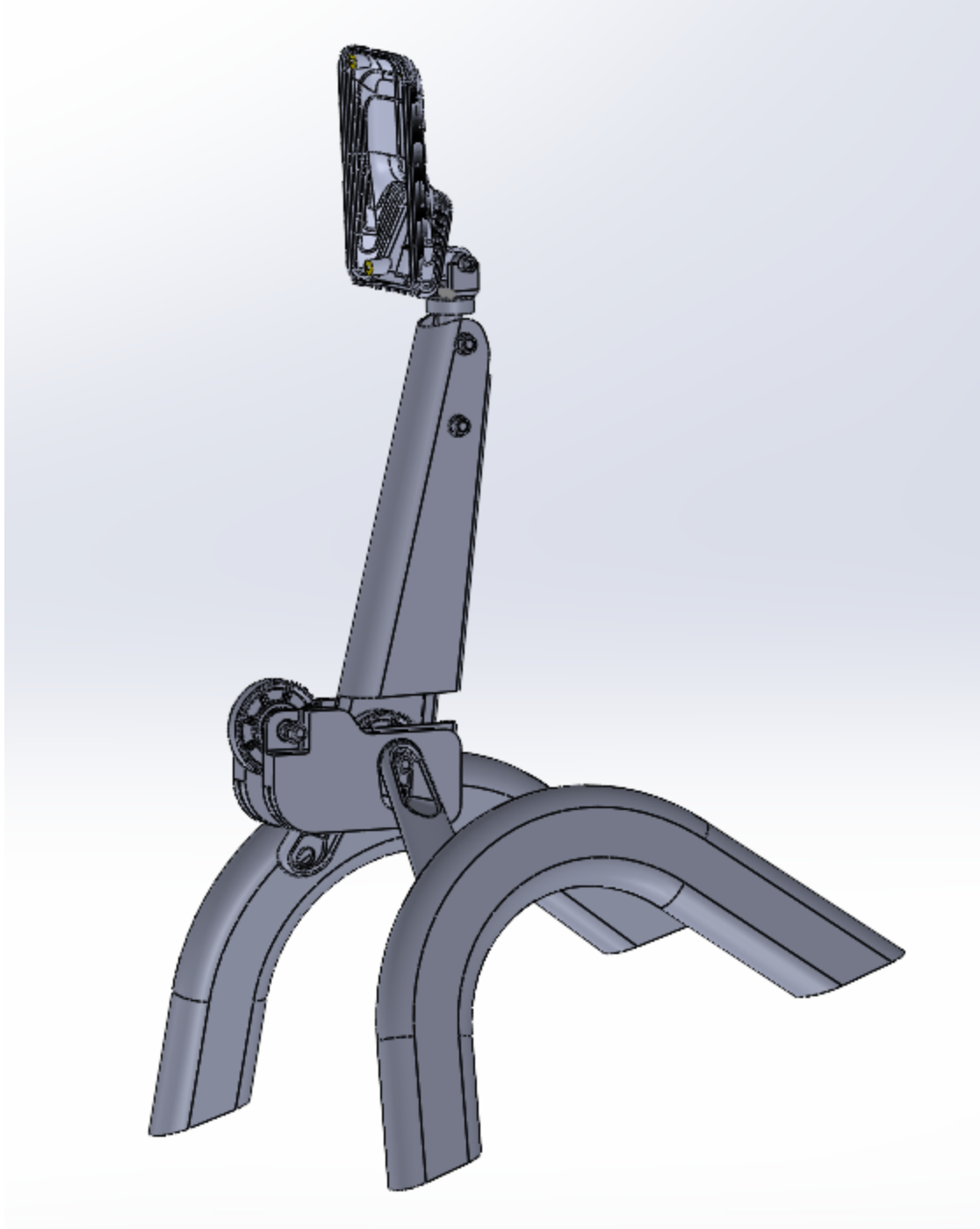
The rower neck serves as the transition point between the standard and adaptive states of the rowing machine. In order to guide the rope onto the additional pulley to row from the adapted side, a slit was cut in the right side of the rower neck. This cut was modeled in SolidWorks (**Figure 7**) to ensure that the cut was wide enough to allow for the rope to pass through, and to ensure that the rope will align with the additional pulley. This part and the model were then sent

to Johnson Health Tech for fabrication of the cut. The full SolidWorks model of the pulley support plates, swivel bracket, and cut rower neck can be seen in **Figure 8**.



**Figure 7. Rower Neck with Slit.** The rower neck has a slit in the right side that allows for the rope to be transitioned from the standard to the adaptive side.



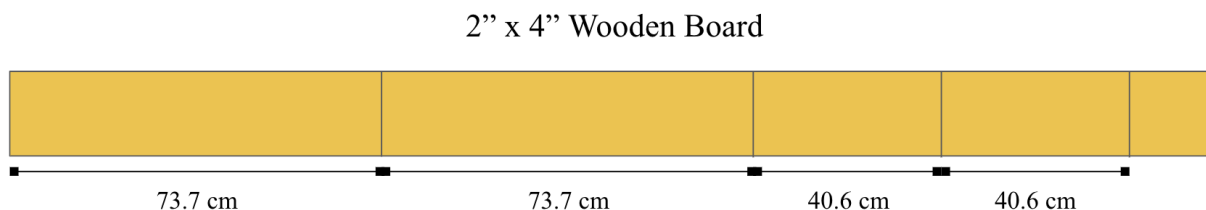


**Figure 8. Full SolidWorks Assembly.** The adaptations made to the original rower include adding an additional pulley stabilized by mirroring support plates, cutting a slit into the rower neck to transition the rope and handlebar from one side to the other, and a swivel bracket that allows the user to rotate the console to face correctly in either the standard or adaptive forms.

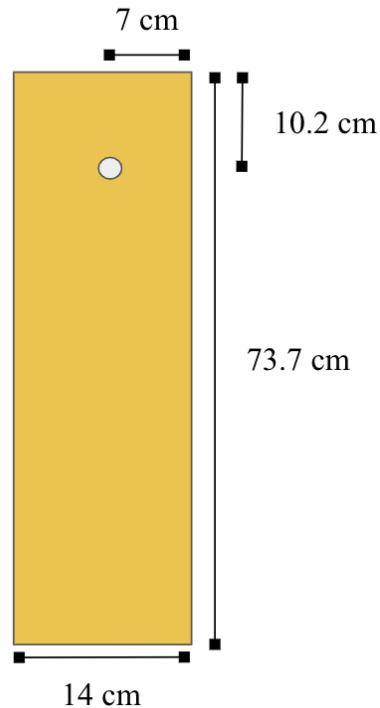
## b. Wooden Base

The wooden support base is used to keep the wheelchair and user stable throughout the rowing exercise. The adjustable straps connected to the support base provide a forward reaction force to the wheelchair while the user is rowing, which prevents the wheelchair from tipping backwards. The wooden base consists of both 2" x 4" and 2" x 6" wooden boards, screws, and adjustable straps. For the purpose of this prototype, the wooden base was fabricated to fit the wheelchair used for the testing of the assembly. The fabrication process of the wooden base was split up into three parts: measuring and cutting the wood, connecting the pieces to one another, and spray-painting the assembly.

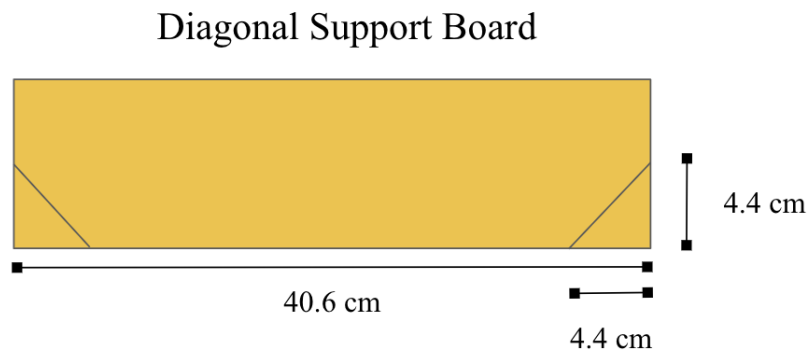
Using a pencil and a tape measure, the 2" x 4" and 2" x 6" boards were measured and marked at specific locations to prepare for the cutting phase. First off, to make the vertical boards with the 2" x 4" board, a notch was marked on the board with the pencil at 73.7 cm from one end. A second mark 73.7 cm from the first notch was made to make two boards of the same length. To make the diagonal supports with the remaining portion of the 2" x 4" board, two 40.6 cm marks were made with a pencil. These markings on the 2" x 4" can be seen in **Figure 9**. For both of the 73.7 cm boards, a 2.5 cm diameter circle was traced out in the center of the board width-wise and 10.2 cm from the edge of the board using a pencil (**Figure 10**). On the two diagonal support boards, markings were made with a pencil at 4.4 cm along the width of the board and 4.4 cm along the length (**Figure 11**). A pencil was then used to connect these two points, forming a diagonal line along one corner of the board. The same markings and line were traced on both the left and right sides of each diagonal board.



**Figure 9. Measurements on 2" x 4" Board.** Two 73.7 cm markings were made on the 2" x 4" board along with two 40.6 cm markings.



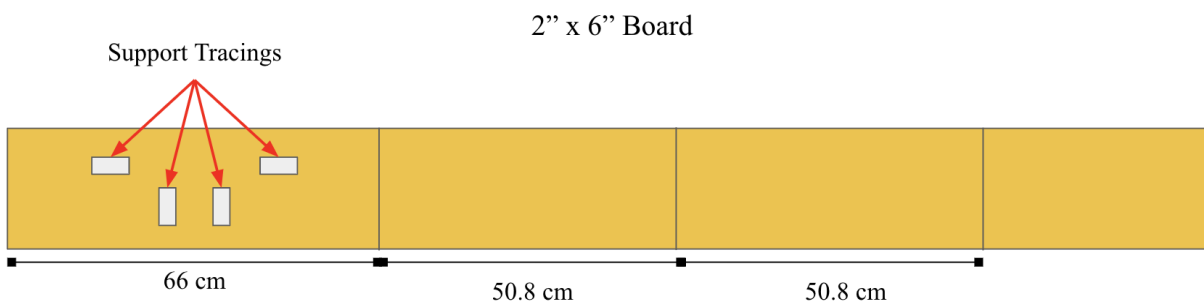
**Figure 10. Hole Marking for Vertical Support Board.** Markings were made 7 cm across the width and 10.2 cm down the length of the 73.7 cm vertical support boards. The holes that were drilled at these markings held the support straps that attach to the wheelchair.



**Figure 11. Diagonal Support Board Measurements.** On the 40.6 cm diagonal support boards, 4.4 cm markings were made along the width and the length of the board. These markings were then connected with a diagonal line.

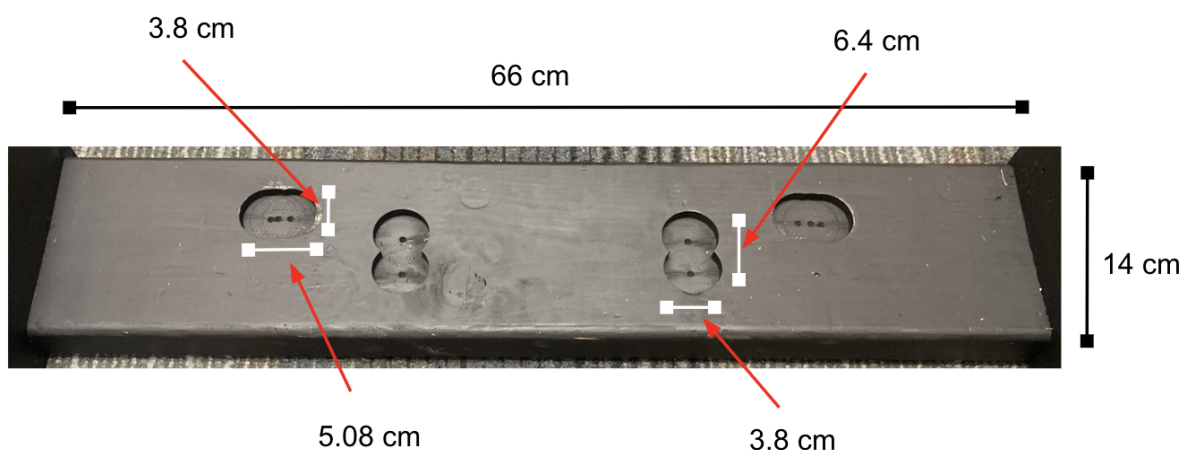
To measure where the base board would be cut, a marking was made 60 cm from one end of the 2" x 6" board. Afterward, this 60 cm portion was placed underneath the front supports of the rowing machine and was centered so that the supports were symmetrically lined up along the board. A pencil was then used to trace the outlines of the two rubber supports and two wheels on the base of the rower onto the base board (**Figure 12**). These four tracings were the only pencil markings that were not cut using the miter saw. After marking the support locations on the base

board, two 50.8 cm markings were made from the edge of the base board marking to denote the cut locations for the horizontal supports (**Figure 12**).



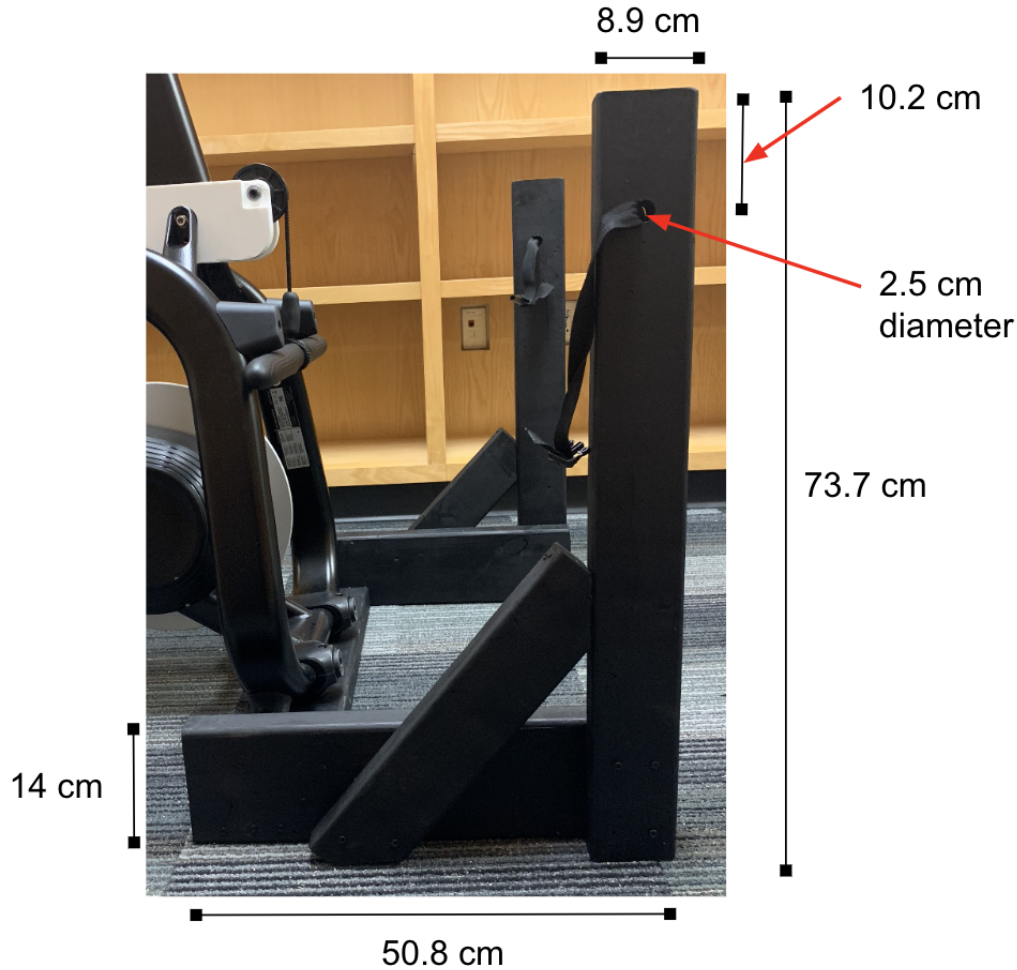
**Figure 12. Markings on 2'' x 6'' Wooden Board.** The 66 cm baseboard marking and two 50.8 cm horizontal support markings were made on the 2'' x 6'' wooden board. The tracings of the rowing machine's front supports were also made on the baseboard portion of the 2'' x 6'' board.

Once all of the measurements were made on the 2'' x 4'' and 2'' x 6'' wooden boards, the boards were cut along the traced lines using a miter saw. In order to drill out the circles on the 73.7 cm vertical support boards, a 2.5 cm drill bit was used along with an electric drill. The boards were secured to the deck using two wood clamps. Once the markings were lined up with the drill bit, the drill was turned on and brought down on the markings until the bit went all the way through the board. For the base board tracings, a 3.8 cm drill bit was used to make the divots in the board. Since these indentations do not go all the way through the board, the depth setting on the drill was set so that each divot would have a depth of 1.3 cm. The removal of wood at each tracing required adjusting the board and clamps along with bringing the drill down multiple times. For the tracings that ran along the length of the board, a 3.8 cm x 5.1 cm divot was created. For the tracings that ran along the width of the board, a 3.8 cm x 6.4 cm divot was created. See **Figure 13** for the locations and side of the divots on the baseboard.



**Figure 13. Base Board for Wooden Support.** The base board for the wooden support base rests underneath the rowing machine. The divots in the board allow for the rubber supports and wheels of the rowing machine to remain in place without movement during rowing.

After all of the cutting was completed, each board was spray painted using black spray paint. Once the spray painting was completed, the various support boards were attached using an electric hand drill, a 0.3 cm drill bit, and 7.6 cm (#8x3") screws to make the full support base assembly. First, the base board was placed under the rower such that the supports of the rowing machine rested in the 1.3 cm depth divots. Next, the 50.8 cm 2" x 6" horizontal support boards were connected to the baseboard. Two through holes were first drilled into the horizontal support board and through the side of the baseboard. The screws were then drilled into these holes. The same process was completed with the other horizontal support on the opposite side. The vertical support boards were then connected to the horizontal support board. Two through holes were drilled into each vertical and horizontal support board at the ends opposite of the base board. Screws were then drilled into these holes to firmly secure the boards in place. The same process was repeated for the vertical support on the opposite side. The last boards that were attached were the diagonal support boards. They were placed outside of the horizontal support boards and rested directly against the vertical supports. Two pairs of through holes were drilled through the diagonal support board. The first set of holes also went into the horizontal support board while the second pair of holes went through the vertical support. Once the through holes were created, screws were then drilled in the holes to firmly attach the diagonal support to both the horizontal and vertical supports. The same process was repeated for the diagonal support on the other side. After all of the attaching of boards was completed, the straps were then fed through the 2.5 cm diameter holes on the vertical support boards. For a picture of the complete wooden assembly, see **Figure 14**.

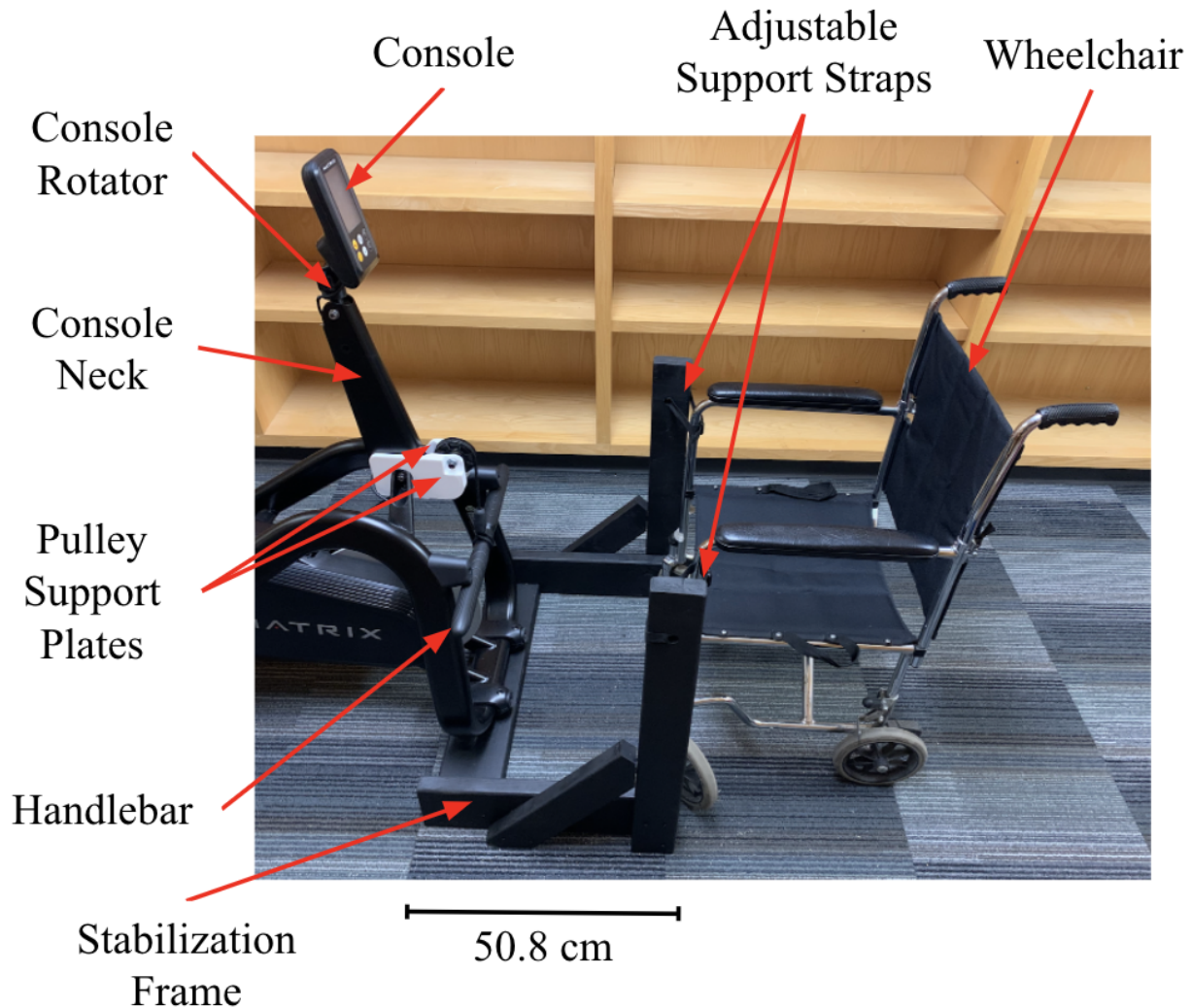


**Figure 14. Side View of Wooden Support.** The 50.8 cm boards that are attached to the baseboard create separation from the rowing machine to allow for the user to complete the rowing motion comfortably. Additional diagonal supports were added to the base to further enhance the strength and stability of the wooden support base. The 2.5 cm diameter holes in the vertical boards house the strap that attaches to the wheelchair.

### c. Full Assembly

After 3D printing the console rotating mechanism and the pulley support plates, cutting the slit in the rower neck, and fabricating the wooden base, all components of the design were attached to the rowing machine to complete the full assembly (**Figure 15**). The rotational mechanism was placed at the top of the rower neck and was attached with the screw that was originally holding the console in place. The pulley support plates and second pulley were attached to the support arms of the rower neck with one on each side of the neck. Once the support plates were on, the neck of the rower was then reattached to its original location. Finally, the rowing machine was lifted up and the wooden base was placed underneath so that the supports of the machine rested in the grooves of the base board.





**Figure 15. Full Assembly.** The full assembly includes the pulley support plates, the console rotator, and the wooden support base. The wheelchair is locked into the support base using adjustable straps.

#### References for Appendix C:

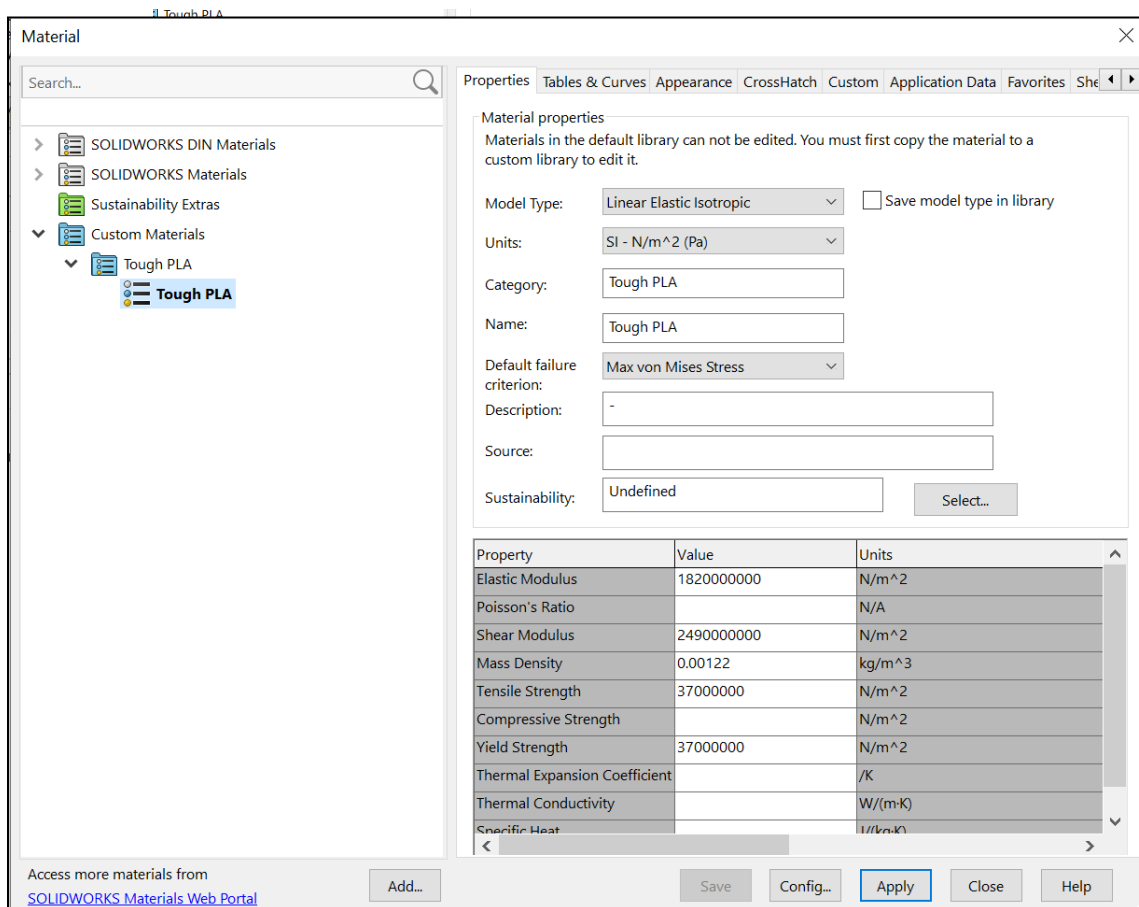
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[https://www.amazon.com/dp/B078P8N2D6?smid=A2292T76OSDPAM&ref\\_=chk\\_typ\\_imgToDp&th=1](https://www.amazon.com/dp/B078P8N2D6?smid=A2292T76OSDPAM&ref_=chk_typ_imgToDp&th=1) (accessed May 01, 2022).

## Appendix D: BME 301 Testing & Results

### I. Testing Methods

#### A. SolidWorks

A solidworks simulation was conducted to analyze the stresses and displacements acquired due to a maximum, worst case load. In order to properly test the strength and geometry of the pulley support plates, the plates were modeled as Tough PLA in SolidWorks. This was done by creating a new material and altering the mechanical properties as shown in **Figure 1**. This ensured that the stress and displacement data that was acquired was representative of the material that the plates were printed in. To test the strength of the pulley support plates, a maximum load of 1050 N was applied to the inner circular cavity on each plate. Ideally, this load would be transmitted equally to each pulley plate. Thus, this load has a safety factor of two, and represents the maximum loading of the plates [4]. To model a worst case scenario, the load was applied directly downward onto this cavity. This is where the plate sits on the additional pulley bearing. Thus, if any force were directed onto the pulley plates, it would be transmitted to this inner cavity surface. During a typical rowing motion, tension in the rope follows along a path parallel to the floor. Thus, the worst case scenario was modeled as the maximum load placed on the plates perpendicular to the floor. The cavity that sits on the two rower neck support arms was also held fixed during the simulation to model the plates when sitting on these support arms, as they should not move. Testing of the stresses and displacements that develop revealed the strength and rigidity of the chosen material and geometry of the support plates, which in turn revealed how well the plates stabilized the additional pulley under typical rowing conditions.





**Figure 1. Tough PLA Material Specifications.** The pulley support plates were modeled as Tough PLA, to accurately predict the stresses and displacements that will develop in the plates under a maximum load.

## **B. Tension Protocol**

Testing of the tension developed by both the standard and adapted sides of the rowing machine indicated whether or not the adapted side was able to provide workouts of varying difficulty due to changes in resistance. To complete this testing, the tension in the rope was measured during rowing at different resistance levels on both the standard and adapted sides. One end of a 45 kg (100 lb) spring gauge was attached to the middle of the handlebar of the rowing machine while the other end was held onto by the user. Starting from the standard side, the user sat on the rowing machine seat and practiced the rowing motion while holding the spring gauge to develop a comfortable rhythm. Afterward, at a resistance level of 1, the user rowed from the standard side for 15 reps. The first five reps were completed to have the user calibrate the rowing pace to 22-25 strokes per minute (spm). The user was asked to remain within this stroke rate range in order to standardize the effort output between testing of different resistance levels. For the next ten reps, a video was taken on a phone to track the tension in the spring gauge during each rep. After the 15 reps were completed, using the video recording from the phone, the maximum tension in the rope was recorded for each rep.

After completing these steps for resistance level 1, the same steps were repeated for resistance levels 5 and 10. Once the testing on the standard side was completed, the handle and spring gauge were transitioned to the adapted side. The console was also rotated so that it faced the adapted side. The testing participant then sat in the wheelchair on the adapted side of the rower. Due to the length of the spring gauge, it was not possible to develop enough tension in the rope while rowing with the user locked into the straps on the wooden base. Thus, the user moved back the length of the spring gauge and was instead held rigidly in place by another team member. This allowed for the rope to be pulled adequately to develop tension. The brakes on the wheelchair were also locked into place as well. The protocol for testing tension on the standard side was then repeated on the adapted side to get tension data for resistance levels of 1, 5, and 10. The major difference between the standard and adapted side protocols was that the lower extremity muscles of the test participant were not allowed to be used to aid in the rowing. Just like on the standard side, a video was taken for each level of resistance while rowing to track the tension in the rope.

## **C. Kinovea Protocol**

Displacement of the wooden support base and wheelchair indicates failure in the stabilization of the user. In addition, external motion could interfere with the mechanics of the

rowing motion, which could lead to injury or improper technique while rowing. Therefore, there should be zero displacement. This is to make sure that the user has an equivalent upper body workout as a standard user.

Displacements were measured on the adapted side and under maximum resistance (level 10) settings using Kinovea. In order to successfully analyze a video in Kinovea, trackers were placed onto visible areas of the wheelchair and the wooden frame. For the purpose of this test, a 2.5 cm x 2.5 cm (1 in x 1 in) colored square was placed onto the wheelchair armrest and on top of the left vertical wooden board of the frame using tape. A camera was then set up to capture the motion resulting from rowing. After the camera was set up, the test subject was recorded while rowing under maximum resistance and effort for 30 seconds. Before analysis of the video began, a measurement of an object within the frame of the video was required. Once acquired, the video was uploaded to Kinovea and used to measure the maximum displacements.

The displacements were found by applying trackers onto the 2.5 cm x 2.5 cm boxes. It was important to ensure that the trackers followed the paper boxes frame by frame in order to ensure proper measurements. Once this was complete, the calibration measurement was input into the software to find the displacement using the line tool. Two additional lines were then made to obtain the maximum displacement of the wooden base and the wheelchair. The distance values provided by the lines served as the approximated displacement of the two components. The raw data was then exported as an excel file and uploaded to MATLAB. Simple coding was required to generate a displacement plot with a legend. A scale was added manually through the figure customization available in MATLAB using the displacement values from Kinovea.

#### **D. Survey**

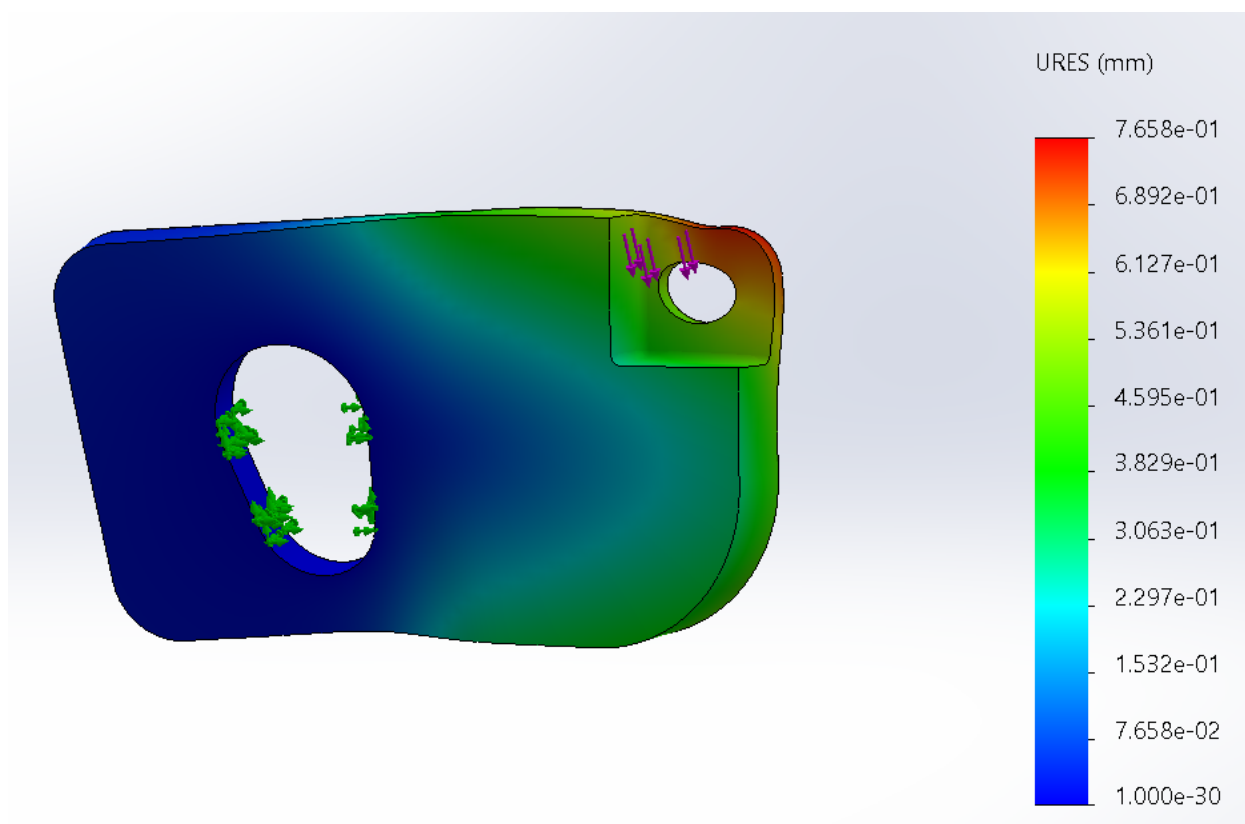
A survey was created to quantify the experience of using the adaptive side of the rowing machine in comparison to the standard side of the rowing machine. Testers rated their experience based on a list of criteria, including safety, comfort level, and ease of use. Additionally, test subjects were encouraged to give feedback and express improvements that could be made to the device.

## **II. Results**

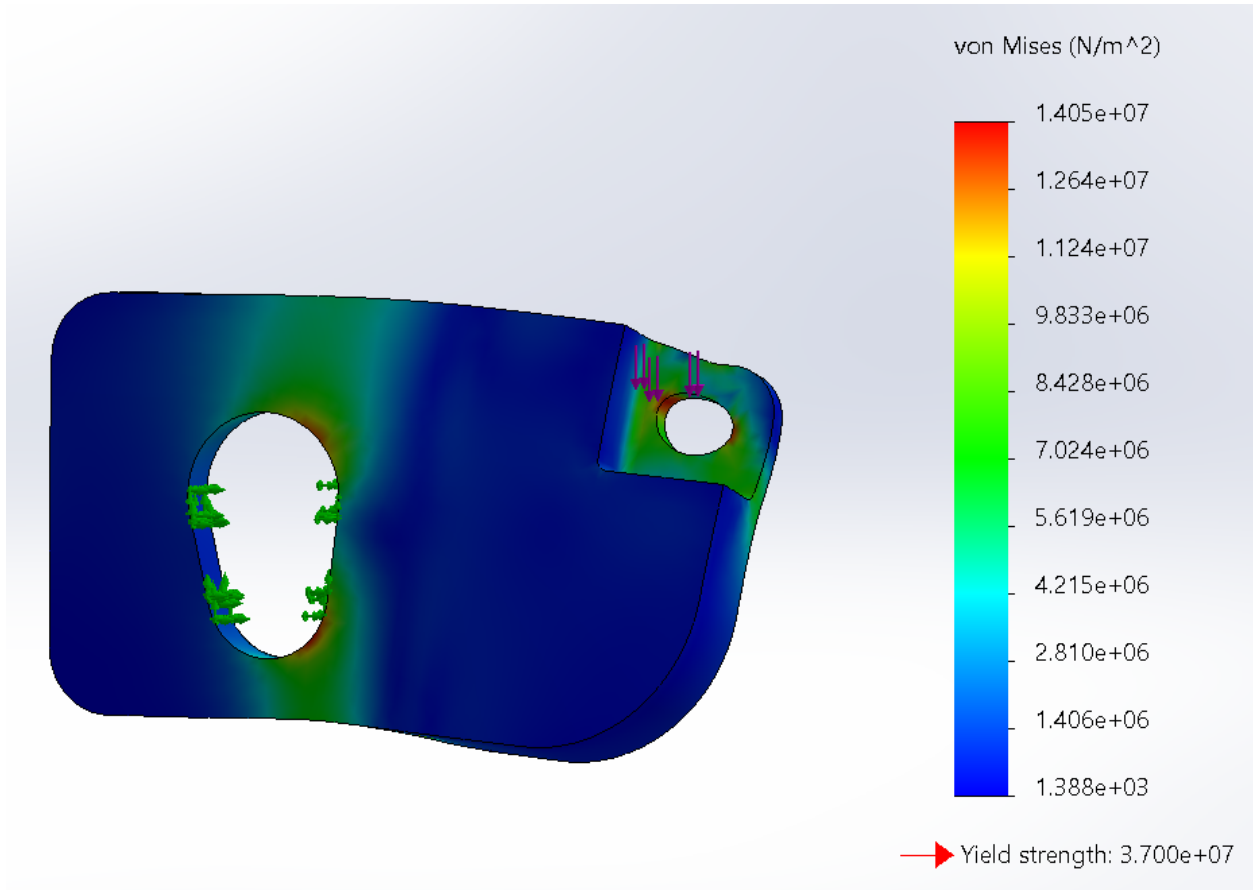
### **A. SolidWorks Simulation**

After completing the SolidWorks simulation testing on the pulley plates, the resulting stresses and displacements were analyzed to determine the strength of the Tough PLA material and the designed geometries. After applying a 1050 N load to the inner bearing surface of the pulley plates, a maximum displacement of 0.7658 mm occurred at the top corner of the left plate, near where the load was applied (**Figure 2**). This was expected because this is the thinnest region

of the plate, and thus has the least amount of structural integrity. This displacement is incredibly small, and will likely be even less during actual load bearing, due to the metal pulley bearing being inserted into this cavity and accepting some of the applied load. Throughout the rest of the plate, displacements were also less than 0.7658 mm, proving that the geometry for the left plate will be strong enough to withstand typical rowing loads. Additionally, the maximum stress that developed under this maximum load was only 14.05 MPa (**Figure 3**). This is much less than the yield strength of Tough PLA of 37 MPa [2]. This maximum stress developed along the inner surface of the bearing cavity, and along the front inner surface of the fixed cavity. This was expected because when the load is applied, the fixed cavity will be pushed into the metal support arms. Loading with a safety factor of two shows that the left pulley support plate will be able to withstand loads well under this maximum, like the loads experienced during typical rowing, and thus should hold the additional pulley stable.



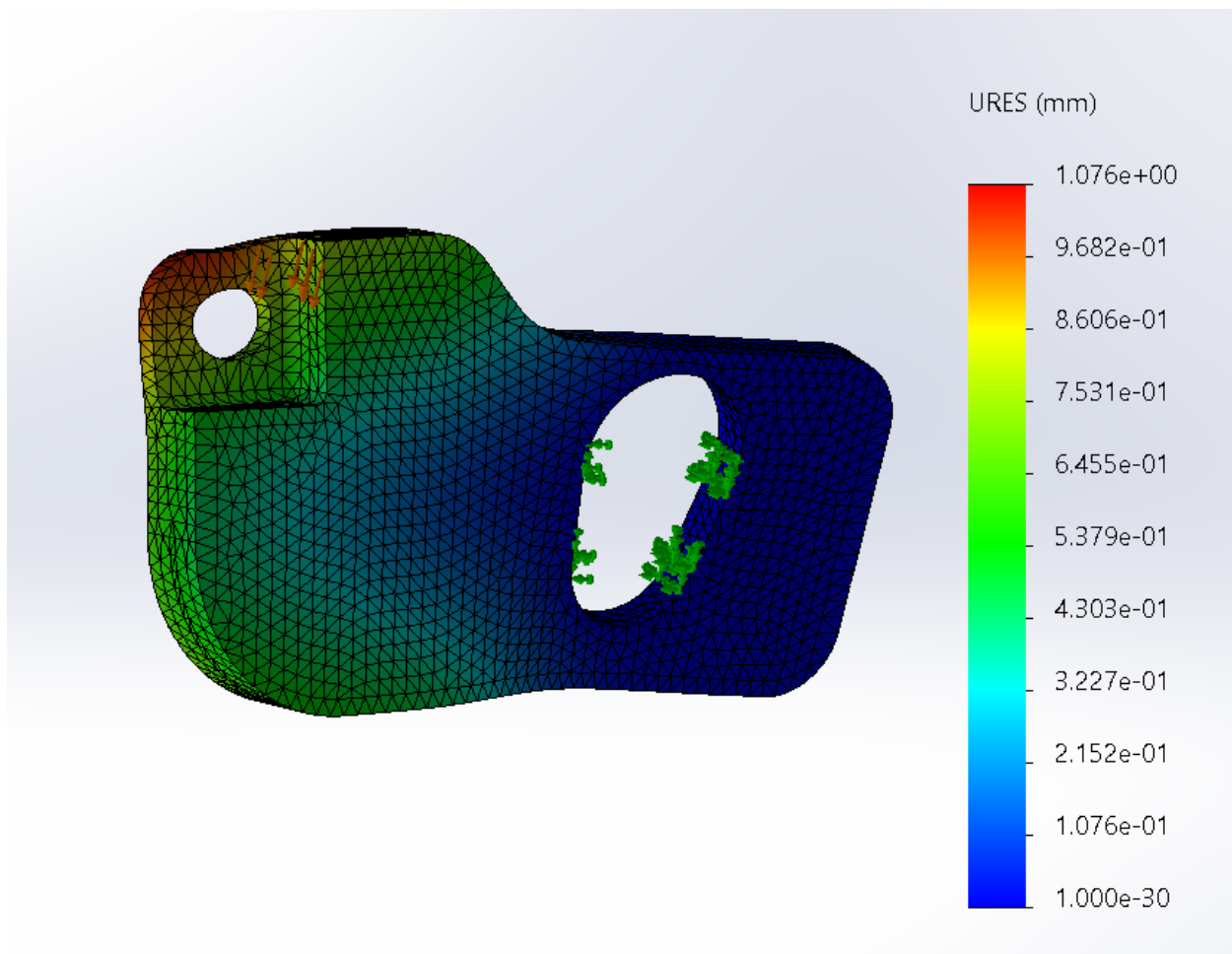
**Figure 2. Displacements for Left Pulley Support Plate.** The left pulley support plate only experiences a maximum displacement of 0.7658 mm under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.



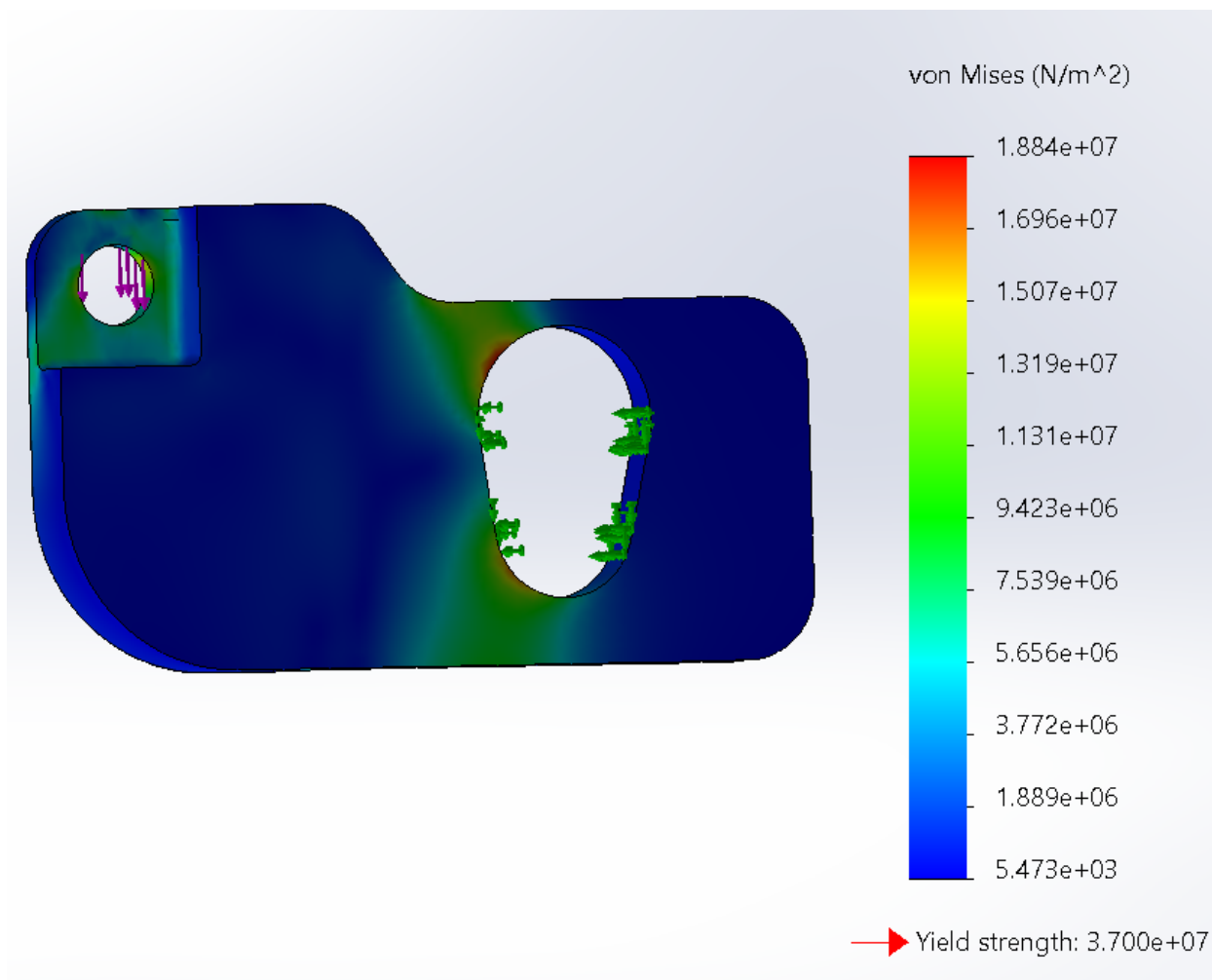
**Figure 3. Stresses for Left Pulley Support Plate.** The left pulley support plate only experiences a maximum stress of 14.05 MPa under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

After applying a 1050 N load to the inner bearing surface of the right pulley plate, a maximum displacement of 1.076 mm occurred at the top corner of the plate, near where the load was applied (**Figure 4**). This was expected because this is the thinnest region of the plate, and thus has the least amount of structural integrity. It is expected for there to be more displacement in this location as compared to the left pulley plate due to the lack of material along the top surface. This lack of material decreases the strength of the plate, which is why it displaces slightly more. However, this displacement is still incredibly small, and will likely be even less during actual load bearing, due to the metal pulley bearing being inserted into this cavity and accepting some of the applied load. Throughout the rest of the plate, displacements were also less than 1.076 mm, proving that the geometry for the right plate will be strong enough to withstand typical rowing loads. Additionally, the maximum stress that developed under this maximum load was only 18.84 MPa (**Figure 5**). This is much less than the yield strength of Tough PLA of 37 MPa [2]. This maximum stress developed along the inner surface of the bearing cavity, and along the front inner surface of the fixed cavity. This was expected because when the load is applied, the fixed cavity will be pushed into the metal support arms. Loading with a safety factor of two shows that the right pulley support plate will be able to withstand

loads well under this maximum load during typical rowing, and thus should hold the additional pulley stable. Overall, the SolidWorks simulation testing justified the chosen geometric design and material selection for the pulley support plates. Since the plates show minimal displacements and stress well below the yield stress, the plates are expected to perform well under loadings less than this maximum load. Any stresses that develop under typical loading (less than 1050 N) should not cause the plates to yield or break. Any small displacements that do occur in the fixed cavities will be resisted by the metal rower support arms. Additionally, if the plates do start to slip inward, the metal rower neck will prohibit the plates from sliding completely off, as it will offer a reactive force outwards on the inner surface of the plates.



**Figure 4. Displacements for Right Pulley Support Plate.** The right pulley support plate only experiences a maximum displacement of 1.076 mm under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

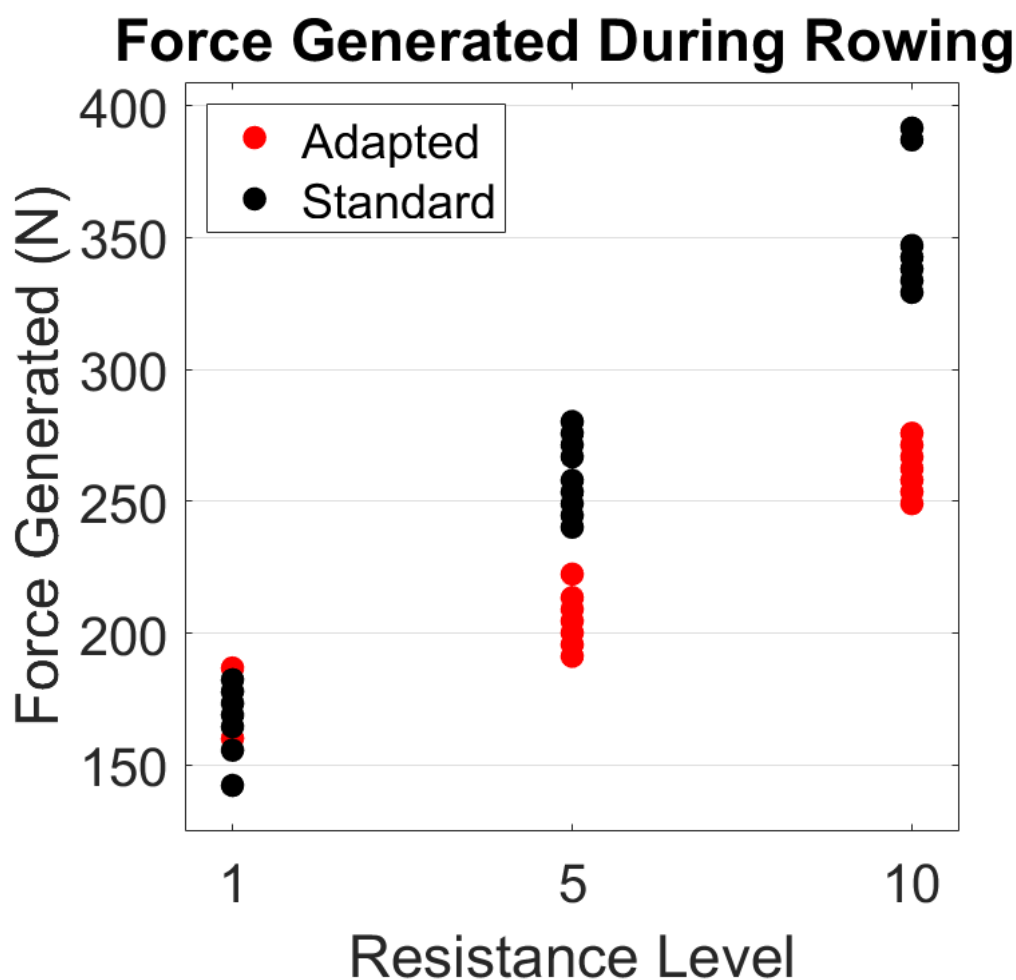


**Figure 5. Stresses for Right Pulley Support Plate.** The right pulley support plate only experiences a maximum stress of 18.84 MPa under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

## B. Rope Tension Analysis

In order to evaluate the tension developed in the rope while rowing on the adaptive and standard sides of the rowing machine, ten maximum force measurements were taken on each side for three different resistance levels (1, 5, and 10). After being recorded in a spreadsheet, the results were analyzed and plotted in MATLAB (**Figure 6**). After analysis of the rope tension data, it was found that as the resistance level of the rowing machine increased, the tension that developed in the rope while maintaining a standard stroke rate also increased. This was expected because as the resistance level of the rowing machine increases, the rope should be more difficult to pull back. However, less force was developed in the rope on the adapted side, as seen in red, as compared to the standard side, as seen in black. This decrease in tension on the adapted side is due to both the wheelchair backrest preventing the user from extending backward in their chair along with the user not being able to use their legs to output additional force for the drive phase.

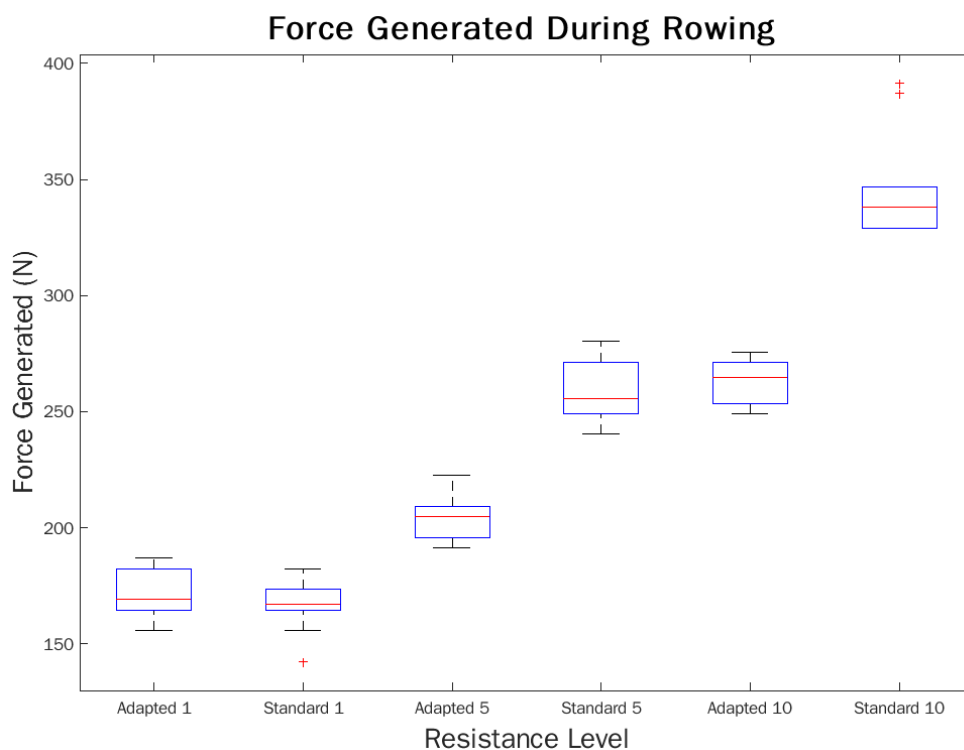
Since wheelchair users cannot use their legs to further extend themselves backward while rowing, measurements of the tension developed in the rope on the adapted side were done without the use of the users legs. Since the user cannot extend themselves as far back as if rowing on the standard side, the user will have a smaller range of motion to pull the rope. Thus, the rope will be pulled a lesser distance and this develops less tension, as tension in the rope increases both with resistance and extension length. Therefore, as shown in **Figure 6**, a user rowing on the adaptive side cannot generate the same amount of tension in the rope as a user rowing on the standard side. However, the general increase in force generated shows that the workout can be tailored on the adapted side as well as the standard side by changing the resistance level. This proves the ability for users to finetune workouts from both sides of the machine and still be able to properly exercise their upper body muscles on the adaptive side.



**Figure 6. Force Generated During Rowing.** The force generated during rowing on each side plotted against the resistance level was taken ten times for resistance levels of 1, 5, 10. More force was generated on the standard side, but the overall force generated increased at each resistance level for both the standard and adapted sides.

The rope tension data were also plotted in the form of a box-plot to better show the separation between the tension developed on the standard and adaptive sides (**Figure 7**). A

Paired-Sample T-Test with an alpha level of 0.05 was completed to compare the mean tension on the standard side to that of the adapted side at each of the three resistance levels in which data were collected (levels 1, 5, and 10). This analysis was completed through the statistical testing software VassarStats [5]. A Paired T-test was chosen due to the need to compare a mean value. Additionally, it was an appropriate test due to having the same subject perform all of the trials in which data were collected. Thus, there was correlation between the trials because the test subject was not randomized and was consistent throughout the experiment. The Paired-Sample T-Test resulted in p-values of 0.123,  $< 0.0001$ , and  $< 0.0001$  for the difference in mean tension developed in the rope on the standard and adaptive sides at resistances 1, 5, and 10, respectively. Since the acquired p-values are less than 0.05 for the resistance levels of 5 and 10, there is a statistically significant mean difference between the standard and adapted forces developed at these two resistance levels. The statistically significant difference between resistance levels 5 and 10 can be attributed to the user not being able to use their legs while rowing on the adapted side, as previously described.

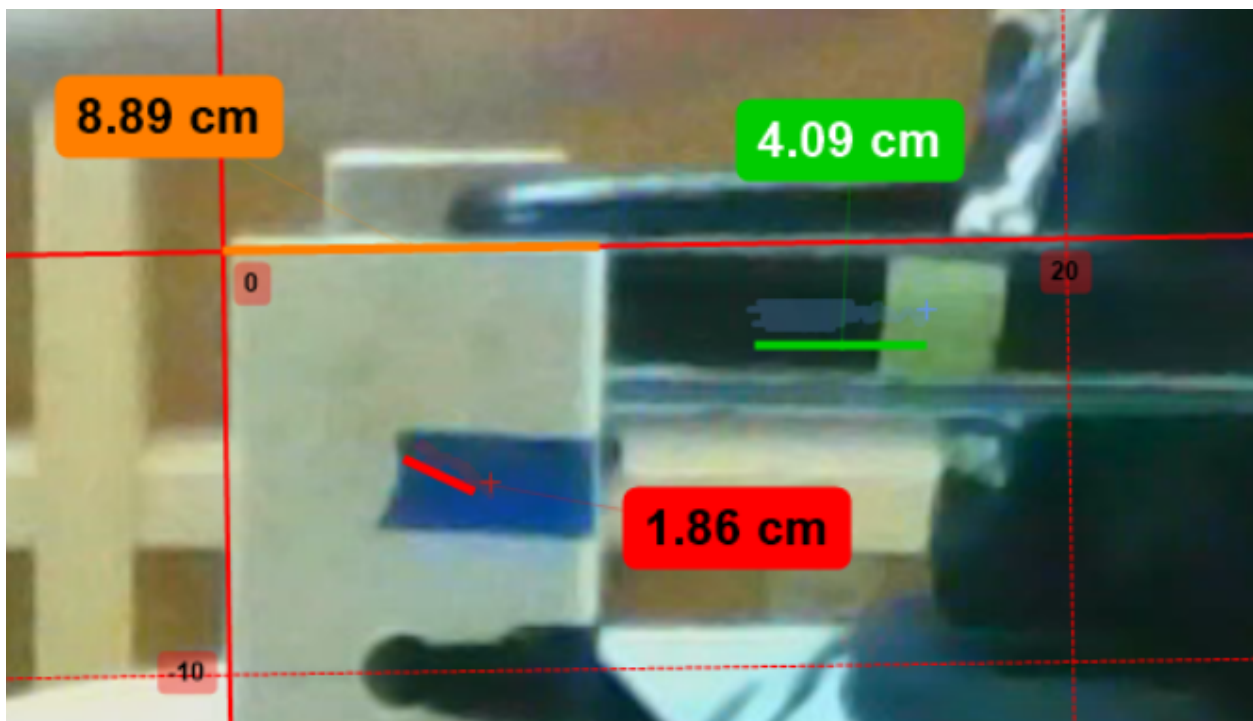


**Figure 7. Box Plot of Force Generated During Rowing.** The box plot for the rowing conducted at resistance levels of 1, 5, 10 demonstrates the general increase in force generated for each resistance level. The red asterisks indicate outliers in the ten data points for each side at each resistance level.

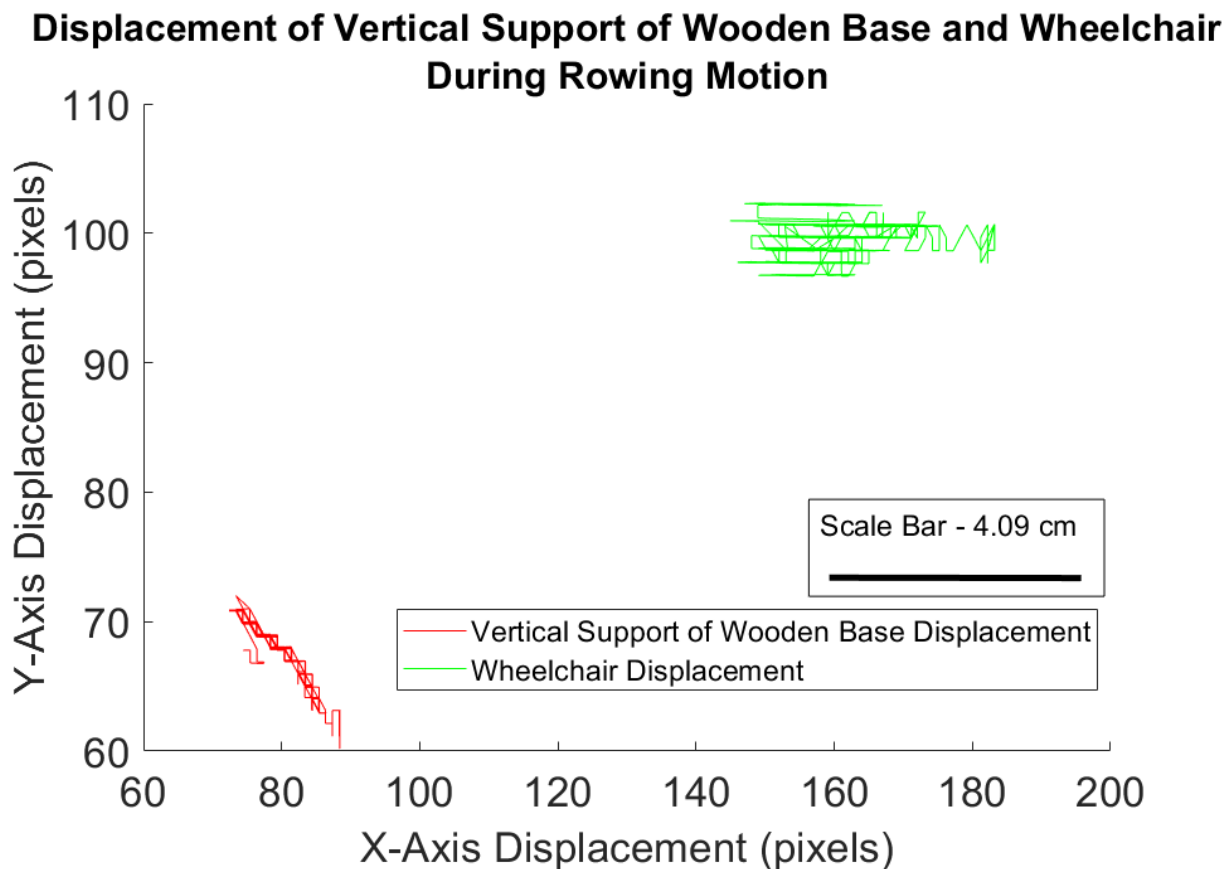


### C. Kinovea Motion Capture

The completion of displacement testing through Kinovea led to approximated translation values for the wheelchair and the wooden stabilizing frame. The movement seen in the wheelchair and the vertical support of the wooden base were both over the threshold of zero displacement that was set in the PDS. The wheelchair moved 4.09 cm in the forward direction, relative to the test subject, while the vertical support bars moved 1.86 cm in a forward and upward direction as shown in **Figure 8**. Additionally, the brakes on the wheelchair used during testing were worn. Thus, the brakes could not be used to help limit the forward / backward translation of the wheelchair while rowing. If the brakes prevented movement, less movement of both the wheelchair and vertical support bars would have been observed. Tracking of the wheelchair and vertical support movements can be seen in **Figure 9**. The movement seen in the vertical support of the wooden base can be attributed to the weak connections between the baseboard and the horizontal supports in addition to the flexing of the horizontal supports. Lack of support at this connection results in an inward torque when a user pulls at the bar. The pull also causes an upward motion due to the structure preventing the tipping motion. The upward motion of the wooden base counteracts the moment that would cause the wheelchair to tip. Despite these small displacements, movements of the wheelchair and stabilizing frame did not impede the ability to properly row from the adapted side.



**Figure 8. Maximum Displacement in Vertical Support of the Wooden Base and Wheelchair.** The orange label and line contain the known distance for the calibration curve. The green label and line highlight the displacement of the wheelchair. The red label and line indicate the displacement of the vertical support of the wooden base.

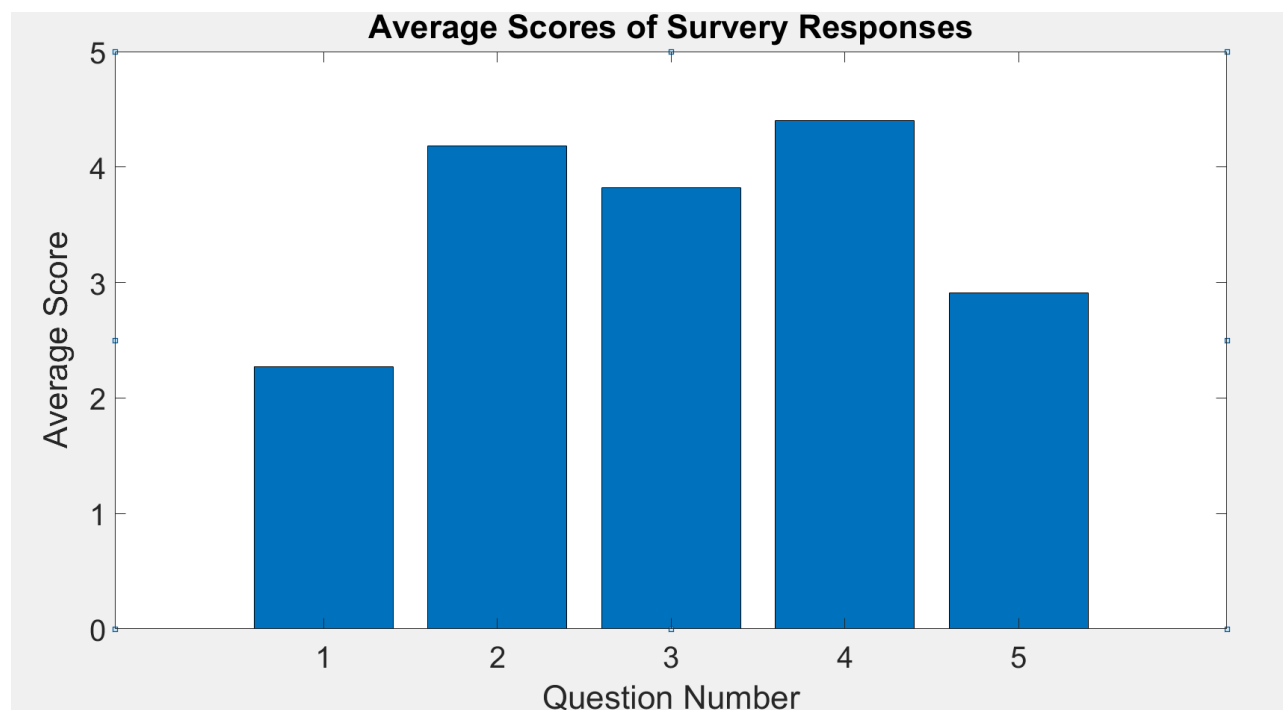


**Figure 9. Movement Data Plot for Vertical Support of Wooden Base and Wheelchair.** The red line represents the movement exhibited by the vertical support of the wooden base. The green line represents the movement exhibited by the wheelchair.

#### **D. User Survey**

Eleven test subjects were recruited to use the rowing machine and compare experiences rowing on both the standard and adaptive sides. The survey consisted of five numerically rated questions, and three free response questions. For all of the numerically rated questions except for the first one, a score of zero is the lowest or least satisfactory, and a score of five is the highest or most satisfactory. The first numerical question was “Throughout the duration of the exercise, how much did you feel like you required the use of your legs for stability?”. This question received a score of 2.3, which indicates that users thought it was moderately difficult to refrain from using their legs during rowing. For this question, a score closer to 0 means that users felt they didn’t need to use their legs for stability. The second question was “How secure did you feel in the wheelchair from tipping backwards throughout the duration of the session?”. This question received a score of 4.2, which indicates that users felt significantly secure and stable while rowing. The third numerical question was “How well did the adaptive side emulate the action of rowing? (without the use of lower body)”. For this question, the average response score was 3.8. This is indicative of the adaptive side of the rowing machine emulating the traditional rowing

motion in an accurate manner. For the fourth numerical question, participants were asked “How intuitive was the adaptive side to use?”. Users felt that the adaptive side was easy to use as the question received an average score of 4.4. For the last numerical question, users were asked “How easy did you find it to transform the rower from regular use to adapted use?”. The majority of participants found it moderately difficult to transform the rope from the standard to the adaptive side, so this question’s average score was 2.9. For the five numerical questions in the survey, the average of each response can be seen graphically in **Figure 10**.



**Figure 10. Average Score of Survey Responses.** The average responses to each of the five numerically rated questions are displayed to summarize user feedback from using the Adaptive Rower.

After compiling the three free response answers, the most prevalent feedback was that users felt stable in the wheelchair during rowing, the adaptive side emulated the action of rowing well, and the adaptive side was intuitive and easy to use. Five of the participants expressed that rowing on the adaptive side was a more taxing exercise than rowing on the standard side. However, this could be due to participants having to lift their legs off of the ground and refrain from using them while rowing in order to mimic being wheelchair bound. Suggested improvements to the prototype included a mechanism to release tension from the rope for easier transformation from the standard to the adaptive side, a chest cushion or seat belt for added stability while rowing, and an adjustable base frame to fit wheelchairs of varying sizes.

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- [5] “VassarStats: Statistical Computation Web Site.” <http://vassarstats.net/> (accessed May 02, 2022).

## **Appendix E: Competing Designs**

### **I. Existing Devices and Competition**

Many rowing ergometers do not have disability design considerations, and exercise machines in general are not designed specifically for individuals in wheelchairs. Most adaptive products are third-party and will void the warranty of the machines [6]. The two most common methods to accommodate rowing for wheelchair users are replacing the sliding seat with a fixed seat, or removing the sliding rail altogether [7]. The fixed seat method requires the user to transfer themselves from their wheelchair to the fixed seat on the rower which is often not possible without outside assistance [8]. However, this method does allow a quick transition between the adaptive and non-adaptive forms as the seats are easily screwed on and off. Alternatively, removing the sliding rail allows the wheelchair users to operate the rowing ergometer directly from their wheelchair. This method makes the rowing machine more accessible, however, it is likely that disabled individuals will require assistance to remove the sliding rail. It is unlikely that this method would be employed at fitness facilities due to the need to maximize space and usage of the machines.

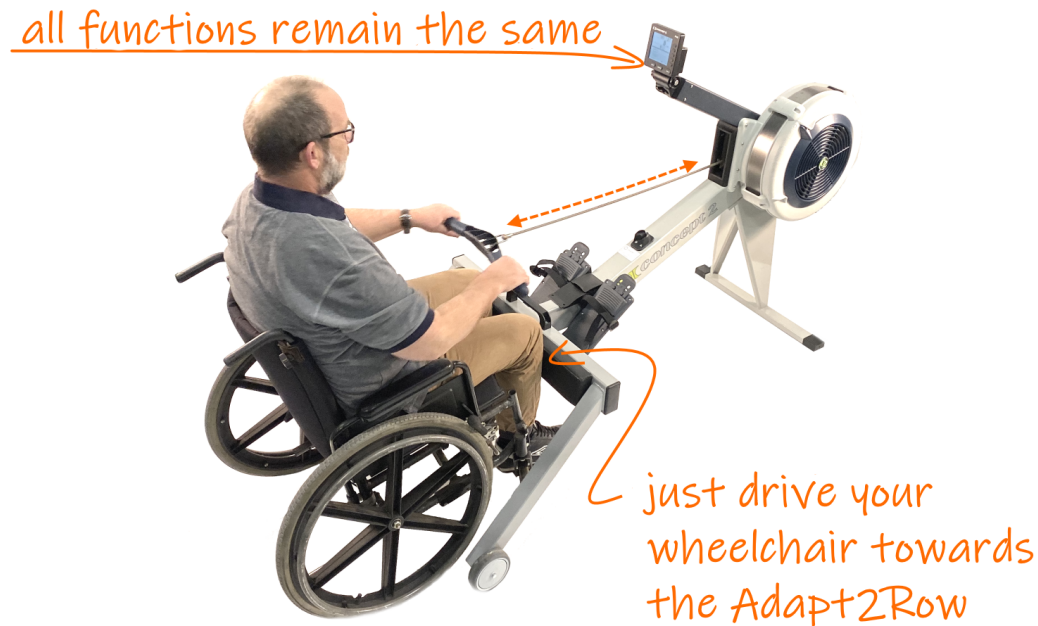
Researchers at the British Columbia Institute of Technology designed the Adaptive Rowing Machine (AROW). The design and fabrication instructions are free on their website [7]. The adaptations, which can be seen in **Figure 1**, were designed specifically for the Concept 2 rowing ergometer. The design involves removing the sliding rail so that operation of the rowing machine can be completed directly from the wheelchair. The adaptations to the Concept 2 include permanently attaching an aluminum truss onto the frame of the rowing machine and securing a plate at the base of the rower. The ends of the aluminum bar are enclosed in padding to support the user’s lower body, and there is an optional bar to support the upper body. The bars are screw adjustable to accommodate different body sizes. The plate at the base of the machine extends to the front wheels of the wheelchair and under the rowing machine to prevent the translation of the ergometer during intensive activity. A shortcoming of the AROW design is the permanent transformation of the rower, which voids the warranty and prohibits standard use of the machine. Additionally, the adaptation requires extensive fabrication instructions, which take a significant amount of time to follow. Lastly, the permanently attached chest bar prohibits the user from interacting with the resistance setting and console during the workout. Despite these

advancements in adaptive rowing machines, a gap in the market remains for a convertible rowing machine that allows for both standard and adaptive use, along with easy access to the interface for workout settings.



**Figure 1. AROW adaptations to Concept 2.** Adaptations for the Concept 2 include a support bar extending to the user's chest and a rigid attachment to the frame of the rower [7].

Adapt2Row is another adaptive rower on the market which allows for standard and adaptive wheelchair use on the Concept2 rowing machine and can be seen in **Figure 2** [6]. During adaptive use, the user is able to row directly from their wheelchair, which eliminates assistance to transfer the wheelchair user to/from a fixed seat on the rower. However, this design does not completely remove the need for outside assistance, as a wheelchair user will likely need assistance to transition the Concept2 rower for adaptive use. Additionally, Adapt2Row is only compatible with the Concept2 rowing machine and the Adapt2Row design is solely shipped in the EU, limiting the accessibility of the device. Due to the need for outside assistance and the difficulty of obtaining Adapt2Row within the U.S., there remains a need for an adaptive rower which does not require outside assistance and allows both standard and adaptive rowing on the same machine.



**Figure 2. Adapt2Row on a Concept2 Rowing Machine.** Adapt2Row allows for both standard and adaptive rowing on the Concept2 rowing machine but still requires outside assistance to transition between both states [9].

#### References for Appendix E:

- [6] “Adapting the Indoor Rower | Concept2.”  
<https://www.concept2.com/adaptive-rowing/adapting-indoor-rower> (accessed Dec. 12, 2022).
- [7] “Rowing Solutions – Adapted Rowing Machine (AROW),” Feb. 08, 2022.  
<https://adaptederg.commons.bcit.ca/rowing-solutions/> (accessed Feb. 07, 2022).
- [8] “Concept 2 Rowing Machine Adaptive Seats – Adaptive Rowing UK.”  
<https://adaptiverowinguk.com/index.php/2019/06/03/concept-2-rowing-machine-adaptive-seats/> (accessed Dec. 11, 2022).
- [9] “Adapt2Row: rowing on a Concept2 rowing machine from your wheelchair.”  
<https://gerofitness.nl/export/406-adapt2row.html> (accessed Dec. 12, 2022).

## **Appendix F: BME 400 Designs & Design Matrices**

### **I. Preliminary Design and Evaluation**

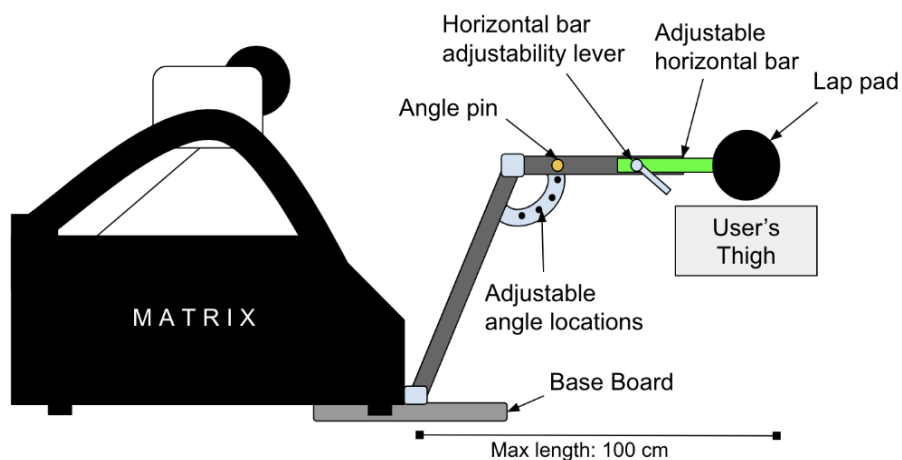
#### **A. Stabilization Frame**

##### **a. Stabilization Frame Design 1: Base Stabilization Frame**

This design is the same as the design from BME 301. Please see **Appendix C: BME 301 Final Design & Fabrication.**

##### **b. Stabilization Frame Design 2: Pad Support**

The Pad Support design features a pad attached at the end of a horizontal bar that secures the user and wheelchair in place during the rowing exercise (**Figure 1**). This pad provides a downward reaction force on the user's thighs that prevents the wheelchair from tipping backwards. Additionally, the pad provides a backward reaction force at the hip during the drive portion of the rowing motion, prohibiting the user from being pulled out of the wheelchair. To accommodate different sized users and wheelchairs, the Pad Support design includes two mechanisms for adjustability: the angle-pin mechanism and the lever mechanism. The angle-pin mechanism allows the user to adjust the height of the horizontal bar with the pad on the end. By rotating the horizontal bar and locking the pin at various points, the Pad Support design can accommodate users/wheelchairs of varying heights. For users with different arm lengths, a lever mechanism incorporated into the Pad Support design adjusts the length of the horizontal bar. The horizontal bar section is made of two separate bars, one which rests inside the other. By pressing the lever in, the position of the smaller bar slides within the larger bar to move the pad closer to or farther from the rower. Similar to the Base Stabilization Frame, the rowing machine rests on cut-out grooves in the base board of the Pad Support design.



\*Note: Drawings not to scale

**Figure 1. Pad Support Design.** The Pad Support design prevents the user from tipping over backwards by providing a downward reaction force on the user's thighs. The design also incorporates both angle-pin and lever adjustability mechanisms to account for different heights and reaches of users, respectively.

### c. Stabilization Frame Design Criteria

The stabilization frame design criteria include safety/security (30%), adjustability (25%), ease of fabrication (15%), ease of use (15%), cost (10%), and integration to environment (5%). Safety/security is the most important design criteria for the stabilization frame. The stabilization mechanism should prevent the user and wheelchair from tipping over backwards during use. Users are expected to lock the wheels of their wheelchair while utilizing the adaptive rower. While the user is completing the drive phase of the rowing motion, the support mechanism should prevent the user from being pulled forward out of the wheelchair. Adjustability accounts

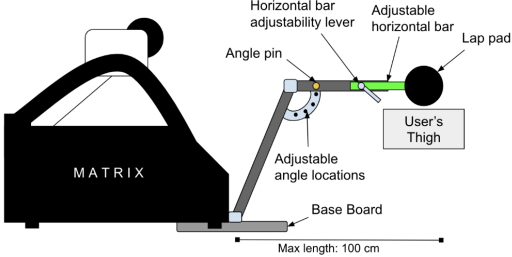
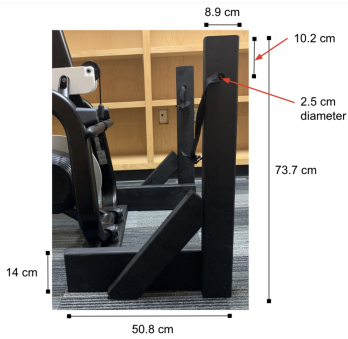
for the support mechanism's ability to accommodate different sized users and wheelchairs. The mechanism should be able to fit users with varying heights, widths, and reaches. A design that accounts for more degrees of adjustability will receive a higher score.

Ease of fabrication indicates how strenuous the fabrication process will be for a given design. Designs with less intensive fabrication methods will score higher than more complicated designs. Ease of use is determined by how easily the user can secure/detach themselves to/from the stabilization mechanism. Additionally, a design that can be adjusted with minimal effort will receive a higher score than a design that requires more effort to adjust. In terms of cost, the materials used to construct the mechanism must fall within the \$250 budget allotted for this component of the design. A design that has a lower cost will receive a higher score. Lastly, the integration to environment criteria denotes how much space the design will occupy. A design that occupies less space will receive a higher score because it will require less space in a fitness center.

#### **d. Stabilization Frame Design Matrix**

**Table 1. Design Matrix.** The design matrix compares the two support mechanism designs based on the following criteria: safety, ease of fabrication, adjustability, ease of use, cost, and integration to environment.



Design	<p style="text-align: center;"><b>Pad Support</b></p>  <p style="text-align: center;">*Note: Drawings not to scale</p>		<p style="text-align: center;"><b>Base Stabilization Frame</b></p> 	
Safety / Security (30%)	5/5	30	3/5	18
Adjustability (25%)	5/5	25	1/5	5
Ease of Fabrication (15%)	2/5	6	4/5	12
Ease of Use (15%)	4/5	12	5/5	15
Cost (10%)	3/5	6	4/5	8
Integration to Environment (5%)	5/5	5	3/5	3
<b>Total for each design:</b>	<b>84</b>		<b>61</b>	

#### e. Stabilization Frame Proposed Final Design and Design Matrix Discussion

The team compared the Pad Support design to the previous Base Stabilization Frame design using a design matrix (Table 1). The Pad Support design received the higher score of the two, with an 84/100. This design includes both pin-angle and lever adjustability mechanisms to accommodate users and wheelchairs of varying sizes. A pad at the end of the horizontal support

will rest against the user's thighs during the rowing exercise. The downward reaction force provided by the pad will prevent the user from tipping during the exercise. Additionally, the backward reaction force provided by the pad will prevent the user from being pulled forward out of the wheelchair during use.

The Pad Support design scored highest in the most heavily weighted criteria, safety/security, receiving a 5/5. This high score was awarded because the design includes a thigh pad that prevents the user from both tipping backward and falling forward out of the wheelchair. In comparison, the Base Stabilization Frame design only prevents the wheelchair from tipping backwards during use; the design does not prevent the user from falling out of the wheelchair. For this reason, the Base Stabilization Frame design received a 3/5 for the safety/security criteria.

Adjustability was the second-highest weighted criteria. The Pad Support design scored a 5/5 for adjustability for its accommodation of different heights, widths, and reaches. This design features both pin-angle and lever mechanisms to allow for vertical and reach adjustability. The Base Stabilization Frame received a lower score of 1/5 for adjustability since the frame is not able to adjust to different heights or reaches and only fits wheelchairs with widths smaller than the space between the vertical supports. Specifically, the Base Stabilization Frame could only fit wheelchairs up to 66 cm wide between the horizontal base supports. Since the Pad Support design does not have base supports, there is no width restriction.

For ease of fabrication, the Pad Support design scored a 2/5 due to the complexity involved with creating the pin-angle and lever adjustability mechanisms. The drilling of holes in the semicircular angle piece adds complexity to the fabrication of the design. Additionally, installing the horizontal bar lever mechanism will be difficult but necessary to accommodate various arm lengths. For the Base Stabilization Frame design, there are no adjustability mechanisms and therefore no added fabrication complexities associated with them. Both designs will require the use of welding to connect the support segments to one another. Since the Base Stabilization Frame design only requires the use of welding and no other complex methods, it received a higher score of 4/5 for ease of fabrication.

Both designs scored relatively high for the ease of use criteria, with the Pad Support earning a 4/5 and the Base Stabilization Frame earning a 5/5. However, the Pad Support received a slightly lower score than the Base Stabilization Frame design due to the complexity involved with using the adjustability mechanisms. The Pad Support design requires the user to change the angle-pin and lever mechanism to secure themselves to the machine. Since the Base Stabilization Frame only requires the user to attach the adjustable support straps to the front bars of the wheelchair, using this design would be slightly easier than the Pad Support design.

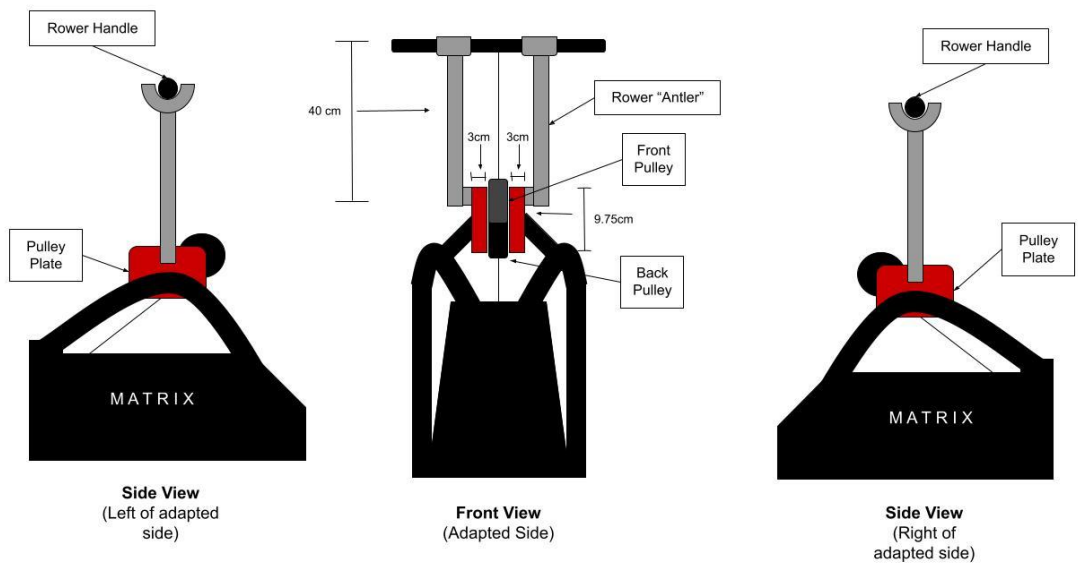
For cost, the Pad Support design received a 3/5 because of the added adjustability mechanisms. Since the Base Stabilization design does not include these mechanisms, it received a higher score of 4/5. Both designs will require the purchasing of aluminum or steel bars, which can be expensive depending on the vendor. This is why neither design received a 5/5 for cost.

The last design criteria addressed integration to environment. The Pad Support design received a 5/5 in this category since the design does not take up a large amount of floor space. When the design is not in use, the horizontal arm will be resting in the air and can be adjusted so that it is not extending far from the rower. The Base Stabilization Frame received a lower score of 3/5 for this criteria since this design occupies a larger floor space. Because this design takes up more space, there is a higher likelihood the design would need to be removed from the rower between uses, which adds complexity regarding setting up the Adaptive Rower in a congested gym floor plan.

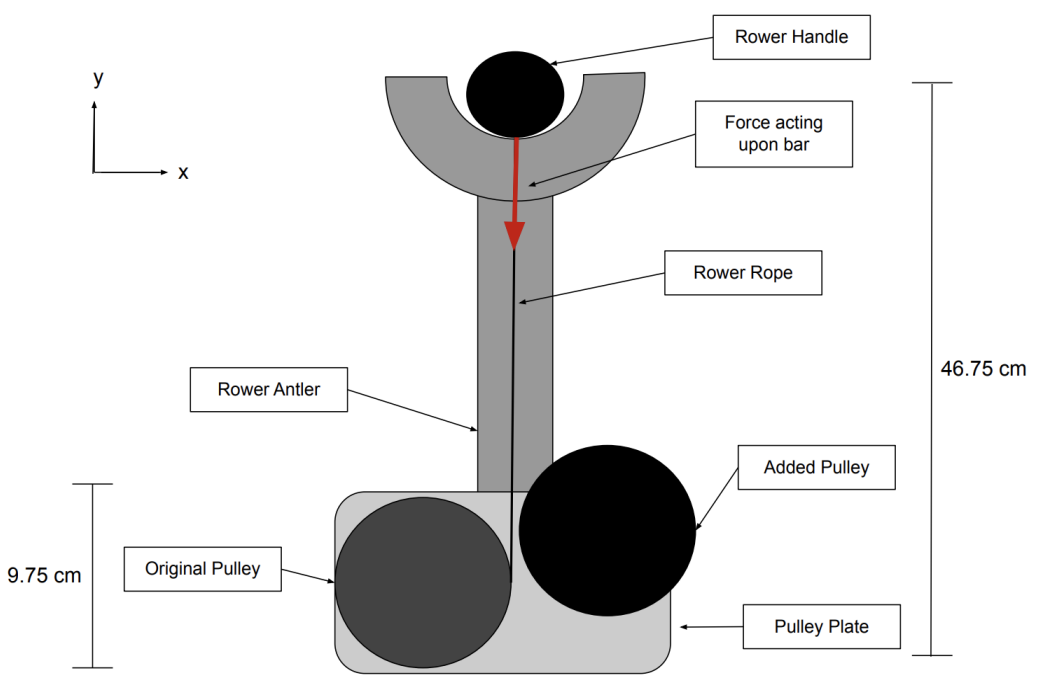
### **B. Antler Design**

The previously implemented Two Pulleys with Slit design requires the user to remove tension in the rope in order to transition the rower handle between the standard and adaptive sides of the rowing machine. This decreases the functionality of the design for wheelchair users since outside assistance will most likely be required to transition the rower handle. As a result, the antler design was created to mechanically solve the tension-removal issue present in the prior semester's design.

Similar to the Two Pulleys with Slit design, the antler design (**Figure 2**) features two pulley plates that hold an added pulley directly in line with the rower's original pulley. In this design, the rower neck will be removed, and two antler-like structures will attach to the pulley plates for the purpose of holding the rower handle when the machine is not in use. The antlers will be placed such that the rower handle is held directly between the two pulleys; thus, the only force acting on the bar will be directly downward (**Figure 3**). This design solves the tension removal issue by placing the handlebar in a more central location that only requires the user to pull up against the downward tensile force on the bar and move the rower handle toward themselves to begin the rowing motion. This transition of the rower handle between the standard and adaptive sides is more user-friendly and ergonomic. To use the rowing machine from the standard side, the handlebar would have to be taken from the antlers and placed back in its standard resting position so that users are able to reach it.



**Figure 2. Antler Design.** This design relocates the handle bar of the rower to a more central location and allows the user to row from the adaptive or standard side of the rower without needing to remove rope tension before transitioning the bar.

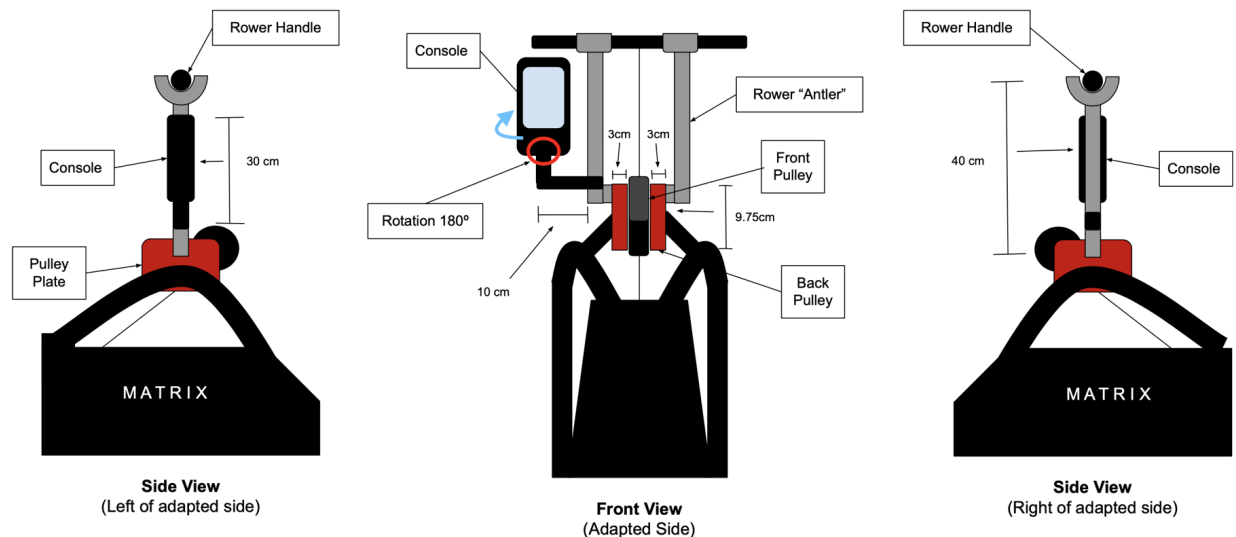


**Figure 3. Tension on Handlebar of Antler Design.** As part of the antler design, the handlebar is relocated such that it lies directly in between the two pulleys on the rower. Therefore, the net tension acting upon the bar is directly downward.

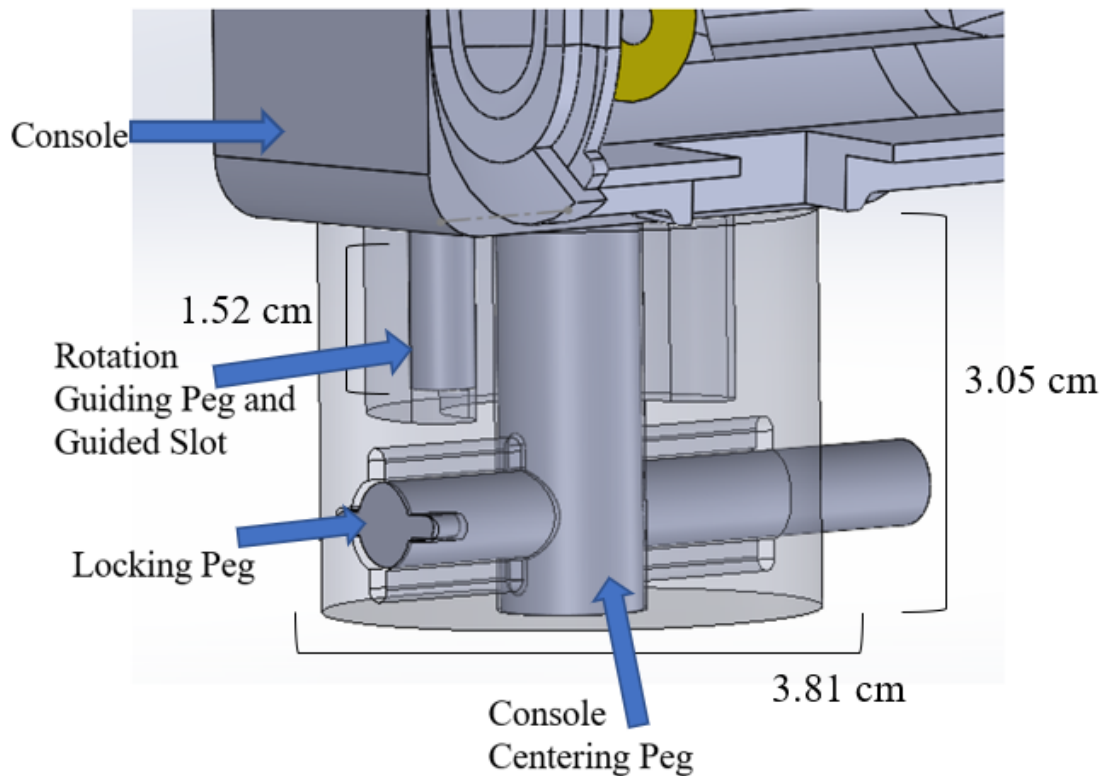
### C. Console Rotation

### a. Console Design 1: 1 Pivot Point

The 1 Pivot Point design (**Figure 4**) supports the console as an extension of the antler design. The structure attaches to an arbitrarily chosen antler with screws/bolts, such that the distance of the console from the midline of the machine is minimized. The console is secured to the structure at a pivot point that allows rotation between the standard and adaptive sides of the machine. Similar to the swivel bracket from BME 301, the pivot point incorporates a locking peg to prevent unintended movement (**Figure 5**). After removal of the peg, the user manually rotates the console within its bracket to the desired orientation. The guiding peg moves along a curved channel present on one half of the circular portion of the structure. The channel limits the rotation of the console to  $180^\circ$  and prevents the electrical wires from tangling and/or restricting rotation. When the console faces either the standard or adaptive sides of the machine, the locking peg inserts into the console centering peg. The user then rotates the locking peg by  $90^\circ$  and pushes the peg into the cross-shaped keyhole on the structure.



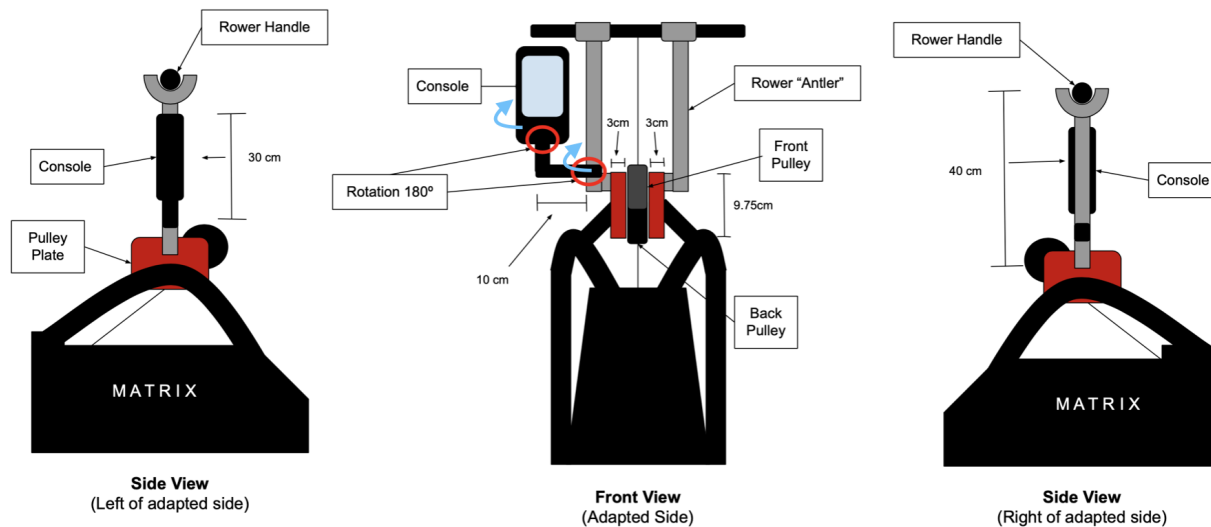
**Figure 4. Console Design 1: 1 Pivot Point.** This design secures the console to one of the antler structures. A pivot point directly below the console allows  $180^\circ$  manual rotation between the standard and adaptive sides of the machine.



**Figure 5. Updated Console Swivel Bracket with Locking Peg.** The updated console swivel bracket contains a locking peg to prevent unwanted rotation of the display. When unlocked, the display can rotate 180° to face either the standard or adaptive sides of the machine. Locking only occurs in these two positions, and not at any other point along the guided slot.

#### **b. Console Design 2: 2 Pivot Points**

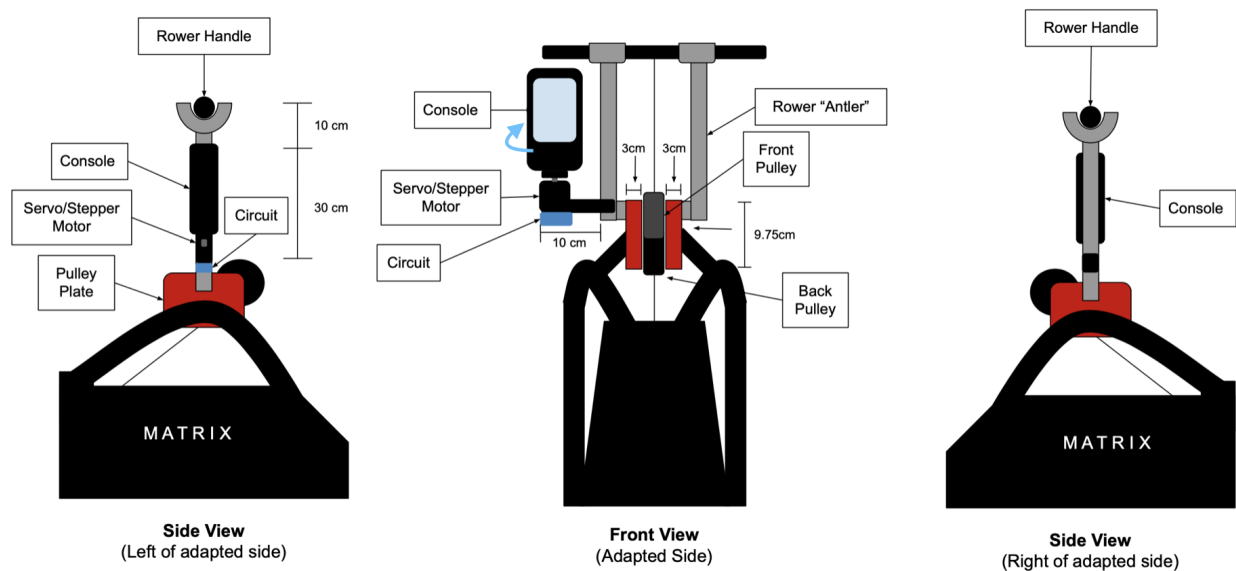
The 2 Pivot Points design (**Figure 6**) supports the console by attachment to an arbitrarily chosen antler with screws/bolts, such that the distance of the console from the midline of the machine is minimized. The design utilizes two pivot points that improve the viewability and reachability of the console. One pivot point occurs at the connection between the antler and console support. Rotation of the console about this point allows the user to move the display closer to themselves and the midline of the Matrix rower. Positioned directly below the console, the second pivot point rotates the display 180° to face either the standard or adaptive sides of the machine. Adjustment of both pivot points is accomplished with the same console swivel bracket (**Figure 5**) previously described for the 1 Pivot Point design (See **Section I.C.a**).



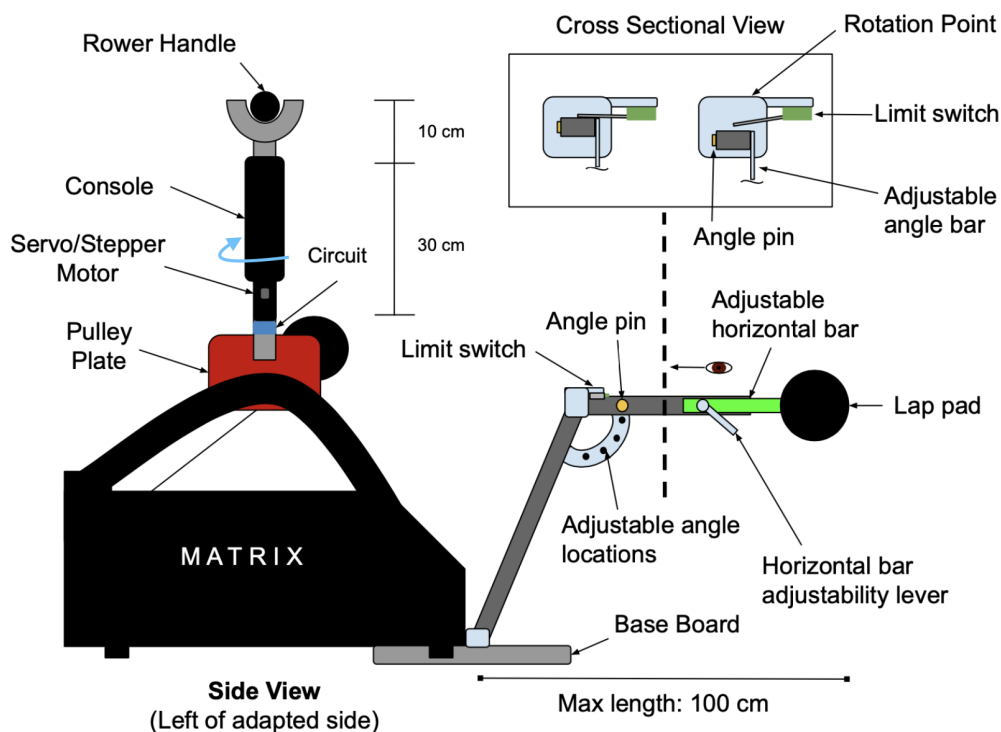
**Figure 6. Console Design 2: 2 Pivot Points.** This design secures the console to one of the antler structures. Two pivot points increase the viewability and reachability of the display. One pivot point allows the console to swing towards the user and the midline of the machine. The other pivot point allows 180° rotation of the display between the standard and adaptive sides of the machine.

### c. Console Design 3: Motor

The Motor design (**Figure 7**) attaches the console to an arbitrarily chosen antler with screws/bolts, such that the distance of the console from the midline of the machine is minimized. The console attaches to a motor that allows 180° rotation between the adaptive and standard sides of the machine. The transition from one side to the other is automated with the use of a limit switch placed above the lap bar near its pivot point (**Figure 8**). When the lap bar is all the way up in its unused position, the limit switch is depressed. As the lap bar is lowered to secure the user, the force applied to the limit switch is removed. An Arduino program controls the rotation of the console based on feedback from the limit switch. The coding flowchart in **Figure 9** illustrates the foundational logic of the design. The loop starts by checking the state of the limit switch. If it is depressed, indicating that the adaptive side is not in use, and the console is already on the standard side, nothing will happen. If the console is not already on the standard side, the motor will rotate 180°. Similarly, if the limit switch is not depressed, the code will check the position of the console and ensure that it faces the adaptive side. Therefore, the console will face the standard side of the machine by default and when a wheelchair user secures themselves with the lap bar, the console will automatically rotate to face them, and they can begin rowing. Once the workout is complete, the wheelchair user returns the lap bar to its upright position, and the console automatically rotates to the standard side.

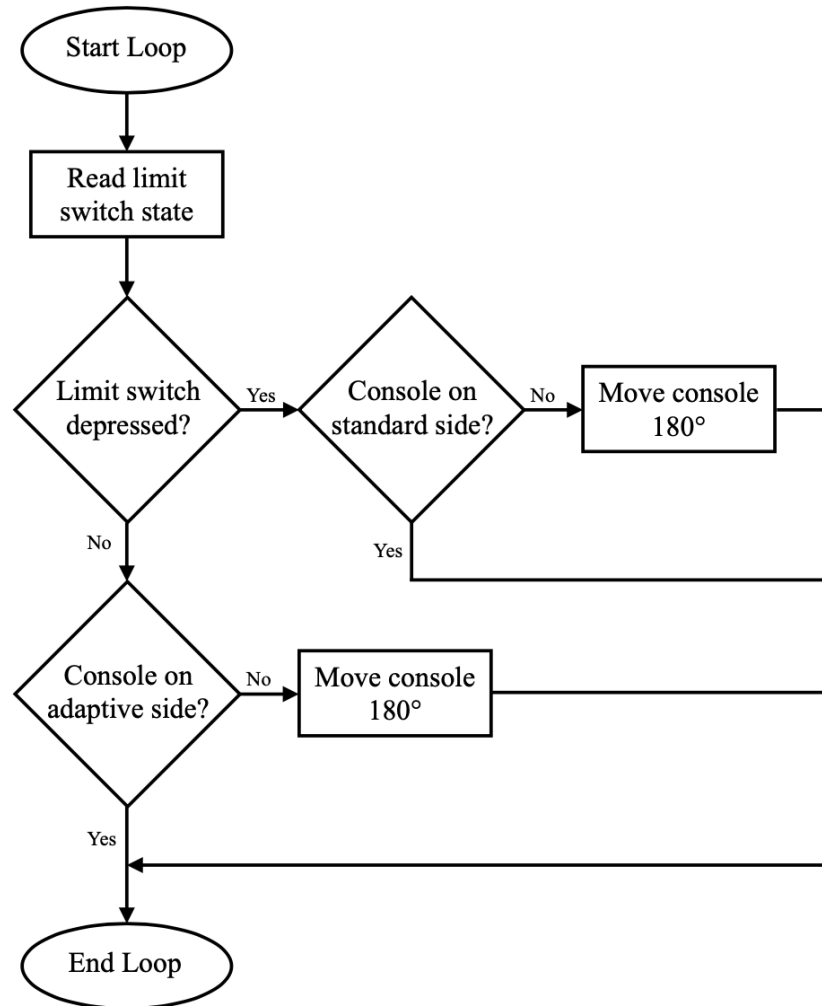


**Figure 7. Console Design 3: Motor.** This design utilizes a servo/stepper motor to electronically turn the console 180°. All circuit components, except the limit switch (not depicted), motor, and their associated wires will be stowed in a compartment (shown in blue) below the console support for safety and aesthetic purposes.



**Figure 8. Limit Switch Placement.** A limit switch placed above the lap bar near its pivot point provides feedback to the Arduino program about whether the adaptive side is in use or not. Wires (not depicted) run along the stabilization frame and Matrix rower to the electronics box near the console (shown in blue).





**Figure 9. Coding Flowchart.** The position of the console is determined by feedback from the limit switch. The console will face the standard side of the machine by default and automatically rotate to the adaptive side when a wheelchair user is secured by the stabilization frame.

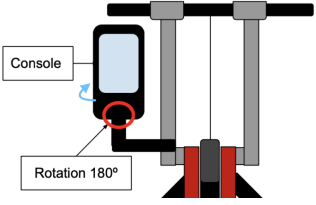
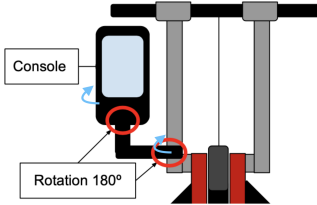
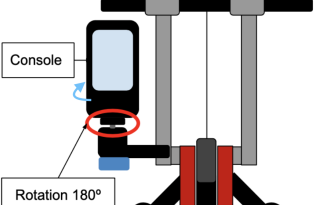
#### d. Console Rotation Design Criteria

The antler design eliminates the Matrix rower neck, which originally supported the console. Consequently, three design options were created for repositioning the console. The console rotation design criteria include ergonomics (30%), ease of rotation (20%), ease of fabrication (20%), durability (15%), safety (10%), and cost (5%). Ergonomics was chosen as the most important design criteria. The console display should be easily accessible for individuals in a wheelchair, and not require outside assistance for proper use. While using the rowing machine from either the standard or adaptive side, the user should be comfortable accessing and viewing the console. The console should be positioned as close to the midline of the rowing machine as possible. In other words, the design should minimize the angle at which the user must turn their head to view the console. Designs with smaller displacements from the midline will receive a higher score. The user should not have to alter their rowing form in order to easily view the display.

Ease of rotation is the ability of the display console mechanism to easily change between the adaptive and standard states. The rotation mechanism should minimize the complexity of transitioning between states. Ease of fabrication evaluates the effort required to build/manufacture a particular design. Options with a greater ease of fabrication will score higher than more complicated designs. All components of the design should be readily available for purchase. As for durability, the console swivel design can accumulate general wear and tear, but must be operational for the lifetime of the rowing machine: ten years or 8 million meters. The design must withstand extreme loads placed on the rotation mechanism/structure. In terms of safety, electrical or mechanical malfunctions should not pose significant health risk to the user or compromise the original rowing machine's integrity. Lastly, the total cost for the antler design and console must remain within the \$250 of the \$500 budget allotted for this component of the design. A design that is more cost-effective will receive a higher score.

### e. Console Rotation Design Matrix

**Table 2. Design Matrix.** The design matrix compares three designs for the evaluation of the rotation mechanism of the display console.

Design	Design 1: 1 Pivot Point		Design 2: 2 Pivot Points		Design 3: Motor	
						
Ergonomics (30%)	4/5	24	5/5	30	4/5	24
Ease of Rotation (20%)	3/5	12	2/5	8	5/5	20
Ease of Fabrication (20%)	5/5	20	4/5	16	4/5	16
Durability (15%)	4/5	12	3/5	9	5/5	15
Safety (10%)	5/5	10	4/5	8	3/5	6
Cost (5%)	5/5	5	5/5	5	4/5	4
<b>Total for each design:</b>	<b>83</b>		<b>76</b>		<b>85</b>	

### f. Console Rotation Design Matrix Discussion and Proposed Final Design

Three designs were compared for the console rotational mechanism: 1 Pivot Point, 2 Pivot Points, and Motor using a design matrix (Table 2). Although the 1 Pivot Point and Motor

designs scored similarly, the desired design to proceed forward with was the Motor design. This design incorporates a stepper/servo motor on which the console will rest. The motor automatically rotates the console 180° between the standard and adaptive sides of the machine based on feedback from a limit switch.

The 2 Pivot Points design scored the highest in ergonomics with a 5/5, and the 1 Pivot Point and Motor designs received a slightly lower score of 4/5. The second pivot point allows the user to bring the console closer to the midline of the rowing machine, as well as closer to the user in general. It minimizes the angle at which the user must turn their head to view the display and decreases the distance the user must reach to use the console. Therefore, the 2 Pivot Points Design is the most viewable and reachable option and the least likely to alter a user's rowing form. Both the 1 Pivot Point and Motor designs do not incorporate the second pivot point and cannot move closer to the user or the midline of the rowing machine. Consequently, they received the same score. While these designs are limited by the single pivot point, the distance of the console from the midline of the machine will still be minimized. For this reason, the designs received a relatively high scoring of 4/5.

Ease of rotation describes the amount of effort by the user to transition the console from the standard to the adaptive side and vice versa. The Motor design scored 5/5 in this category because the console rotation is automatic. The 1 Pivot Point and 2 Pivot Points designs scored significantly lower because the user must manually rotate the console. Both designs secure the console with a pin mechanism after rotation. The 1 Pivot Point design has one point at which the user must adjust the device, whereas the 2 Pivot Points design has two pivots that require user adjustment. The ease of rotation declines with the addition of each new pivot point, and that is reflected in the scoring; the 1 Pivot Point design scored 3/5 and the 2 Pivot Points design scored 2/5 in ease of rotation.

For Ease of Fabrication, the 1 Pivot Point design scored the highest at 5/5. Since it only requires one point of rotation, as compared to two points of rotation, its fabrication process will inherently be easier than two pivots. This design is attached to the antler and incorporates the updated console swivel bracket for rotation. The 2 Pivot Points and Motor designs each received a score of 4/5 because their fabrication processes would be slightly more complex than the 1 Pivot Point design. The 2 Pivot Points design requires the addition of a second rotational mechanism at the location where the structure attaches to the antler, which requires a more robust fabrication process to ensure that location is strong and able to rotate freely. The Motor design requires the fabrication of an electronic circuit and code, as well as development of a safe housing compartment for all the electrical components. However, both of these fabrication processes are still feasible, which is why each received a 4/5.

In terms of durability, the Motor design received the highest score of 5/5. This design includes an electronic circuit, a motor, and a housing chamber for the electronics. These components do not have any freedom to move, and thus can be developed as part of the rigid arm that attaches to the antler. Due to the lack of movement, and the strength of the motor, this design utilizes the most durable components. The 1 Pivot Point design scored a 4/5 and the 2 Pivot Points design scored a 3/5 because of the mechanical points of rotation, which are more susceptible to wear and tear. The rigid arm attaching to the antler is similar to that of the arm in the Motor design, but the mechanical rotation mechanism for each is a weakness in the design that may wear quickly or break under improper loading. The 2 Pivot Points design scored lowest because it has two weak points while the 1 Pivot Point design has one.

Although no design poses significant risk to the user, the Motor design scored the lowest (3/5) in safety due to the addition of electrical components (i.e., the motor and accompanying circuitry) that could potentially put the user at risk (i.e., electrocution or fire hazards). The 2 Pivot Points and 1 Pivot Point designs are comparable in regard to safety because they share the same mechanical mechanisms and lack electrical components. However, the 2 Pivot Points design has an extra point of rotation about the base of the antler, increasing the risk of pinching the user's extremities. Therefore, the 2 Pivot Points and 1 Pivot Point designs scored 4/5 and 5/5 in safety, respectively.

Finally, the team compared the cost of the three design ideas. None of the preliminary designs are expected to exceed the \$200 limit given for this portion of the design project; however, some designs are more cost-effective than others. The 1 Pivot Point and 2 Pivot Points designs only differ in the number of rotation points for the console. The fabrication costs would be almost identical for both designs due to the similarity in the quantity and types of materials needed for fabrication. The Motor design, however, will be more expensive due to the addition of a motor, Arduino, battery, limit switch, and other circuit components. Accordingly, the 1 Pivot Point and 2 Pivot Points designs both scored 5/5, whereas the Motor design received a 4/5. Overall, the Motor design most closely adheres to the design criteria outlined in the design matrix and scored the highest at 85/100. Thus, it is the best option for rotating the console between the standard and adaptive sides of the machine.

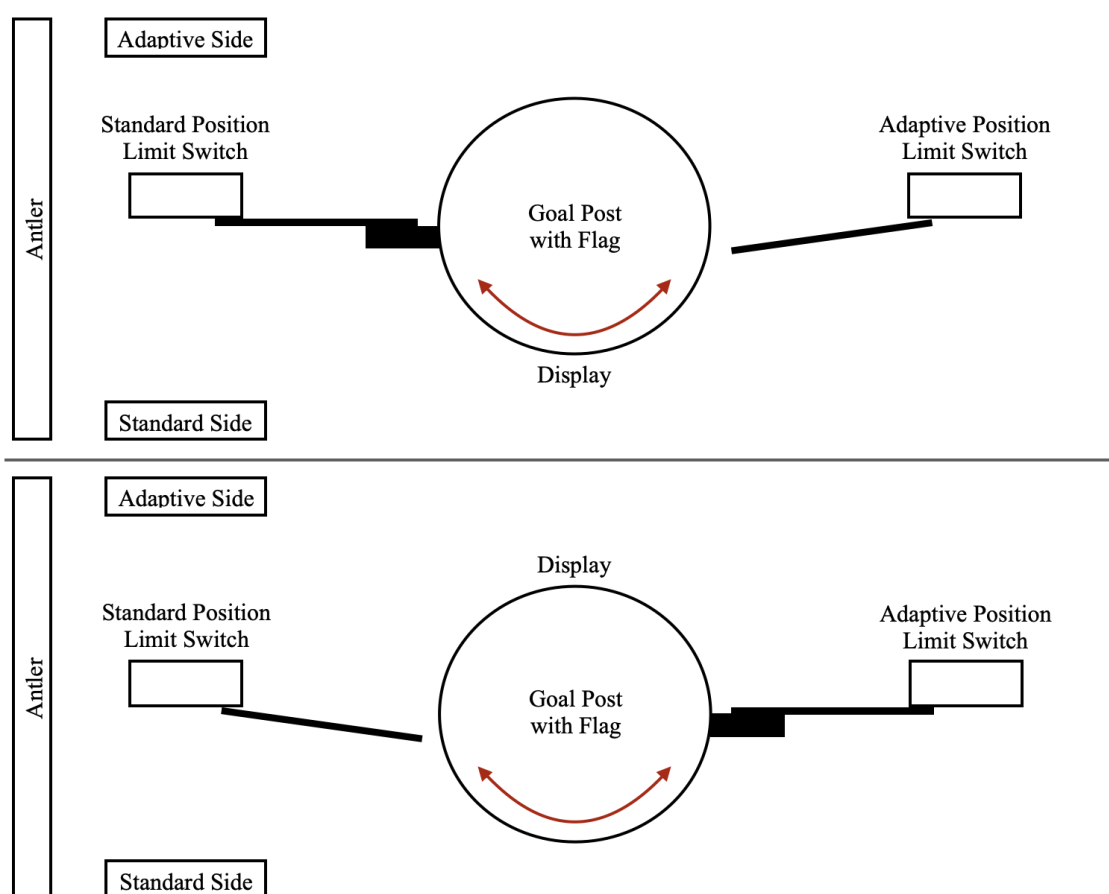
## **Appendix G: BME 400 Final Design & Fabrication**

### **I. Final Design Fabrication**

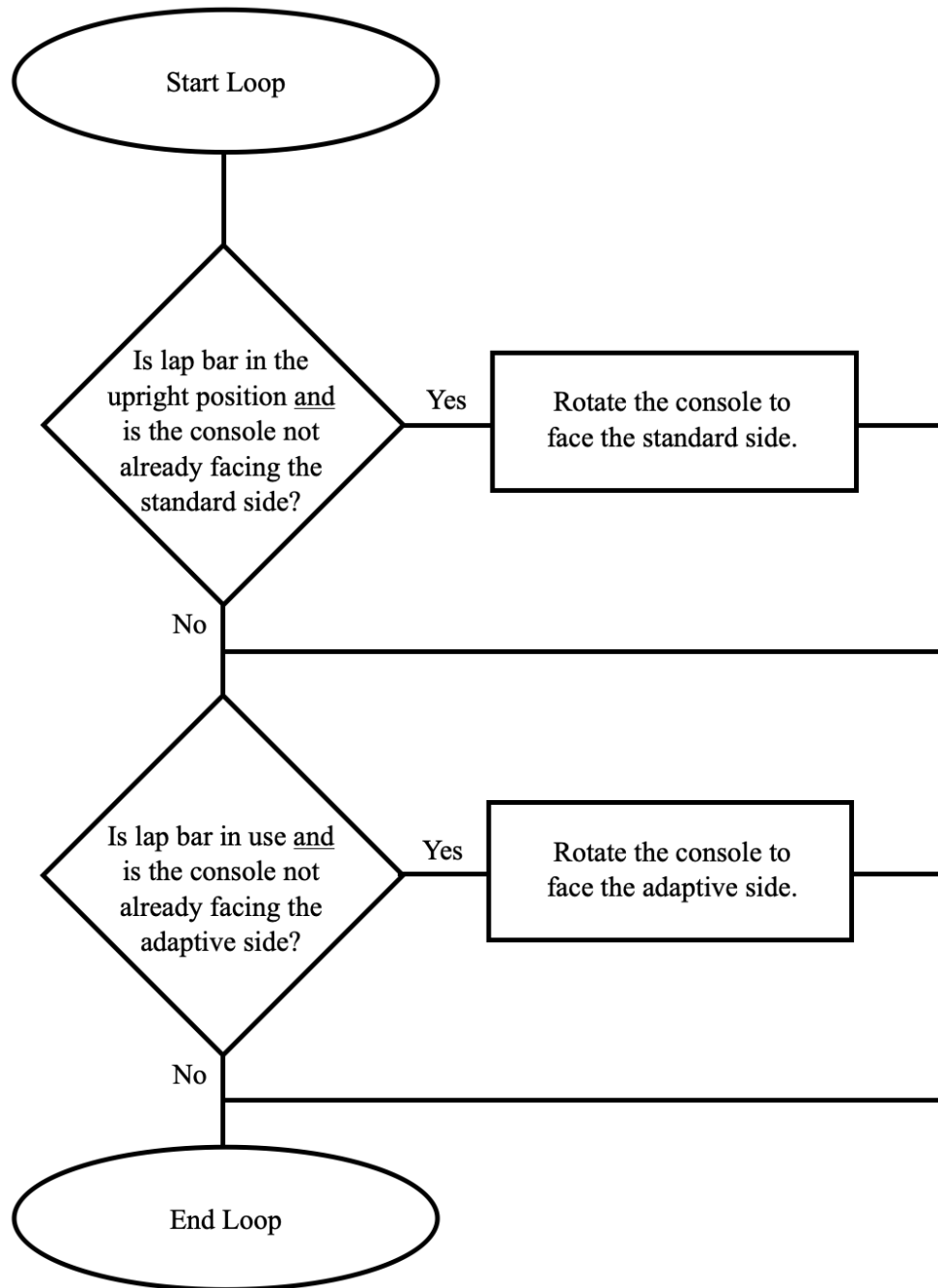
#### **A. Console Rotation**

Last semester, the console was located at the top of the original Matrix rower neck. 3D printed goalposts with a manual pin adjustment allowed the user to rotate the console from one side of the machine to the other. With the removal of the rower neck this semester, the console was repositioned to a point adjacent to one of the antlers. Furthermore, the rotation of the console

between the standard and adaptive sides of the machine was automated with the use of a stepper motor. The transition from one side to the other relies on feedback from a normally open (NO) limit switch placed directly behind the lap bar (on the side with the rower) near its pivot point. Two more NO limit switches placed near the base of the console provide feedback about the orientation of the display (**Figure 1**). If the lap bar is raised, then the adaptive side is not in use and the console should face the standard side. The console will rotate toward the standard side until the standard position limit switch is depressed if the console is not already in the correct orientation. Similarly, if the lap bar is lowered, then the adaptive side is in use and the console should face the wheelchair user. The console will automatically rotate toward the adaptive side until the adaptive position limit switch is depressed if the console is not already in the correct orientation. **Figure 2** illustrates this logic in a coding flowchart.



**Figure 1. Standard and Adaptive Position Limit Switch Placement.** Two limit switches are placed at 180 degrees from each other such that they create stop blocks for rotation between the standard and adaptive sides of the machine. In the top image, the flag on the goal post depresses the standard position limit switch, indicating that the display faces the standard side of the machine. In the bottom image, the flag depresses the adaptive position limit switch, indicating that the display faces the wheelchair user. The console rotates 180 degrees between these two limit switches and does not complete a full 360-degree rotation to avoid tangling the electrical wires leading to the console.

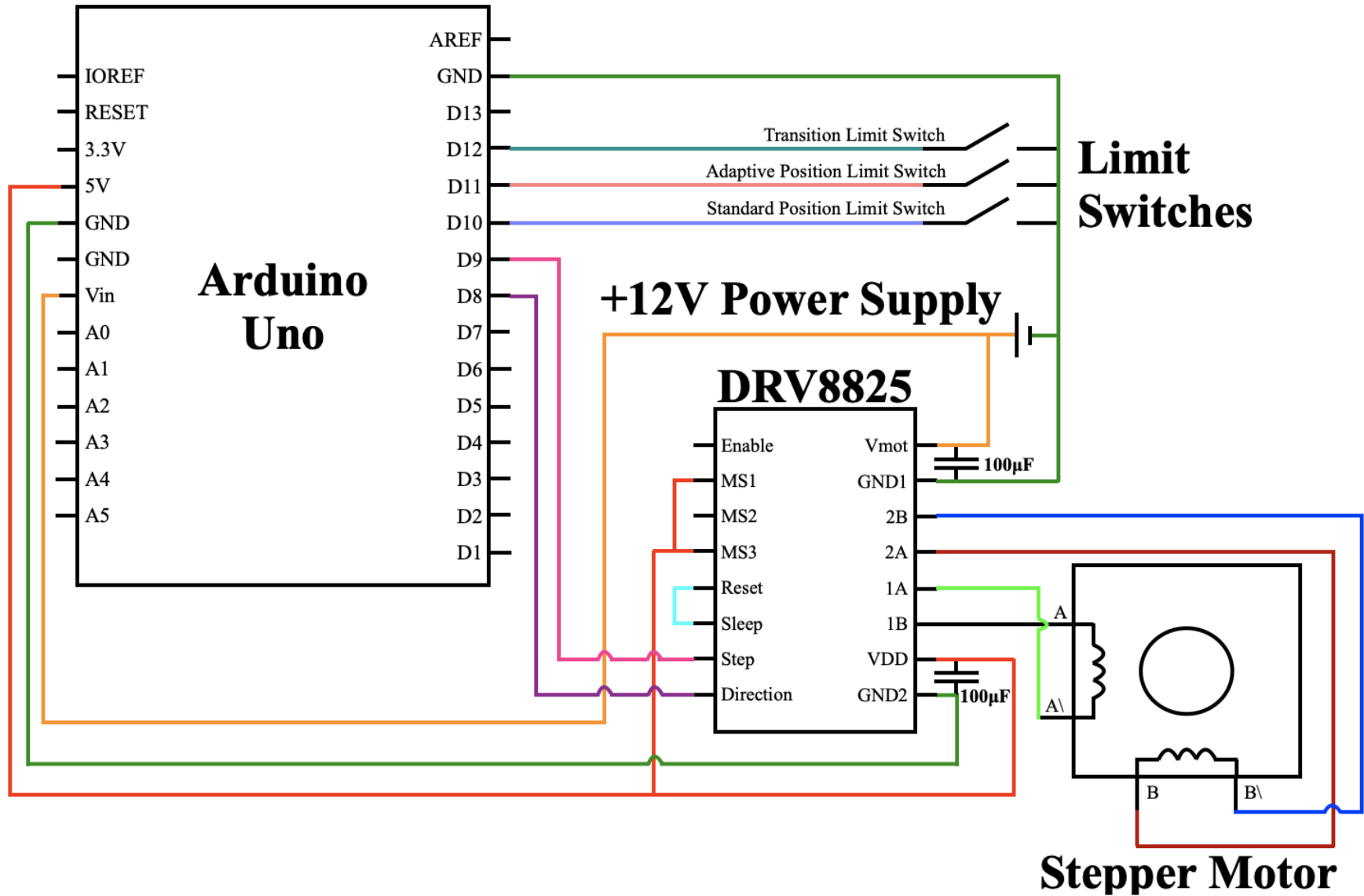


**Figure 2. Final Coding Flowchart.** Each loop iteration, the code checks the position of the console and compares it to its expected location according to the state of the transition limit switch placed near the pivot point of the lap bar. If the lap bar is upright and the console is not already facing the standard side, then the console will rotate to face the standard side. Similarly, if the lap bar is in use and the console is not already facing the adaptive side, then the console will rotate to face the adaptive side. The loop continuously repeats these checks to ensure the console faces the current user.

The circuit required to complete the automatic rotation includes the following components: an Arduino Uno [17], DRV8825 [18], NEMA17 stepper motor [19], +12V power

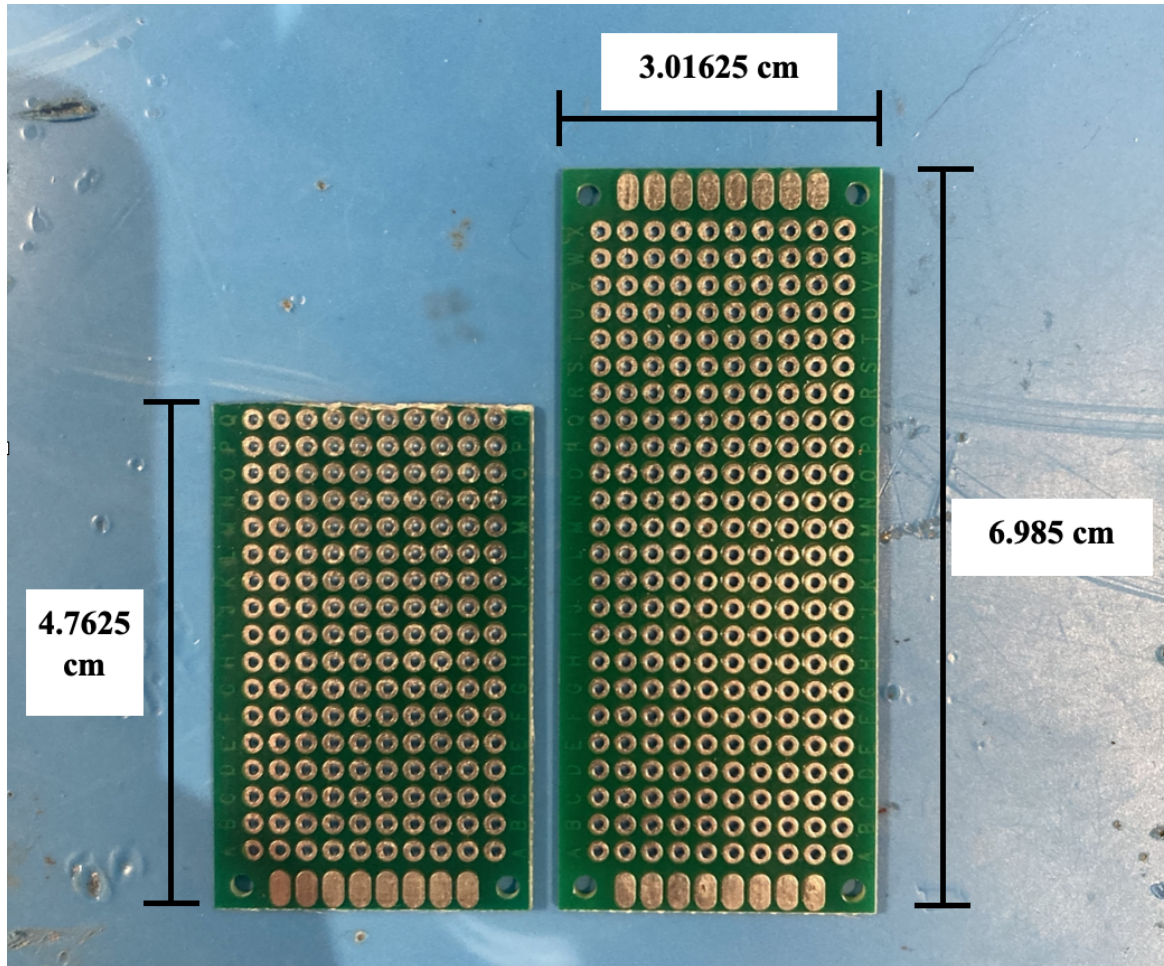
supply [20], two 100  $\mu$ Farad capacitors, and three NO limit switches. The final design schematic (**Figure 3**) illustrates the connections between each component. The Arduino Uno contains the code that receives feedback from the NO limit switches and rotates the NEMA17 stepper motor accordingly. The DRV8825 is a motor driver that interfaces between the NEMA17 stepper motor and Arduino. The state of the DIR pin on the DRV8825 determines which direction (i.e., clockwise or counterclockwise) the motor will rotate while the STEP pin controls the stepping motion of the motor. By setting the MS1 and MS3 pins to high (+5V), the microstep resolution is set at 1/32 steps [21], [22]. The SLEEP and RESET pins on the DRV8825 must be tied for the motor driver to operate [21]. The +12V power supply provides power to the stepper motor and Arduino Uno, and the +5V power supply for the DRV8825 is supplied by the +5V pin on the Arduino Uno. The two 100  $\mu$ Farad capacitors (sourced from the BME 400 storage closet) placed over the power supplies act as decoupling electrolytic capacitors that prevent sudden changes in voltage and protect the DRV8825 from damage [21].





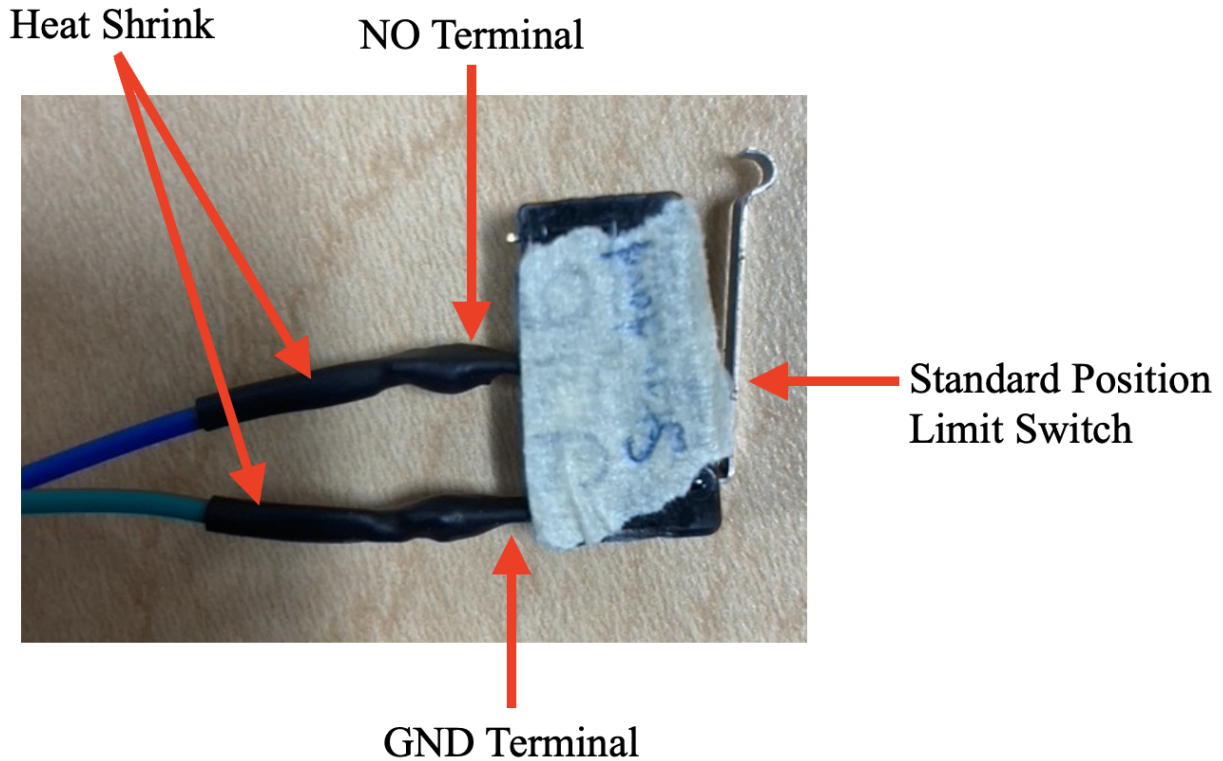
**Figure 3. Final Circuit Schematic.** The final circuit consists of an Arduino Uno, DRV8825, NEMA17 stepper motor, +12V power supply, two 100 µF capacitors, and three NO limit switches. The colored lines represent the wire connections present between each physical component.

After troubleshooting and conducting preliminary testing on a temporary circuit built using a breadboard, the final circuit was constructed. A solder board sourced from the BME 400 storage room was cut from 6.985 cm x 3.01625 cm down to roughly 4.7625 cm x 3.01625 cm using a bandsaw (**Figure 4**). The new dimensions allowed the solder board to fit within the electronics box.



**Figure 4. Solder Board.** The solder board was sourced from the BME 400 storage closet. To fit within the electronics box, its length was cut down to 4.7625 cm from 6.985 cm.

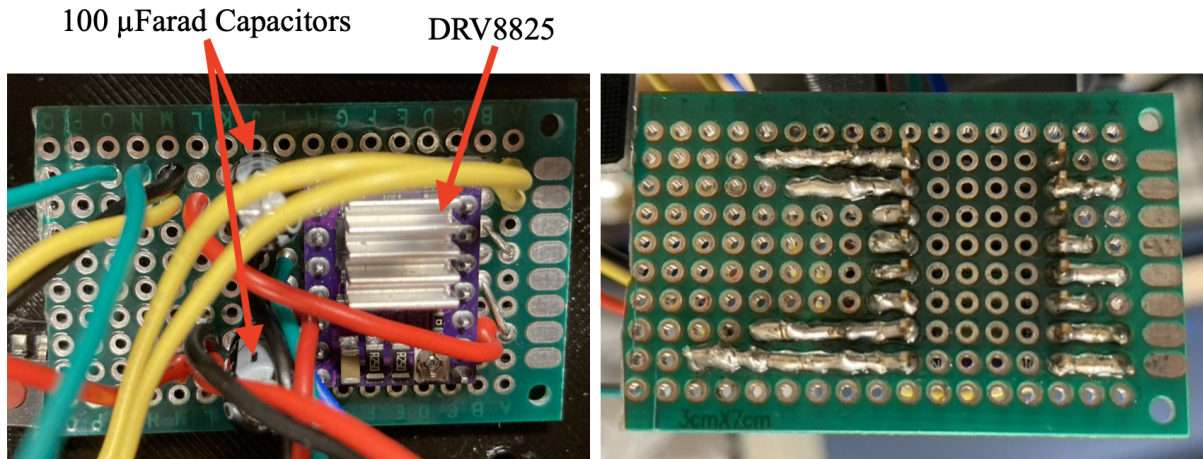
Next, two wires of approximately 20.32 cm in length were soldered to the standard position limit switch. The ground (GND) wire was connected to the terminal labeled "C" and the digital pin wire was connected to the terminal labeled "NO". The exposed metal was covered with heat shrink. **Figure 5** shows the connections to the standard position limits switch. The same process was executed for the adaptive position limit switch. Then, two wires of approximately 91.44 cm were soldered to the transition limit switch that goes to the lap bar on the stabilization frame. The GND wire was connected to the terminal labeled "C" and the digital pin wire was connected to the terminal labeled "NO". The exposed metal was covered with heat shrink.



**Figure 5. Standard Position Limit Switch Connections.** Two wires of approximately 20.32 cm in length are soldered to the standard position limit switch. The green wire (GND) is connected to the terminal labeled with “C” while the blue wire (D10) is connected to the terminal labeled with “NO”. These connections can be extrapolated to the adaptive position limit switch and transition limit switch.

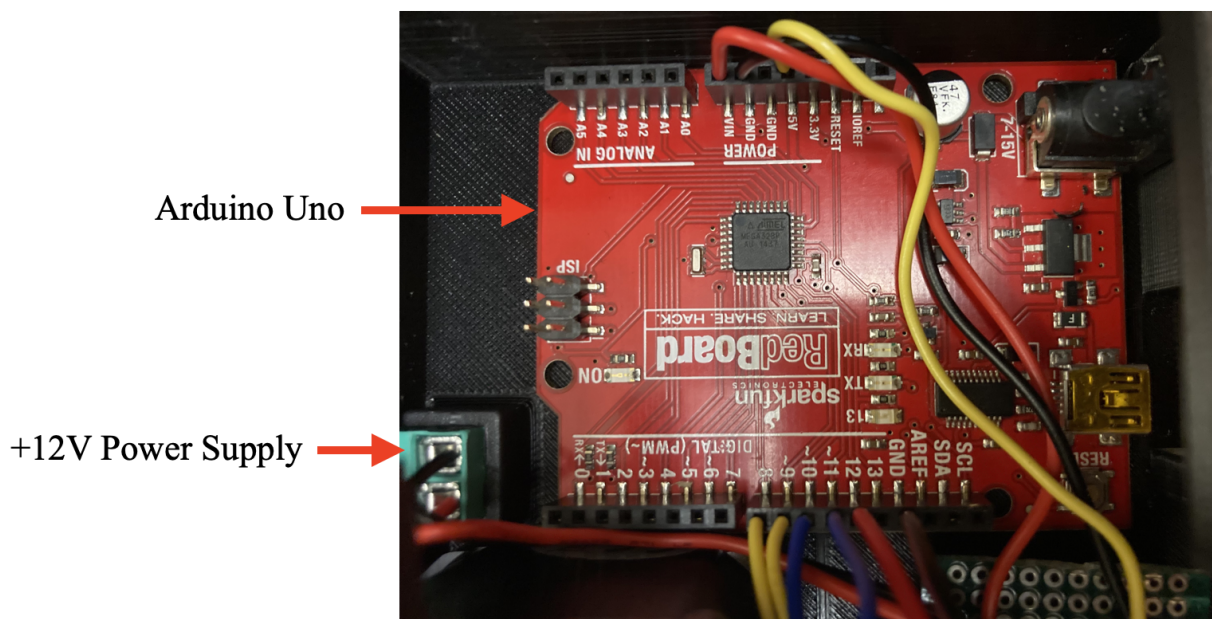
The solder board was populated with the DRV8225 and two 100  $\mu$ Farad capacitors. After cutting the stepper motor wires to approximately 0.394 cm in length, they were soldered to the board using the pin designations from the final circuit schematic (**Figure 3**). The ground wires from the standard and adaptive position limit switches were also soldered to a common ground in the board. The transition limit switch GND was not soldered to the board this semester but will be soldered next semester after the final length of the wires running from the lap bar to the electronics box are determined. Instead, this GND connection was plugged directly into the Arduino GND. The remaining connections to the power sources were soldered to the board. On the back side of the board, the appropriate rows were soldered together to create the connections defined by the final circuit schematic (**Figure 3**). **Figure 6** shows the top and bottom face of the solder board.





**Figure 6. Solder board.** The image on the left shows the top face of the solder board populated with the DRV8825, two 100  $\mu$ Farad capacitors, and wire connections. The image on the right shows the bottom face of the solder board with the ties for each row of connections.

The remaining connections from the solder board (digital pin connections D8, D9; ground; Vin; and +5V) and limit switches (digital pin connections D10, D11, D12) were plugged into the Arduino Uno. The GND and Vin wires from the solder board were also screwed into the terminals on the +12V power supply connector. **Figure 7** illustrates these connections according to the final circuit schematic (**Figure 3**).



**Figure 7. Arduino Uno and +12V Power Supply Connections.** This image shows the wires connecting to the Arduino Uno and +12V power supply.

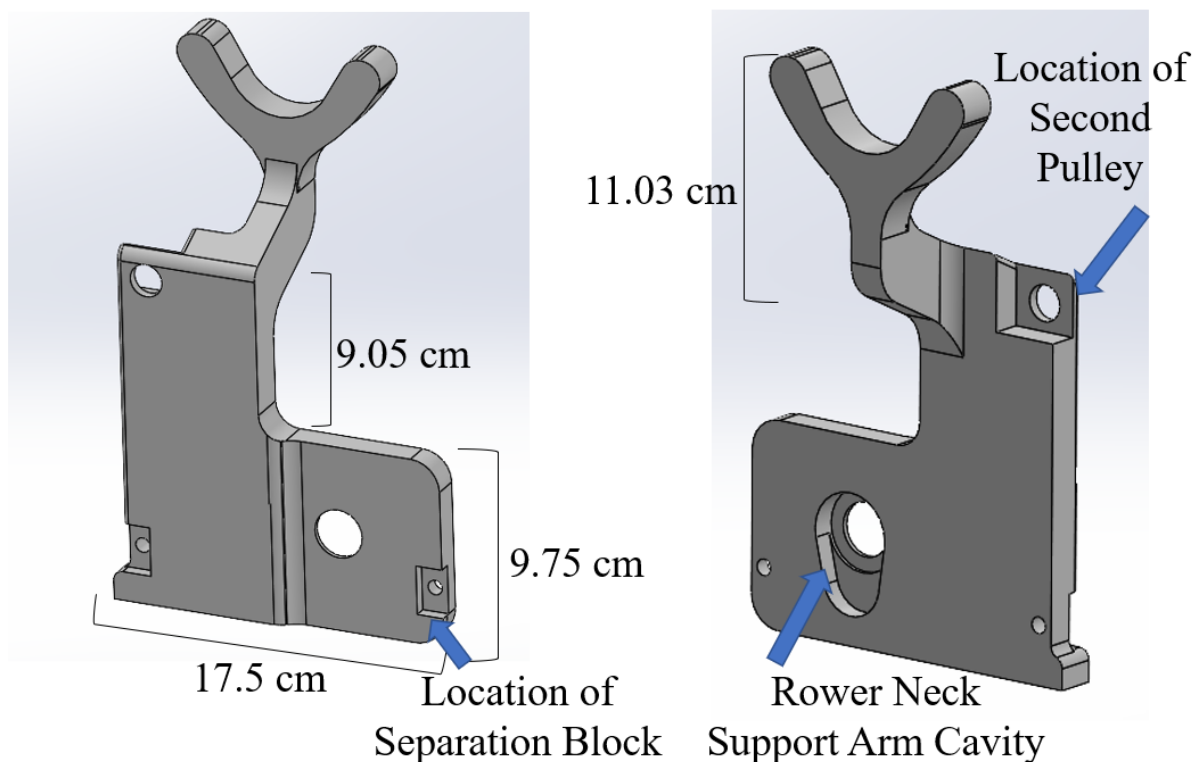
At this point, the final code was uploaded to the Arduino Uno. Within the void loop(), the code checks the state of the transition limit switch and the orientation of the console based on feedback from the three NO limit switches. If the console is not in the correct orientation, the void loop() will call either the rotateToStandard() or rotateToAdaptive() functions to rotate the console to the correct side so that the display faces the user. The speed of rotation is altered manually with the use of pulse width modulation (PWM). After uploading the code to the Arduino Uno and supplying the circuit with power using the +12V power supply, the current potentiometer on the DRV8825 was adjusted with a screwdriver such that the current was enough to rotate the motor but as low as possible to limit noise and vibration.

### **B. SolidWorks**

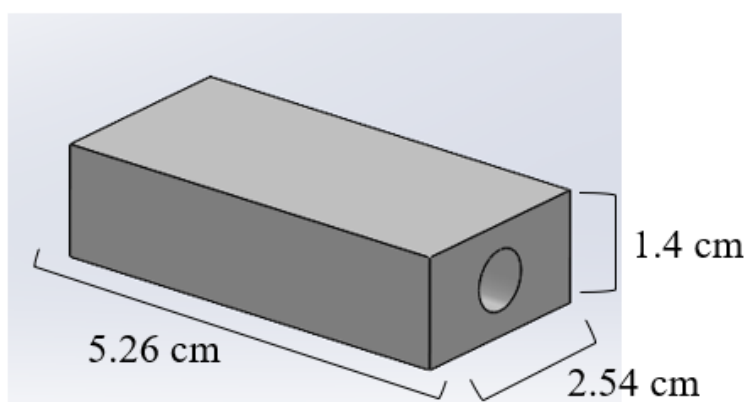
The pulley support plates and antlers (**Figure 8**) are used to stabilize the second pulley that is added to the design to allow for rowing from the adaptive side. The sole purpose of these plates is to hold the additional pulley in place under normal loads experienced during typical rowing motions. Each plate has a layered cavity that allows it to slip onto the outside surface of the two metal support arms that previously connected to the rower neck (the neck is now removed from the current design). Since these support arms are metal and welded to the bottom frame of the rowing machine, the cavities in the plates were designed to remain fixed around these support arms in order to keep the additional pulley stationary. Each pulley plate also has a circular cavity that fits around the rotational bearing of the additional pulley. This allows the plates to replace the two washers that were previously on the pulley and fit tightly onto the bearing to prevent any unwanted motion of the pulley. Compared to the previous semester's pulley plates, the pulley itself is now raised 9 cm higher than before to accommodate the inclusion of the updated stabilization frame. This is because the stabilization frame extends above the original placement of the second pulley and would impede the ability to row from the adaptive side. Each plate is held rigidly in place by the tight fit around the two metal support arms on the rower. Furthermore, a stabilization block is screwed in between the two pulley plates on the standard side of the rower, which offers an outward reaction force to help prohibit the plates from slipping inward off the rower neck support arms (**Figure 9**).

The new pulley plate design also includes an antler on each plate (**Figure 8**). The purpose of each antler is to hold the rower handlebar directly between the two pulleys in such a way that the rope is perpendicular to the ground and thus does not apply any force on either pulley until rowing begins. Additionally, by placing the antlers in this location, the handlebar can be easily reached from either the standard or adaptive side of the rower. This design change eliminates the need for external assistance to transition the handlebar from the adaptive side while retaining the ability to still comfortably grab the handlebar from the standard side. The antlers extend 17.2 cm above the top surface of each plate and in an attempt to place the handlebar high enough to not hit the other components of the design, such as the console hitting the antlers. Currently, the console does slightly contact the antlers and this issue will be addressed by increasing the antler height. The right and left pulley plates with antlers are exact mirror images. Each plate was

designed in SolidWorks and 3D printed out of Tough PLA because of its high elastic modulus and yield strength. Additionally, a layer height of 0.2 mm and a 100% infill were used during printing to reduce the printing time and increase the strength of the plates, respectively.



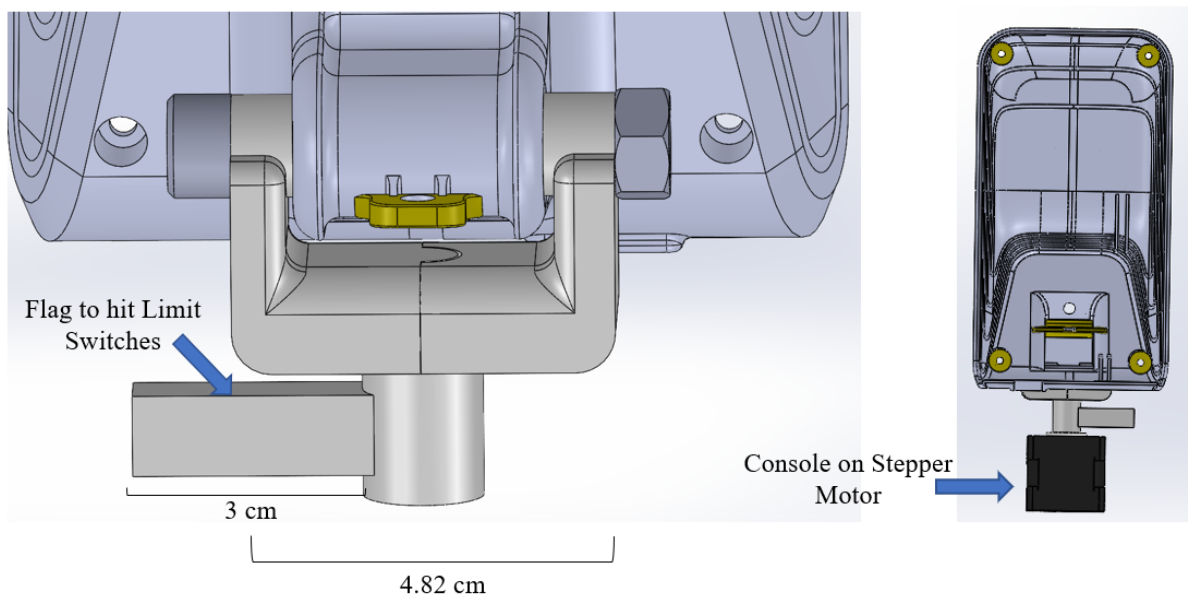
**Figure 8. Pulley Support Plates with Antlers.** The left and right pulley support plates are mirror images and fit tightly around the pulley bearing with a cavity that fits around the metal support arms for the rower neck. The antler extending upward on each plate holds the handlebar in a neutral location which allows it to be easily reachable from both the standard and adaptive sides of the rower.



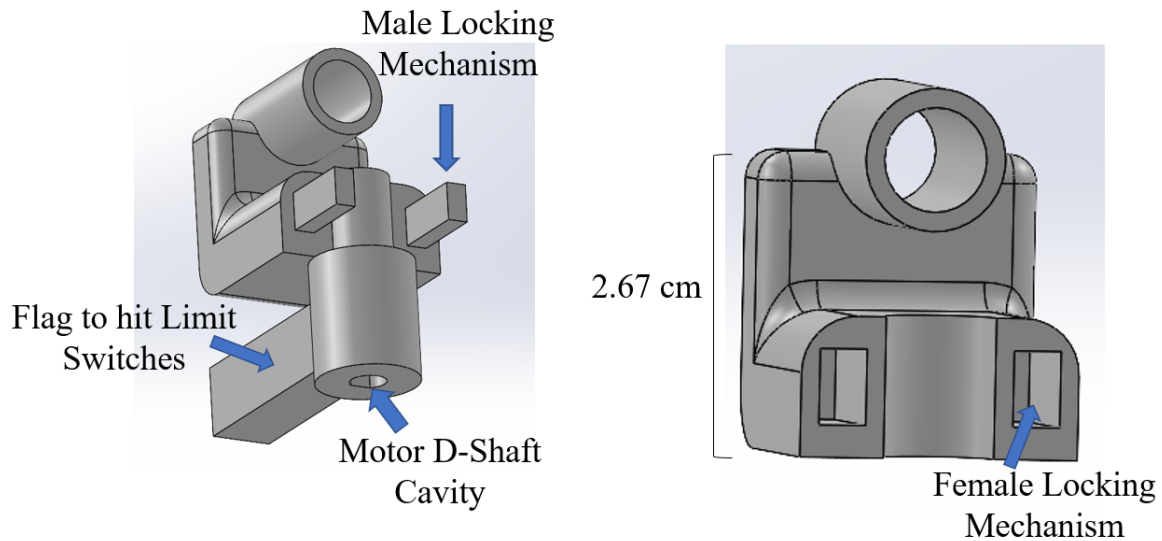
**Figure 9. Pulley Support Plates Back Separation Block.** The back separation block is inserted between the two pulley plates on the standard side of the rower to offer an outward reaction force that prevents the plates from slipping off the rower neck support arms inward.

The console field goal posts are used to allow the console to rotate 180° so that it is visible from both the standard and adapted sides. Each of the field goal post components have a

cylindrical tube that replaces the metal cylindrical tubes in the back of the console (**Figure 10**). This allows the user to adjust the angle of the console. The male field goal post has two extruded rectangle inserts that fit into cavities on the female field goal post. These act as a locking mechanism that secures the pieces tightly together to prevent the console from becoming loose and slipping off. Additionally, the male field goal post has a large peg that extends downward. This large peg has a cavity cut out in the shape of the motor D-shaft, which allows for this piece to be press fit onto the stepper motor (**Figure 11**). This will stabilize the console on the motor as it rotates. The female field goal post has a semicircular cavity that accepts half of that peg so that the two field goal posts sit flush together. The male and female components can be seen in **Figure 11**. The male field goal post also includes a rectangular prism flag that extends directly off to the side. This flag contacts the limit switches to tell the motor when to stop rotating in a given direction. Similar to the previous parts, each of these three components were printed out of Tough PLA due to its high elastic modulus and yield strength. Additionally, a layer height of 0.2 mm and a 100% infill were used during printing to reduce the printing time and increase the strength of the assembly, respectively.



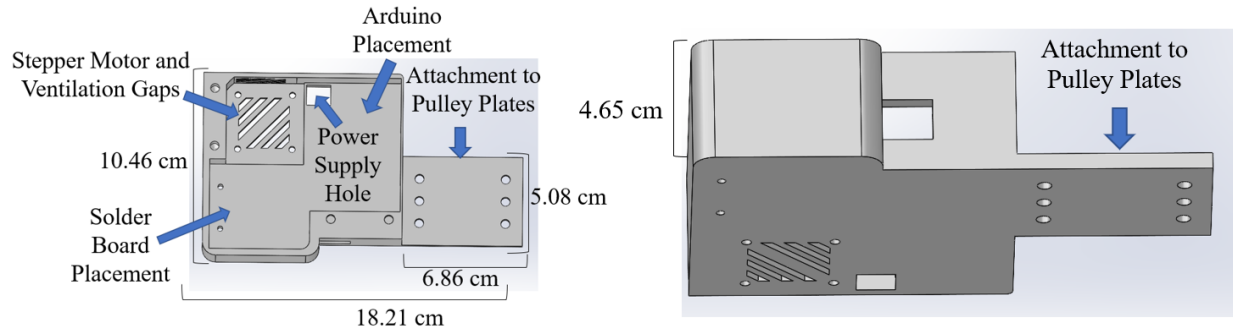
**Figure 10. Field Goal Posts Allow Console Angle Adjustment.** The field goal posts have cylindrical components that insert into the back of the display console to permit rotation about its original axis (left). This allows the user to adjust the angle at which the console is bent. The full console-field goal post assembly is shown attached to the stepper motor (right).



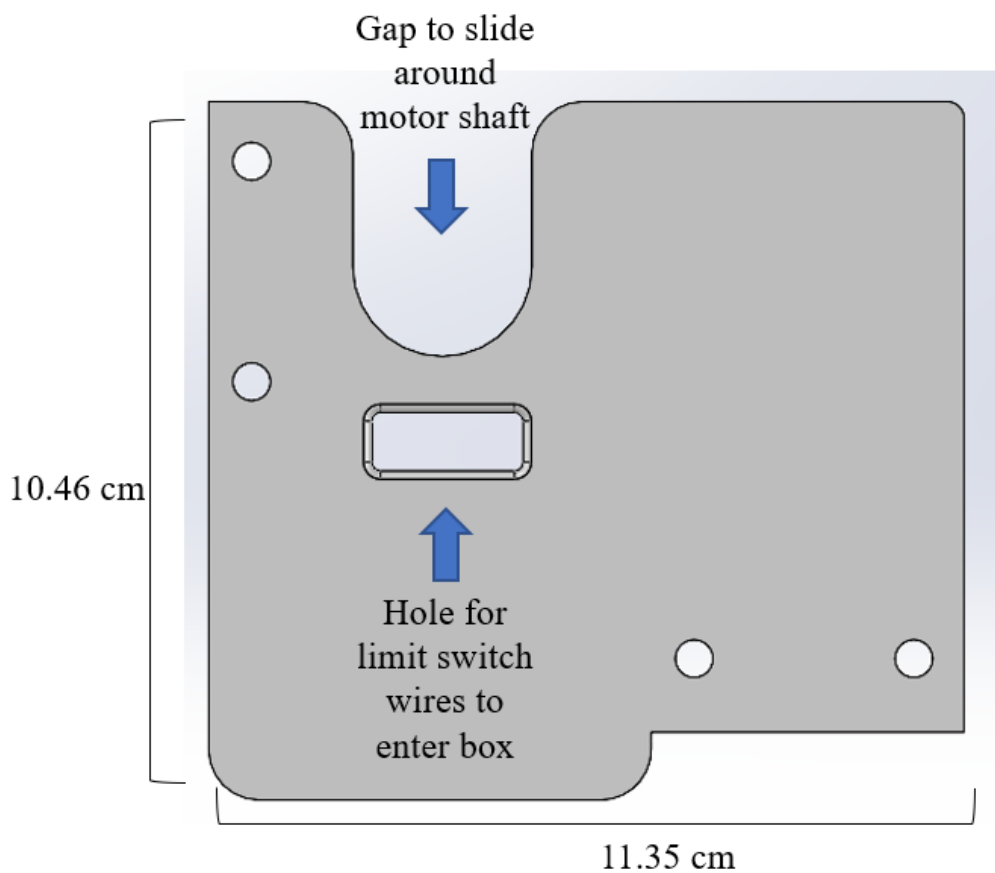
**Figure 11. Female and Male Field Goal Posts.** The male (left) and female (right) field goal posts fit together via extending inserts on the male piece that fit into corresponding cavities on the female piece. The male piece has a large central peg which press-fits onto the stepper motor's D-shaft and a flag to contact the limit switches.

The electronics box is used to store and secure the electrical design components that allow the console to rotate (**Figure 12**). The box has compartments for each electrical component. First, as viewed in **Figure 13**, the stepper motor sits in the back left corner of the box. The bottom and back faces of this corner have ventilation gaps to allow air flow that prevents the motor from overheating during use. The solder board with the motor driver is screwed into the front left corner of the box. Lastly, the Arduino is set on the right half side of the box. There is a small hole in the bottom face of the box that the power supply goes through. This allows an easy access point for users to plug in and unplug the power source for the system. The electronics box lid (**Figure 13**) is screwed into the top of the electronics box with 4  $\frac{1}{4}$ -20 x 0.5 inch screws. The lid has a gap that goes around the motor shaft that allows users to remove the lid by sliding it forward without having to remove the console. Additionally, the lid has a small hole that feeds the wires from the limit switches, which are secured to the top of the lid and the lap bar, inside the box. Lastly, the box itself attaches to the underside of the two pulley plates via 6  $\frac{1}{4}$ -20 x 0.75 inch screws. This helps to keep the electronics box flush with the pulley plates and parallel to the ground so that the console and interior electronic components do not tilt during use. Each of these components were printed out of Tough PLA due to its high elastic modulus and yield strength. Additionally, a layer height of 0.2 mm and a 100% infill were used during printing to reduce the printing time and increase the strength of the assembly, respectively.





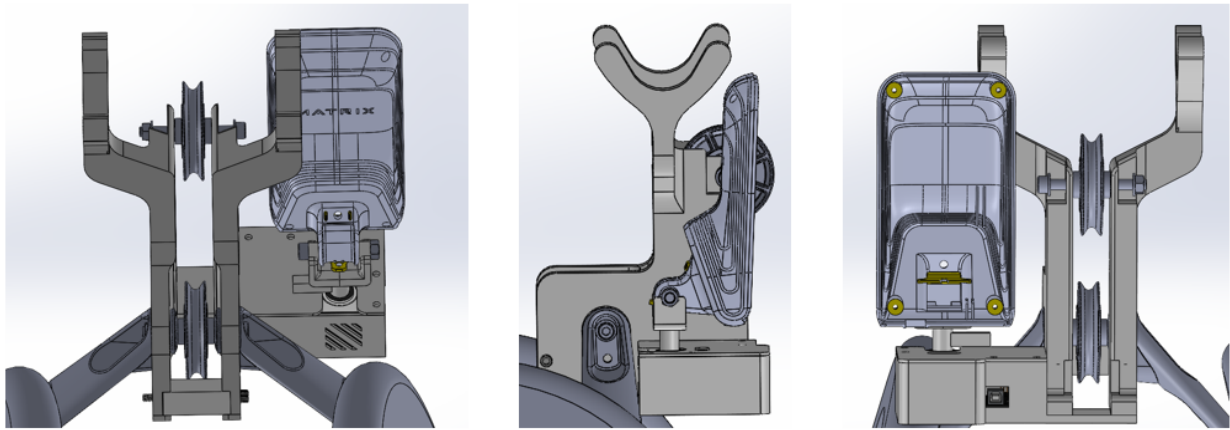
**Figure 12. Electronics Box.** The top view (left) and bottom view (right) of the electronics box shows sections for each electrical component, including the stepper motor, Arduino, and solder board.



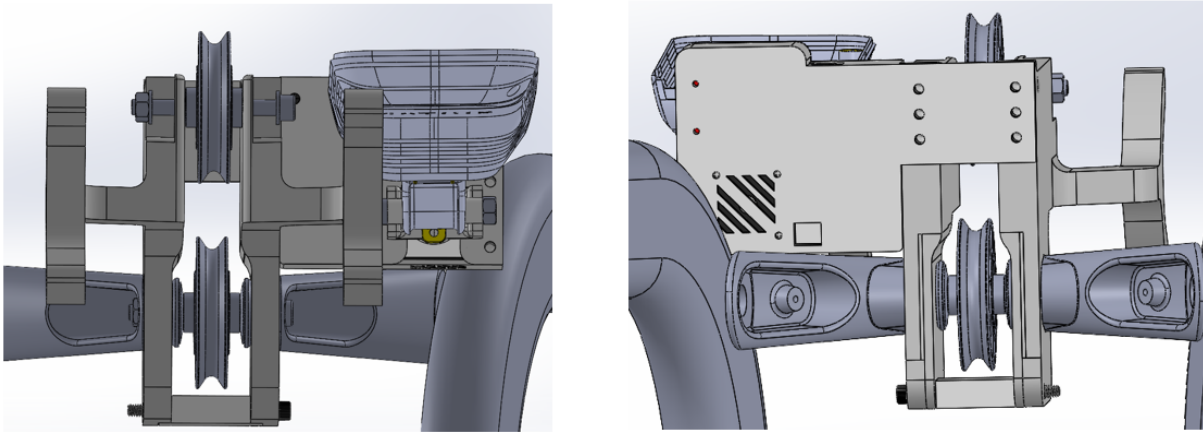
**Figure 13. Electronics Box Lid.** The electronics box lid fits over the electronics box to cover all electrical components. It includes a gap to allow the lid to be slid around the stepper motor shaft, and a hole to guide all limit switch wires into the box.

Once all of these modeled components were printed, they were assembled together. First, all components that required screws had their holes drilled out and tapped. Then, the pulley plates with antlers were slid on to the rower neck support arms and both pulleys were attached. The back separation block was then inserted and screwed into place with a  $1 \frac{1}{4}$ -20 x 3

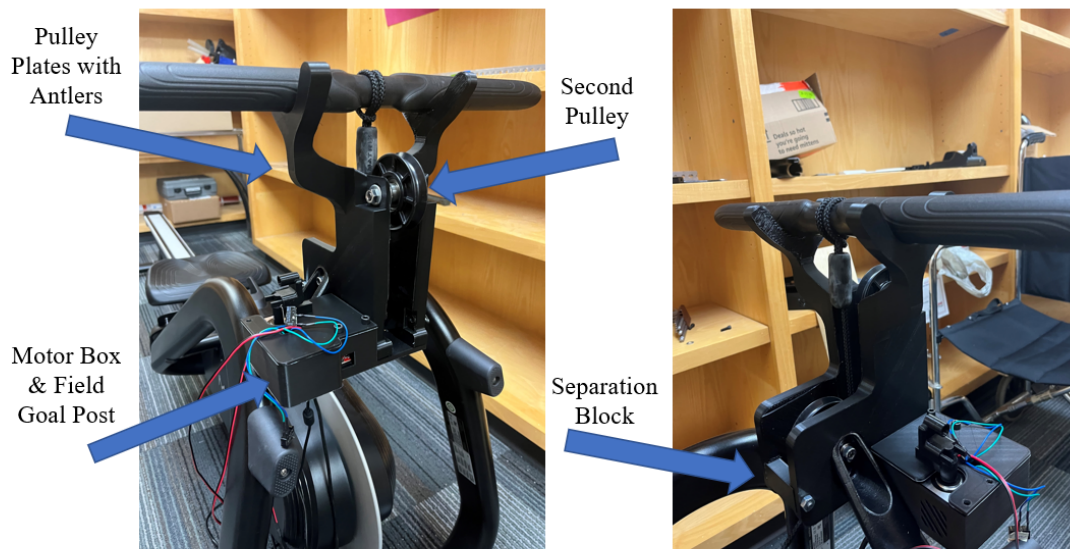
inch screw. Next, all electrical components were secured within the electronics box. To connect the motor to the electronics box, 4 #6-32 x 1.5 inch screws were required. The solder board was connected to the electronics box via 2 #2 x 0.5 inch screws. Originally, the Arduino was supposed to be screwed into the box, but the tapped holes did not line up with the holes on the Arduino, so the component was taped in place instead. To secure the electronics box lid to the electronics box, 4 ¼-20 x 0.75 inch screws were required. The electronics box was then connected to the pulley plates. The connection between the electronics box and the bottom surface of the pulley plates required 6 ¼-20 x 0.75 inch screws. The full SolidWorks assembly can be seen with back, side, and front views in **Figure 14** and in top and bottom views in **Figure 15**. This shows the front aspect of the rower with the second pulley, both pulley plates and antlers, the electronics box with lid, and the console with the updated field goal posts. The model does not include the updated stabilization frame as that was developed in a separate SolidWorks model. The full physically built assembly can be seen in **Figure 16**.



**Figure 14. SolidWorks Assembly Back, Side, & Front View.** The back (left), side (middle), and front (right) views of the rower assembly are shown. The adaptations made to the original rower include adding a second pulley stabilized by mirroring support plates, antlers to hold the handlebar in a central location, and an electronics box to hold all the electrical equipment that rotates the console between the standard and adaptive sides.



**Figure 15. SolidWorks Assembly Top & Bottom View.** The top (left) and bottom (right) views of the rower assembly are shown. The adaptations made to the original rower include adding another pulley stabilized by mirroring support plates, antlers to hold the handlebar in a central location, and an electronics box to hold all the electrical equipment that rotates the console between the standard and adaptive sides.

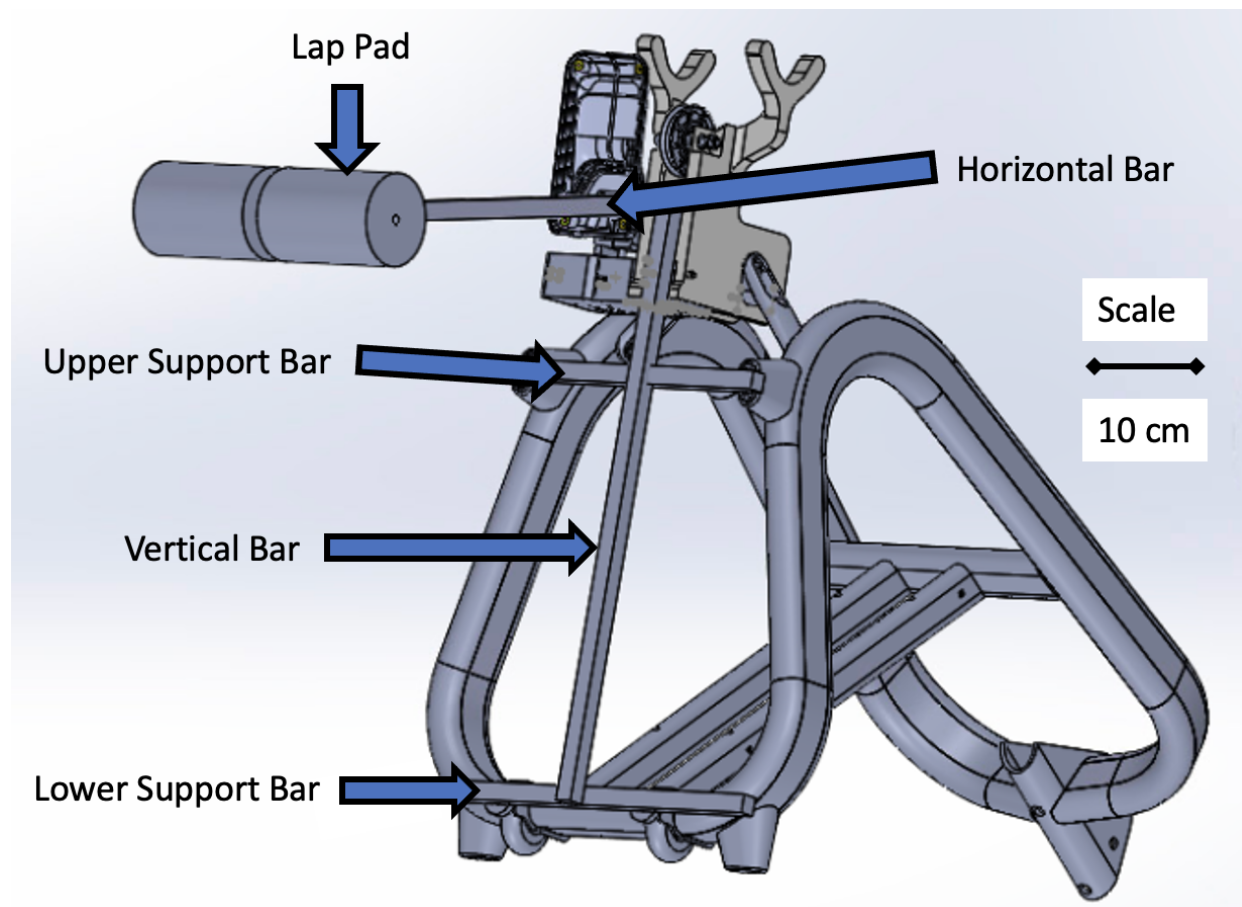


**Figure 16. 3D Printed Components on Physical Assembly.** The pulley plates with antlers, console rotation field goal posts, and electronics box of the full rower assembly are shown in a front (left) and back (right) view.

### C. Stabilization Frame

The stabilization frame is located in the same position as the previous wooden frame design. The purpose of the stabilization frame is to secure wheelchair users in place during the rowing motion such that the wheelchair and user do not tip over backwards during use. Additionally, the stabilization frame prevents the user from being pulled forward out of the wheelchair by the tension in the rope while rowing. In order to withstand the 1050 N maximum force that can develop while rowing, steel bars were used due to their high strength and durability [23].

Prior to sourcing materials from Johnson Health Tech, the Pad Support design was modeled in SolidWorks to determine the correct dimensions of each of the bars (**Figure 17**). A few modifications were made to the preliminary Pad Support design's attachment and adjustability mechanisms. In order to make the connection to the rowing machine more sturdy, nuts and bolts were used to attach the frame directly to the back side of the rowing machine instead of the base board. Additionally, the horizontal adjustment mechanism was removed for the design since a singular horizontal bar was deemed sufficient for accommodating the majority of users.

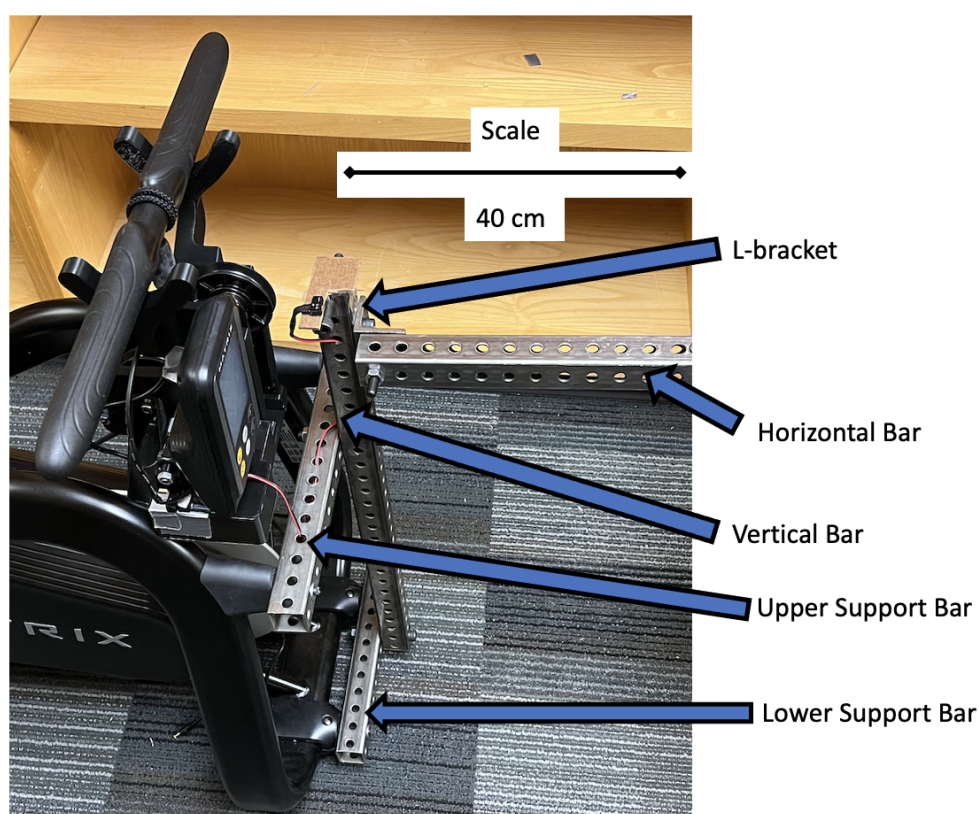


**Figure 17. SolidWorks Model of Stabilization Frame.** Before sourcing the steel bars from Johnson Health Tech, the stabilization frame was modeled in SolidWorks to determine each bar's dimensions.

The stabilization frame includes two support bars (one 40 cm long top bar and one 30 cm long bottom bar), a vertical bar (68 cm long), a horizontal bar (40 cm long), and a pad (**Figure 18**). All bars used are made out of steel. All bolts were tightened using a hexagon wrench. To begin the fabrication of the frame, the two support bars were attached to the back side of the rowing machine. The 30 cm bottom support bar was lined up in the center of the rowing machine with the holes on the back side. Two M-5 50 mm bolts and two M-6 washers were used to secure the bottom support bar to the rowing machine. The same materials were used to secure the 40 cm



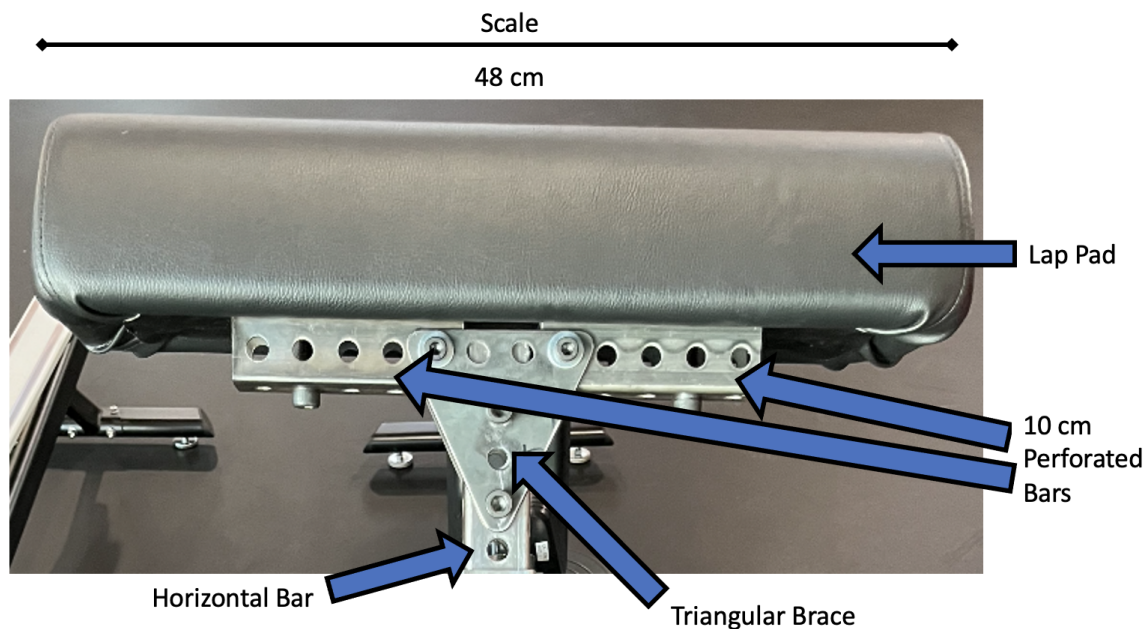
top bar to the back side of the rowing machine. After both support bars were attached to the rowing machine, the vertical bar was aligned perpendicular to both the lower and upper support bars and was offset to the right from the centerline of the rowing machine by one hole. One M-10 nut and 80 mm bolt pair was used to attach the vertical bar to each support bar. An M-10 hexagon wrench was used to secure the bolts. One M-10 90 mm bolt was attached to the top hole of the vertical bar such that the bolt faced toward the centerline of the rowing machine. This bolt was secured using two M-10 nuts. Three holes down from the top of the vertical bar, an L-bracket was attached such that the open section of the bracket was perpendicular to the ground and facing the centerline of the rowing machine. The L-bracket was secured using an M-10 nut and 50 mm bolt. One end of the horizontal bar was then attached using an M-10 nut and 50 mm bolt on the side of the L-bracket that faced towards the centerline of the rowing machine.



**Figure 18. Stabilization Frame Components.** The stabilization frame is attached to the backside of the rowing machine. It is made up of two support bars, a vertical bar, and a horizontal bar. The horizontal bar pivots at the top of the vertical bar via an L-bracket and bolt.

The lap pad was secured to the open end of the horizontal bar using two smaller perforated bars and two triangular braces (**Figure 19**). To connect the lap pad to the horizontal bar, two 10 cm perforated bars were first connected to the lap pad using two M-10 50 mm bolts. A 3.5 cm gap was left between the two smaller perforated bars so that the horizontal bar could fit in between. The horizontal bar was placed between the two 10 cm perforated bars. Four M-10

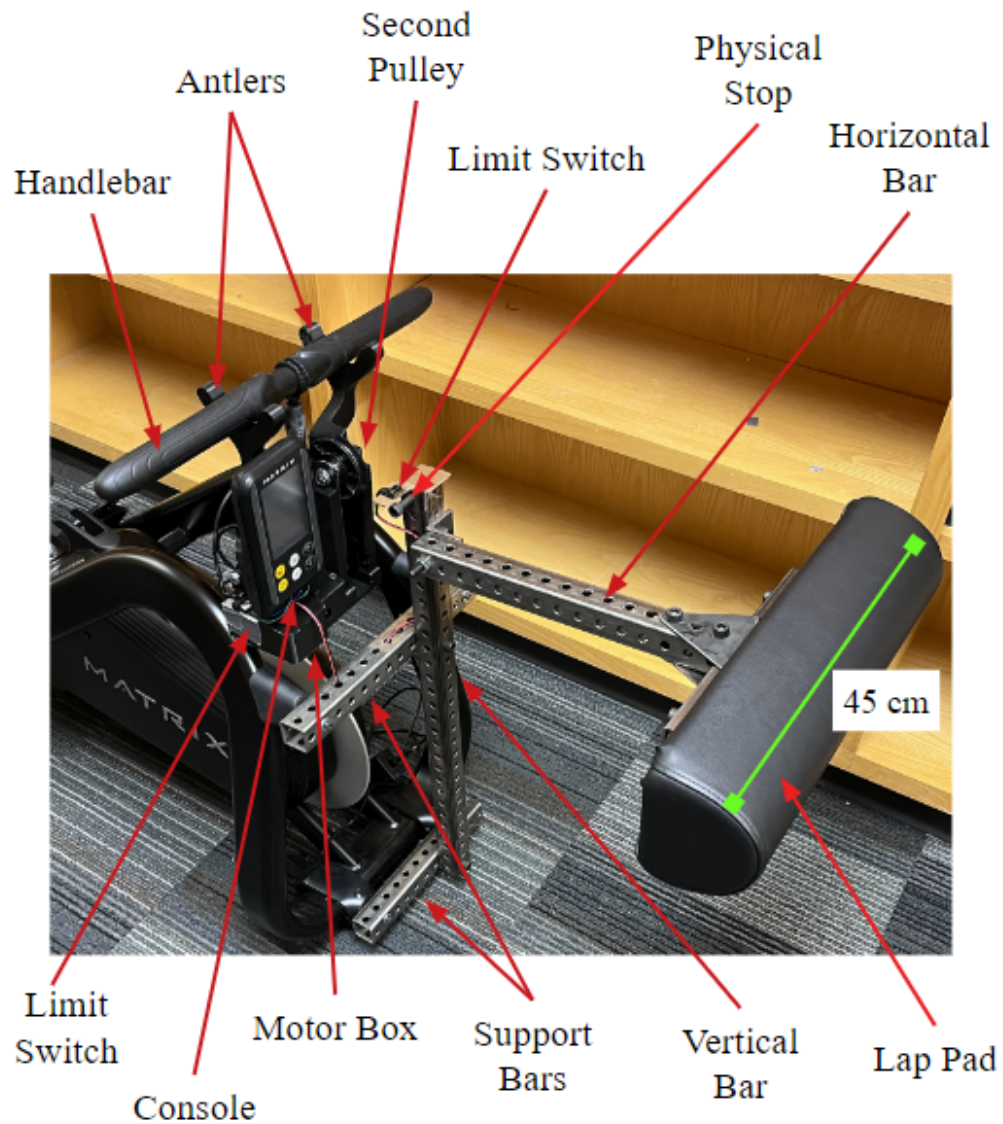
nut and 50 mm bolt pairs were used to secure the two triangular braces to the smaller perforated bars and the horizontal bar (one triangular brace on each side).



**Figure 19. Pad Attachment to Horizontal Bar.** The pad was attached to the horizontal bar using two smaller perforated bars, two triangular braces, and M-10 nuts and bolts.

#### D. Full Assembly

After 3D printing the SolidWorks designs, fabricating the stabilization frame, and creating the circuit, all components of the design were attached to the rowing machine to complete the full assembly (**Figure 20**). The electronics were secured within the electronics box and the console was placed on the motor shaft with the console field goal posts. The pulley support plates and second pulley were attached to the support arms of the rower neck with one on each side of the rower. Once the support plates were on, the electronics box was screwed into the underside of the pulley plates and a 3D printed separation block was inserted on the standard side of the rower between the pulley plates to help push them apart. The handlebar was then lifted into position within the antlers. Finally, the metal stabilization frame was screwed into the base of the rower and all limit switches were hot glued in place, completing the fully updated adaptive rower assembly.



**Figure 20. Full Assembly.** The full assembly includes the pulley support plates with antlers, the console rotation mechanism and electronics box, and the metal adjustable stabilization frame.

## Appendix H: BME 400 Final Arduino Code

// Written by: Annabel Frake

// Class: BME 400

// Purpose: Rotate the console of a Matrix rowing machine between the standard and adaptive sides.

// Include necessary libraries.

#include <ezButton.h>;

```

// Define digital pins for the three limit switches.
byte const transitionSwitchPin = 12; // This limit switch is placed near the stabilization frame.
When its state changes, the rower is transitioned between adaptive and standard use or vice
versa. When this limit switch is pressed, the console should be on the standard side and when it
is not pressed, the console should be on the adaptive side.
byte const standardSwitchPin = 10; // This limit switch is placed near the console on the standard
side. When it is pressed, the console is facing the standard user.
byte const adaptiveSwitchPin = 11; // This limit switch is placed near the console on the adaptive
side. When it is pressed, the console is facing the wheelchair user.

// Create an ezButton object for the transition limit switch.
ezButton transitionSwitch(transitionSwitchPin);

// Define digital pins for the DIR and STEP features of the stepper motor.
byte const dirPin = 8;
byte const stepPin = 9;

// Define the time delay for the manual PWM of the stepper motor.
int speedDelay = 300; // microseconds

void setup()
{
  // Initialize the serial port.
  Serial.begin(9600);

  // Set the stepper pinmodes to OUTPUT.
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);

  // Set limit switch pins to INPUT_PULLUP. An internal pullup resistor reverses the logic.
  When the switch is open, the output is HIGH (1). When the switch is closed, the output is LOW
  (0).
  pinMode(standardSwitchPin, INPUT_PULLUP);
  pinMode(adaptiveSwitchPin, INPUT_PULLUP);

  // Assign the transition limit switch with a debounce time of 50 milliseconds
  transitionSwitch.setDebounceTime(50);
}

```



```

void loop()
{
  // Call the loop() function for the transition limit switch.
  transitionSwitch.loop();

  // If the transition limit switch is pressed, that means the standard side of the machine is now in
  use. Rotate the console to face the standard side.
  if (transitionSwitch.isPressed())
  {
    // Call the function that rotates the console to face the standard side.
    rotateToStandard(standardSwitchPin);
  }

  // If the transition limit switch is released, that means the adaptive side of the machine is now in
  use. Rotate the console to face the adaptive side.
  else if (transitionSwitch.isReleased())
  {
    // Call the function that rotates the console to face the adaptive side.
    rotateToAdaptive(adaptiveSwitchPin);
  }

  // If the transition limit switch state does not change, check the position of the console to ensure
  it is in the correct orientation.
  else
  {
    checkConsolePosition();
  }
}

// A function that checks the current position of the console when the system starts up (or in the
// case of an unintended or intended reset).
void checkConsolePosition()
{
  // If the transition limit switch is pressed, that means the standard side of the machine is in use.
  // If the standard position limit switch is not pressed, rotate the console to face the standard side.
  if (!transitionSwitch.getState() && digitalRead(standardSwitchPin)) // Note: logic is flipped
  because of INPUT_PULLUP.
  {
    // Call the function that rotates the console to face the standard side.
    rotateToStandard(standardSwitchPin);
  }
}

```

```

}

// If the transition limit switch is not pressed, that means the adaptive side of the machine is in
// use. If the adaptive position limit switch is not pressed, rotate the console to face the adaptive
// side.
else if (transitionSwitch.getState() && digitalRead(adaptiveSwitchPin)) // Note: logic is flipped
because of INPUT_PULLUP.
{
    // Call the function that rotates the console to face the adaptive side.
    rotateToAdaptive(adaptiveSwitchPin);
}
}

// A function to rotate the console to face the standard side of the machine.
void rotateToStandard(int standardSwitchPin)
{
    // Specify the direction the motor will rotate: clockwise.
    digitalWrite(dirPin, HIGH);

    // Rotate the motor in the specified direction until the standard position limit switch is
    // depressed.
    while (digitalRead(standardSwitchPin)) // Note: logic is flipped because of INPUT_PULLUP.
    {
        // Manually perform PWM.
        digitalWrite(stepPin, HIGH);
        delayMicroseconds(speedDelay); // use this to change speed
        digitalWrite(stepPin, LOW);
        delayMicroseconds(speedDelay); // use this to change speed
    }

    Serial.println("Console position: standard");
}

// A function to rotate the console to face the adaptive side of the machine.
void rotateToAdaptive(int adaptiveSwitchPin)
{
    // Specify the direction the motor will rotate: counterclockwise.
    digitalWrite(dirPin, LOW);

```

```
// Rotate the motor in the specified direction until the adaptive position limit switch is
depressed.
while (digitalRead(adaptiveSwitchPin)) // Note: logic is flipped because of INPUT_PULLUP.
{
  // Manually perform PWM.
  digitalWrite(stepPin, HIGH);
  delayMicroseconds(speedDelay); // use this to change speed
  digitalWrite(stepPin, LOW);
  delayMicroseconds(speedDelay); // use this to change speed
}

Serial.println("Console position: adaptive");
}
```

## **Appendix I: BME 400 Testing & Results**

### **I. Testing**

#### **A. Circuit and Code Functionality**

To test the functionality of the circuit and code, eight edge cases representing likely operational scenarios were tested. For instance, edge case seven tests the ability of the console to rotate to the proper location after power is disconnected and reconnected during rotation. **Table 1** describes the testing setup and expected outcome of all eight scenarios. During testing, the response (or lack thereof) of the console was recorded and compared to the expected response to determine whether the circuit and code passed or failed the functionality test. Each edge case was tested three times.

**Table 1. Edge Case Protocol Description.** This table contains instructions for implementing eight edge cases that test the functionality of the final circuit and code. The table also specifies the expected outcome of each test.

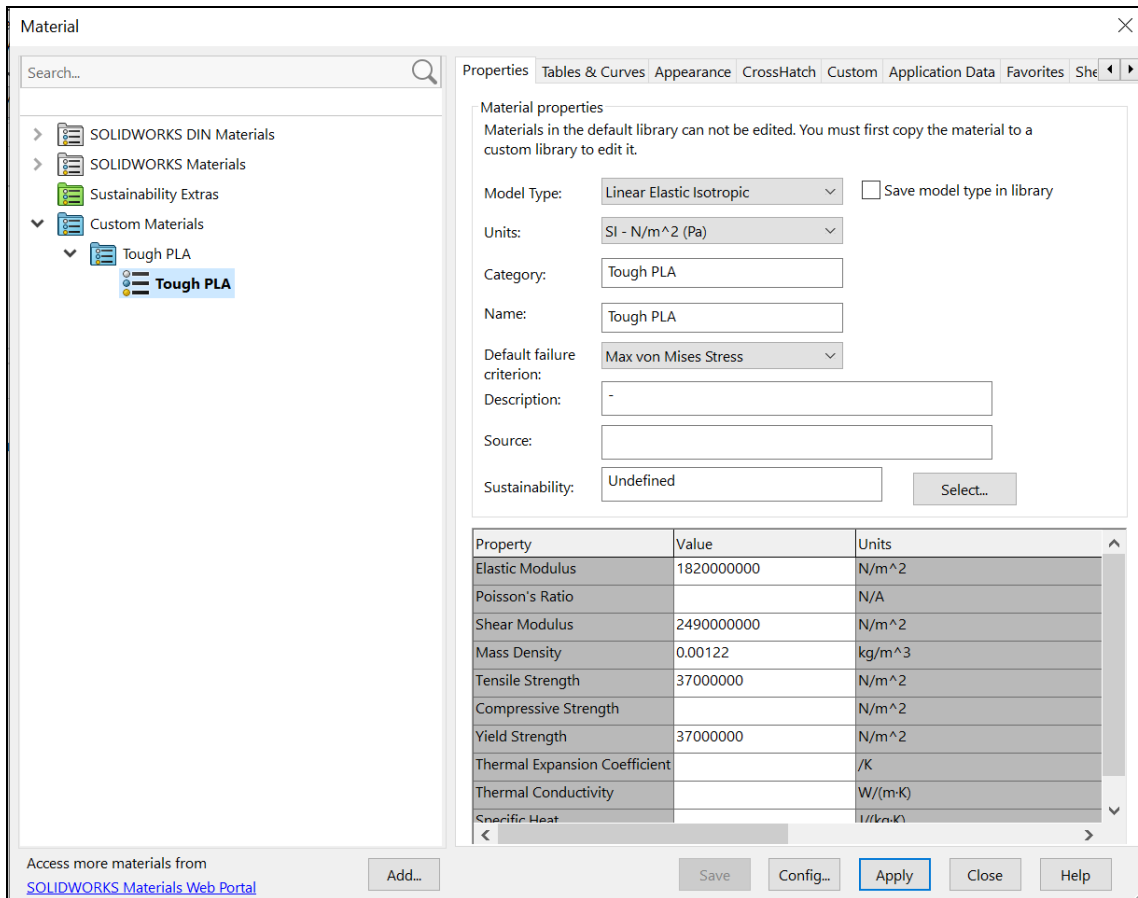
Edge Case	Testing Setup and Implementation Instructions	Expected Outcome
1	<ul style="list-style-type: none"> <li>● Before power application: Position the console in no-man's land (not facing the standard or adaptive sides). Lower the lap bar such that the transition limit switch is not pressed.</li> <li>● Apply power.</li> </ul>	The console rotates to the adaptive side.
2	<ul style="list-style-type: none"> <li>● Before power application: Position the console in no-man's land (not facing the standard or adaptive sides). Raise the lap bar such that the transition limit switch is pressed.</li> <li>● Apply power.</li> </ul>	The console rotates to the standard side.
3	<ul style="list-style-type: none"> <li>● Before power application: Position the console on the adaptive side such that the adaptive limit switch is suppressed. Lower the lap bar such that the transition limit switch is not pressed.</li> <li>● Apply power.</li> </ul>	The console remains stationary until the lap bar is raised such that the transition limit switch is suppressed. Then the console rotates to the standard side.
4	<ul style="list-style-type: none"> <li>● Before power application: Position the console on the standard side such that the standard limit switch is suppressed. Raise the lap bar such that the transition limit switch is pressed.</li> <li>● Apply power.</li> </ul>	The console remains stationary until the lap bar is lowered such that the transition limit switch is no longer suppressed. Then the console rotates to the adaptive side.

5	<ul style="list-style-type: none"> <li>● Before power application: Position the console on the adaptive side such that the adaptive limit switch is suppressed. Raise the lap bar such that the transition limit switch is pressed.</li> <li>● Apply power.</li> </ul>	The console rotates to the standard side.
6	<ul style="list-style-type: none"> <li>● Before power application: Position the console on the standard side such that the standard limit switch is suppressed. Lower the lap bar such that the transition limit switch is not pressed.</li> <li>● Apply power.</li> </ul>	The console rotates to the adaptive side.
7	<ul style="list-style-type: none"> <li>● Apply power.</li> <li>● After power application: Disconnect the power supply while the console is rotating between the standard and adaptive sides (or vice versa). Supply the circuit with power.</li> </ul>	The console rotates to the appropriate side of the rowing machine in accordance with the state of the transition limit switch when power is reconnected.
8	<ul style="list-style-type: none"> <li>● Apply power.</li> <li>● After power application: Induce rotation of the console. Raise and lower the lap bar multiple times (such that the transition limit switch is pressed and released multiple times) during the rotation from one side of the machine to the other (either adaptive to standard or standard to adaptive, the choice is arbitrary). Before the console finishes rotating, either raise or lower the lap bar and keep it there.</li> </ul>	After the console finishes rotating to the position to which it was originally traveling, the console either stays there or rotates to the opposite side in accordance with the state of the transition limit switch.

## B. SolidWorks Simulation

A SolidWorks simulation was conducted to analyze the stresses and displacements acquired due to a maximum, worst case load. In order to properly test the strength and geometry of the pulley support plates, the plates were modeled as Tough PLA in SolidWorks [24]. This was done by creating a new material and altering the mechanical properties as shown in **Figure 1**. This ensured that the stress and displacement data acquired was representative of the material that the plates were printed in. Only the material properties reported in the data sheet were imported into the simulated material. To test the strength of the pulley support plates, a maximum load of 1050 N was applied to the inner circular cavity on each plate where the pulley is connected to the plates. According to the PDS, this would be the maximum load applied to the additional pulley under maximum rowing effort. Ideally, this load would be transmitted equally to each pulley plate. Thus, by applying the full 1050 N load to each plate individually, this load has a safety factor of two, and represents the maximum loading of the plates [13].

To model the worst case scenario, the load was applied directly downward onto this cavity. This is where the plate sits on the additional pulley bearing. Thus, if any force were directed onto the pulley plates, it would be transmitted to this inner cavity surface. During a typical rowing motion, tension in the rope follows along a path parallel to the floor. Thus, the worst case scenario was modeled as the maximum load placed on the plates perpendicular to the floor. The cavity that sits on the rower neck support arms and the two faces in which the front and back separator blocks are rigidly screwed into the pulley plates were held fixed during the simulation. This fixation models the plates sitting on these support arms and being pushed apart by the separator blocks. Testing of the stresses and displacements that develop revealed the strength and rigidity of the chosen material and geometry of the support plates, which in turn revealed how well the plates stabilized the additional pulley under typical rowing conditions.



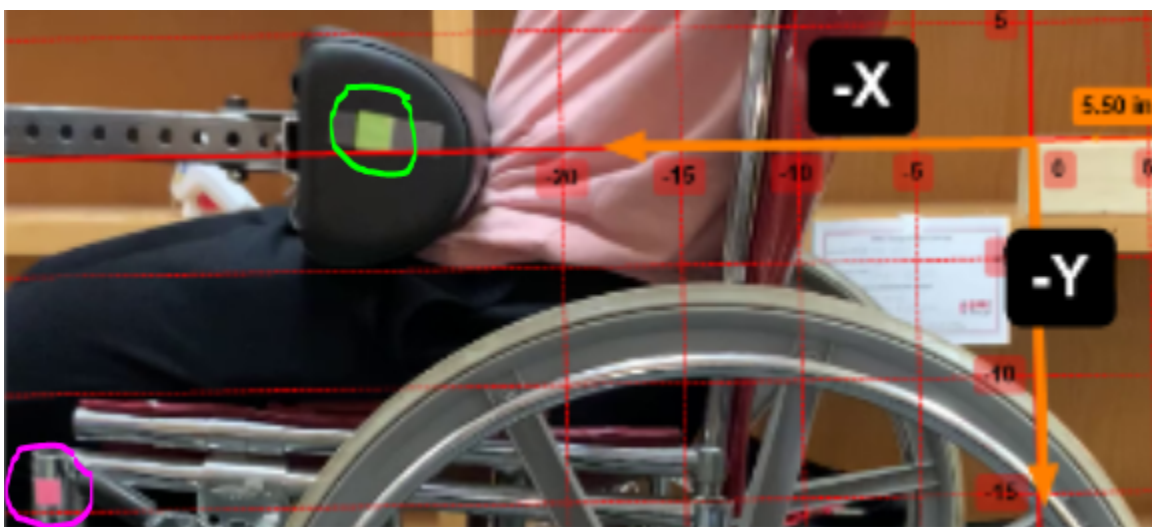
**Figure 1. Tough PLA Material Specifications.** All 3D printed components were modeled as Tough PLA, to accurately predict the stresses and displacements that will develop in the plates under a maximum load [24].

Next, another SolidWorks simulation was conducted to analyze the stresses and displacements acquired due to a maximum, worst case load on the new antlers added to the pulley plates. The antlers were modeled as Tough PLA. To simulate this worst case loading, the same 1050 N load (with a safety factor of two) was applied to two locations. First, this load was applied to the slanted edge of the inner surface of the handlebar cavity on the standard side of the rower directed towards the standard side of the rower. Next, the load was applied to the slanted edge of the inner surface of the handlebar cavity on the adaptive side of the rower directed towards the adaptive side of the rower. The plates were again held rigidly fixed at the two faces in which the plates contact the separator blocks and the cavity where the plate sits on the rower neck support arm. This loading simulates the worst case scenario of a user pulling directly on the handlebar while it is still sitting within the antler handlebar cavity. By placing the loads on either side of this cavity and directing the load to either the standard or adaptive side, this simulation predicts how the antlers will react to an excessive load being applied from either the standard or adaptive side of the rower. Simulation testing for the pulley plates was only conducted on the Left Pulley Plate because the left and right plates are exact mirror images of each other and will thus perform identically.

Lastly, a final SolidWorks simulation was conducted to analyze the stresses and displacements due to a maximum, worst case load on the electronics box. The electronics box was modeled as Tough PLA. To simulate this worst case loading, a 50 N force was directed downward on the bottom surface of the electronics box. This simulates any weight from the electronics, console, or the user slightly pressing down on the box. The box was held rigidly fixed where it is screwed into the two pulley plates. A 50 N force was arbitrarily chosen because the electronics box is not expected to experience more than 5 lbs of weight being placed on it at any time. Thus, by applying a 50 N force (11.24 lbs), the box was tested with a safety factor of 2.25 to ensure its strength and rigidity under both normal and extreme loads.

### C. Kinovea Analysis

Motion capture of the stability frame and wheelchair was conducted to quantify their displacement during rowing. The setup of the displacement testing included two bright markers cut from paper, one taped onto the lap pad, and one taped onto the leg of the wheelchair. The experimental setup is shown in **Figure 2**. A camera was set up to track the motion of the two markers during rowing. A test participant rowed for 25 seconds on both the maximum (10) and minimum (1) resistance settings. The videos were imported to Kinovea for motion analysis. To scale the displacement, a calibration measurement is needed. This was achieved by placing a wooden block of known length in the video frame. In Kinovea, digital trackers were placed on the paper trackers to record their position over time. To ensure accurate measurements, each individual frame is manually examined to confirm the digital trackers were still over the paper markers. The max displacements were calculated by finding the range between the minimum and maximum coordinate values. The raw data from Kinovea was exported as an Excel file and then loaded into MATLAB to create a visualization of the movement of the lap pad and wheelchair.



**Figure 2. Motion Testing Experimental Setup.** Markers (green and pink) placed on lap pad and wheelchair, respectively. Kinovea defaults the coordinate system to originate from the calibration line.



## II. Results

### A. Circuit and Code Functionality

The circuit and code passed all eight edge cases implemented three times each (**Table 2**). A deviation from the testing protocol occurred for edge case eight. During testing, the lap bar did not rotate freely and often became stuck because of the tightness of the pivot screw. As a consequence, the lap bar could not be moved fast enough to press and release the transition limit switch multiple times during the rotation of the console between the standard and adaptive sides of the machine. To simulate the lap bar movement, the tester directly pressed and released the transition limit switch with a finger. Because the circuit and code cannot differentiate between a finger and the lap bar, this deviation still accomplished the intent of the edge case to test the system's reaction to multiple, rapid changes in the transition limit switch state. All in all, the circuit and code functioned as intended and passed all eight edge cases.

**Table 2. Edge Case Protocol Results.** This table contains instructions for implementing eight edge cases that test the functionality of the final circuit and code. Each edge case was tested three times. The experimental results were compared with the expected outcome to determine whether the circuit and code passed or failed each edge case.

Edge Case	Testing Setup and Implementation Instructions	Expected Outcome	Experimental Outcome	Number of Tests	Pass/Fail
1	<ul style="list-style-type: none"> <li>● Before power application: Position the console in no-man's land (not facing the standard or adaptive sides). Lower the lap bar such that the transition limit switch is not pressed.</li> <li>● Apply power.</li> </ul>	The console rotates to the adaptive side.	The console rotates to the adaptive side.	3	Pass
2	<ul style="list-style-type: none"> <li>● Before power application: Position the console in no-man's land (not facing the standard or adaptive sides). Raise the lap bar such that the transition limit switch is pressed.</li> <li>● Apply power.</li> </ul>	The console rotates to the standard side.	The console rotates to the standard side.	3	Pass
3	<ul style="list-style-type: none"> <li>● Before power application: Position the console on the adaptive side such that the adaptive limit switch is suppressed. Lower the lap bar such that the transition limit</li> </ul>	The console remains stationary until the lap bar is raised such that the transition	The console remains stationary until the lap bar is raised such that the transition	3	Pass

	<p>switch is not pressed.</p> <ul style="list-style-type: none"> <li>Apply power.</li> </ul>	<p>limit switch is suppressed. Then the console rotates to the standard side.</p>	<p>limit switch is suppressed. Then the console rotates to the standard side.</p>		
4	<ul style="list-style-type: none"> <li>Before power application: Position the console on the standard side such that the standard limit switch is suppressed. Raise the lap bar such that the transition limit switch is pressed.</li> <li>Apply power.</li> </ul>	<p>The console remains stationary until the lap bar is lowered such that the transition limit switch is no longer suppressed. Then the console rotates to the adaptive side.</p>	<p>The console remains stationary until the lap bar is lowered such that the transition limit switch is no longer suppressed. Then the console rotates to the adaptive side.</p>	3	Pass
5	<ul style="list-style-type: none"> <li>Before power application: Position the console on the adaptive side such that the adaptive limit switch is suppressed. Raise the lap bar such that the transition limit switch is pressed.</li> <li>Apply power.</li> </ul>	<p>The console rotates to the standard side.</p>	<p>The console rotates to the standard side.</p>	3	Pass

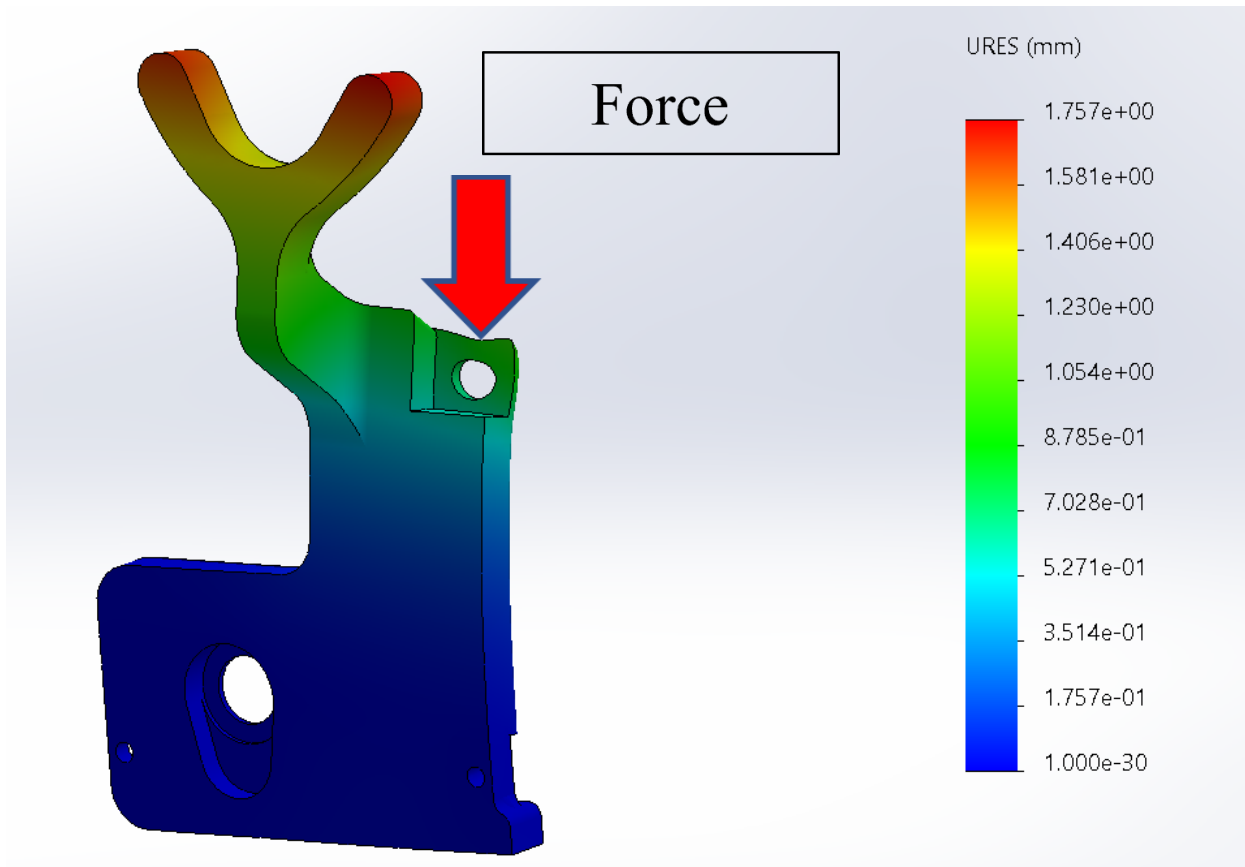
6	<ul style="list-style-type: none"> <li>• Before power application: Position the console on the standard side such that the standard limit switch is suppressed. Lower the lap bar such that the transition limit switch is not pressed.</li> <li>• Apply power.</li> </ul>	The console rotates to the adaptive side.	The console rotates to the adaptive side.	3	Pass
7	<ul style="list-style-type: none"> <li>• Apply power.</li> <li>• After power application: Disconnect the power supply while the console is rotating between the standard and adaptive sides (or vice versa). Supply the circuit with power.</li> </ul>	The console rotates to the appropriate side of the rowing machine in accordance with the state of the transition limit switch when power is reconnected.	The console rotates to the appropriate side of the rowing machine in accordance with the state of the transition limit switch when power is reconnected.	3	Pass
8	<ul style="list-style-type: none"> <li>• Apply power.</li> <li>• After power application: Induce rotation of the console. Raise and lower the lap bar multiple times (such that the transition limit switch is pressed and released multiple times) during the rotation from one side of the</li> </ul>	After the console finishes rotating to the position to which it was originally traveling, the console either stays there or	After the console finishes rotating to the position to which it was originally traveling, the console either	3	Pass*

	machine to the other (either adaptive to standard or standard to adaptive, the choice is arbitrary). Before the console finishes rotating, either raise or lower the lap bar and keep it there.	rotates to the opposite side in accordance with the state of the transition limit switch.	stays there or rotates to the opposite side in accordance with the state of the transition limit switch.		
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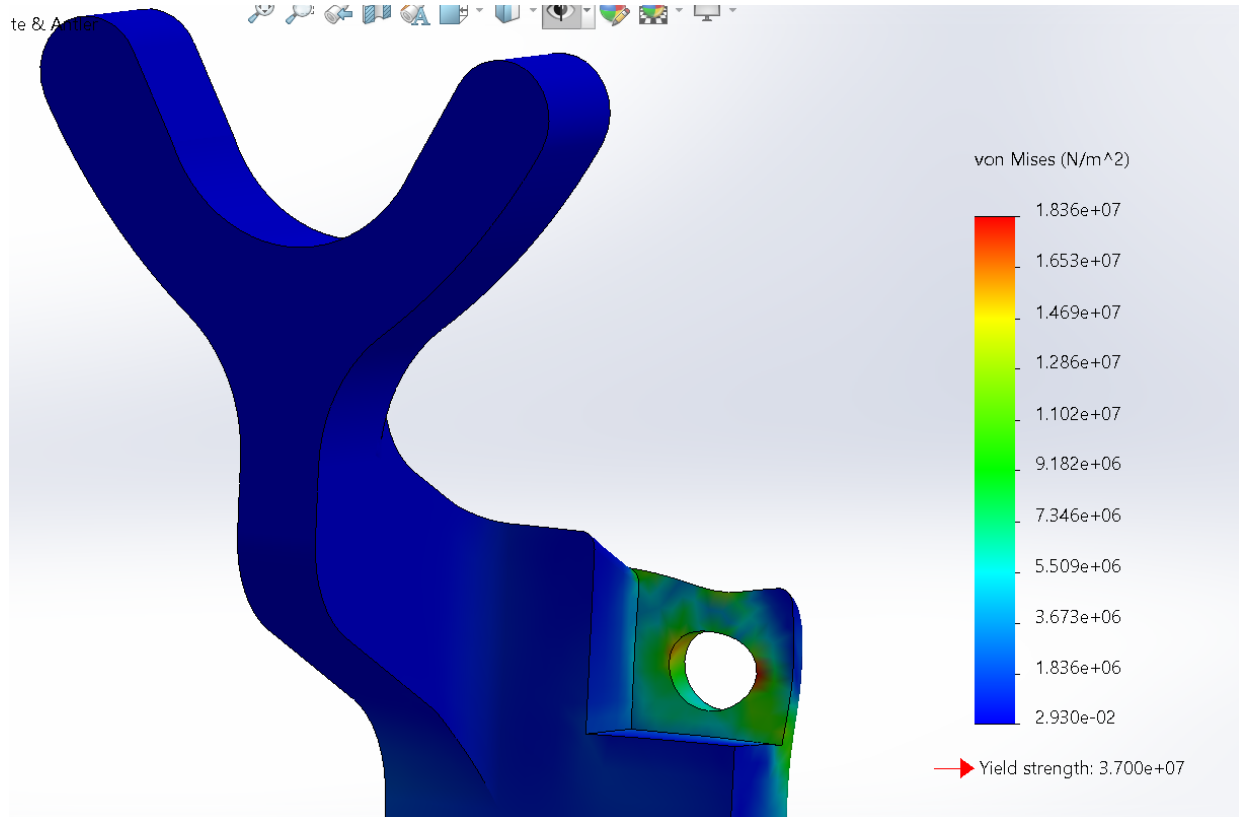
\*Note: A deviation from the testing protocol occurred for edge case eight. The tester used their finger to directly press and release the limit switch

## B. SolidWorks Simulation

After completing the SolidWorks simulation testing on the pulley plates, the resulting stresses and displacements were analyzed to determine the strength of the designed geometries. After applying a 1050 N load to the inner bearing surface of the pulley plates, a maximum displacement of 1.757 mm occurred at the top of the antler handlebar cavity, which is less than the 2.0 mm maximum deflection set by the PDS (**Figure 3**). This was expected because the region in which the load was applied is thin. However, since this cavity is supported by a thick base of Tough PLA material below it, the cavity itself did not deflect excessively. Rather, the less supported antler deflected more because it has the least amount of structural integrity. This displacement is incredibly small, and will likely be even less during actual load bearing, due to the metal pulley bearing being inserted into this cavity and accepting some of the applied load. Throughout the rest of the plate, displacements were less than 1.757 mm, proving that the geometry for both plates will be strong enough to withstand typical rowing loads. Additionally, the maximum stress that developed under this maximum load was 18.36 MPa (**Figure 4**). This is much less than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed along the inner surface of the bearing cavity where the load was directly applied. This was expected because when the load is applied, the cavity would want to fold in on itself. Loading with a safety factor of two shows that both pulley support plates will withstand loads experienced during typical rowing.



**Figure 3. Pulley Plate Deformation.** The pulley plate deformed the most at the tips of the antler handlebar cavity due to having the least amount of structural integrity.



**Figure 4. Pulley Plate Stress.** The pulley plate developed the largest stress concentration at the outer edge of the center of the cavity in which the load was applied due to the cavity wanting to collapse.

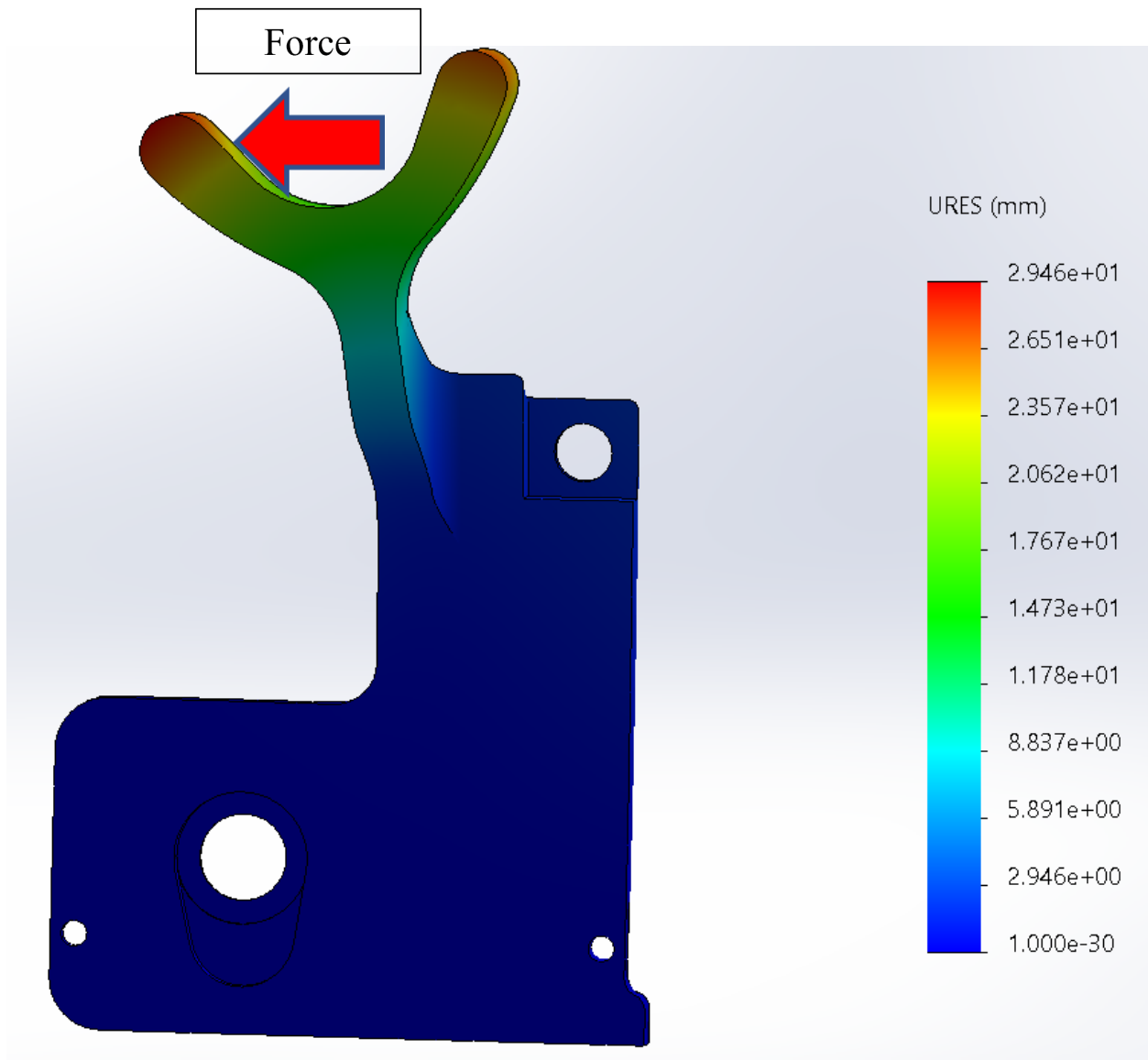
After completing the SolidWorks simulation testing on the antlers, the resulting stresses and displacements were analyzed. After applying a 1050 N load to the slanted edge of the inner surface of the handlebar cavity on the standard side of the rower directed towards the standard side of the rower, a maximum displacement of 29.46 mm occurred at the top of the antler handlebar cavity (**Figure 5**). This was expected because the region in which the load was applied has a relatively weak structural integrity when compared with the rest of the pulley plate. Thus, when an excessive load such as 1050 N is applied, this region will be likely to fail. Throughout the rest of the antler, displacements were greater than 6 mm. Additionally, the maximum stress that developed under this maximum load was 110.7 MPa (**Figure 6**). This is much greater than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed along the slanted surface of the antler which supports the handlebar cavity. This was expected because when the load is applied, the antler arm would want to bend away from the plate and fracture.

After applying a 1050 N load to the slanted edge of the inner surface of the handlebar cavity on the adaptive side of the rower directed towards the adaptive side of the rower, a maximum displacement of 29.57 mm occurred at the top of the antler handlebar cavity (**Figure 7**). This region has a relatively weak structural integrity when compared to the rest of the pulley plate. Subsequently, this was the expected region of maximum displacement when the excessive

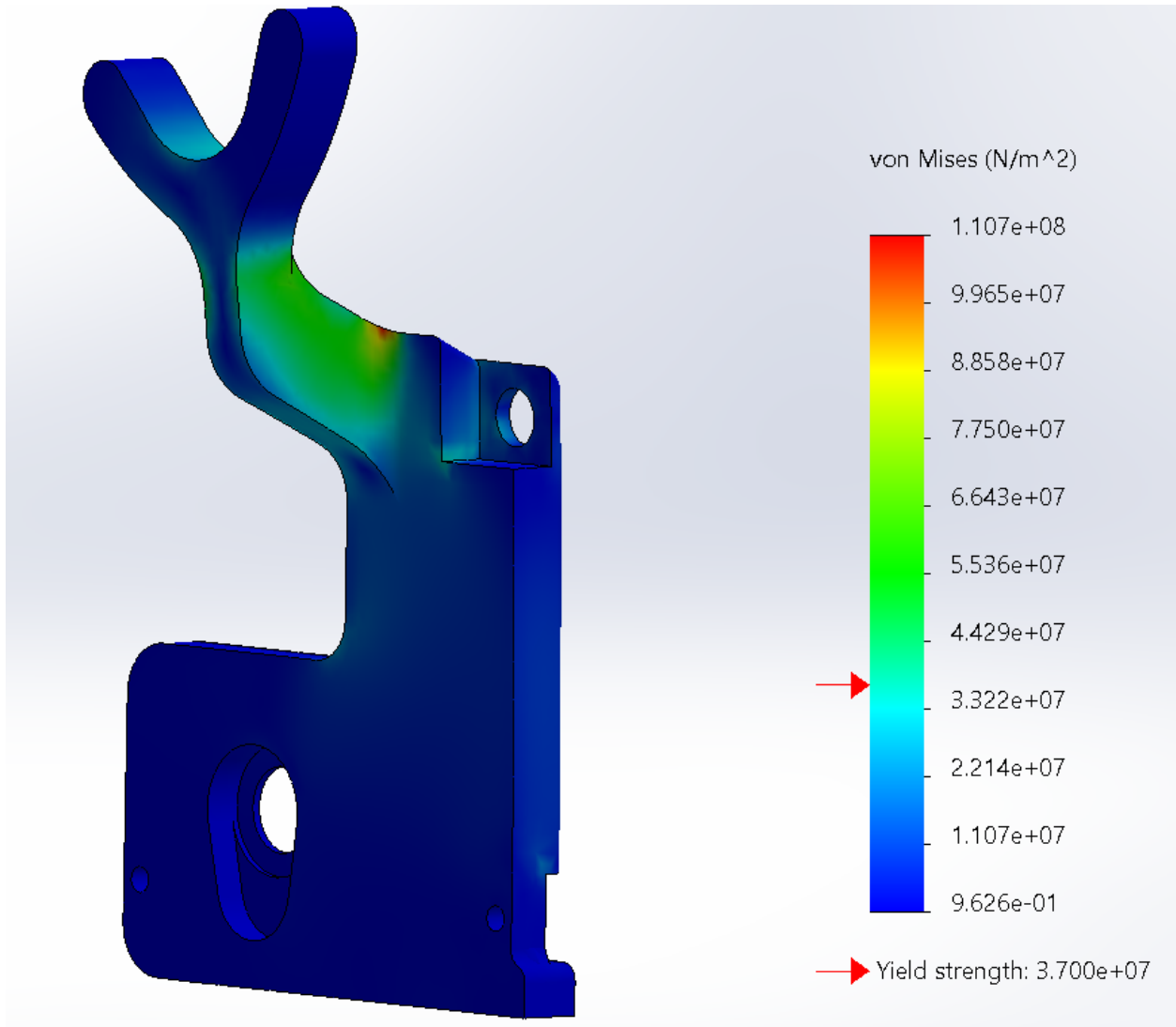


1050 N load was applied. Displacements throughout the rest of the antler were greater than 6 mm. Furthermore, the maximum stress that developed under this maximum load was 111.5 MPa (**Figure 8**). This is much greater than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed in the same place as the previous test and was expected because the antler arm would want to bend away from the plate and fracture during loading.

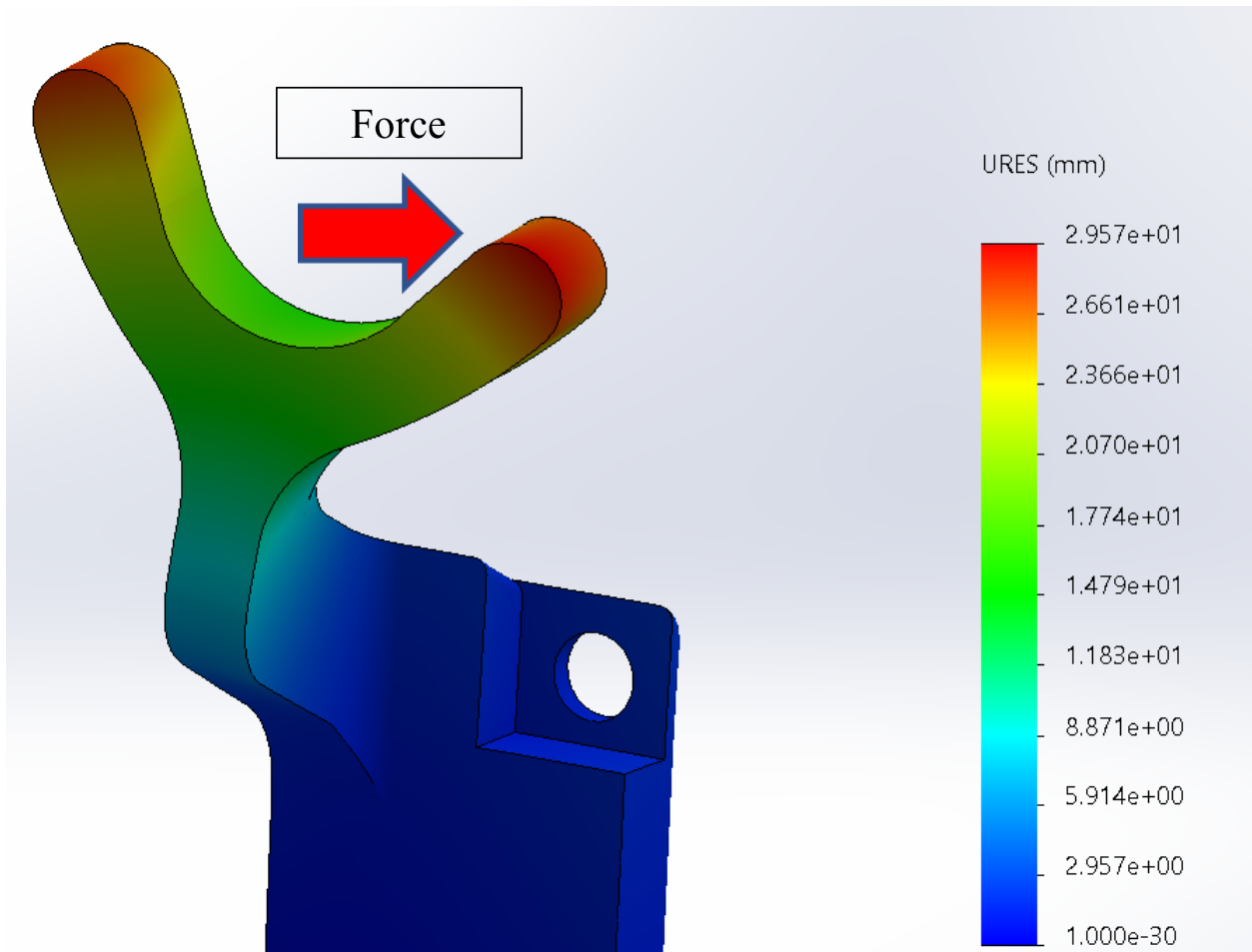
Thus, the predicted stresses and loadings for both loading conditions of the antlers are very similar to one another. Despite the excessive deformations and stresses that the simulation predicts, the antlers are likely to actually experience a much smaller magnitude of force, which would greatly reduce their deformations and stresses. This is because users are not likely to begin rowing with the handlebar still placed in the cavity. Rather, users are more likely to pull strongly on the handlebar by accident, which would be a force much less than 1050 N. Finally, the antlers will be made out of a 100% infill structure of Tough PLA. This extra infill will greatly increase the structure's rigidity and therefore reduce the experienced deformations and stress concentrations. The antlers are predicted to perform as intended under typical loading conditions, but are likely to fail under very extreme loading scenarios.



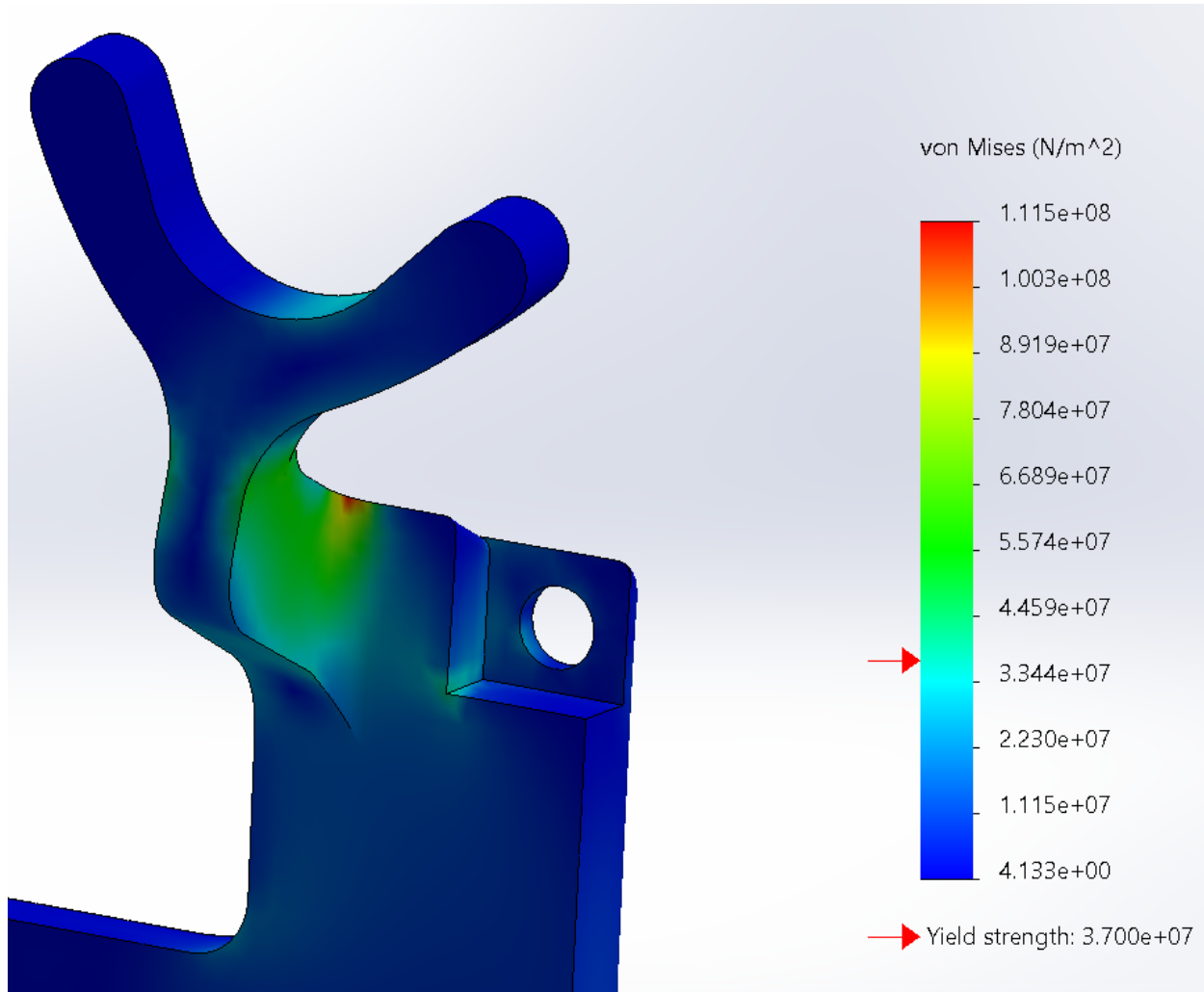
**Figure 5. Antler Standard Side Deformation.** The antler deflects almost 30 mm towards the standard side of the rower when subject to a very high and extreme load.



**Figure 6. Antler Standard Side Max Stress.** The antler develops significant stress in the arm of the antler support under extremely high and excessive loading, causing the structure to fail under this given loading scenario.



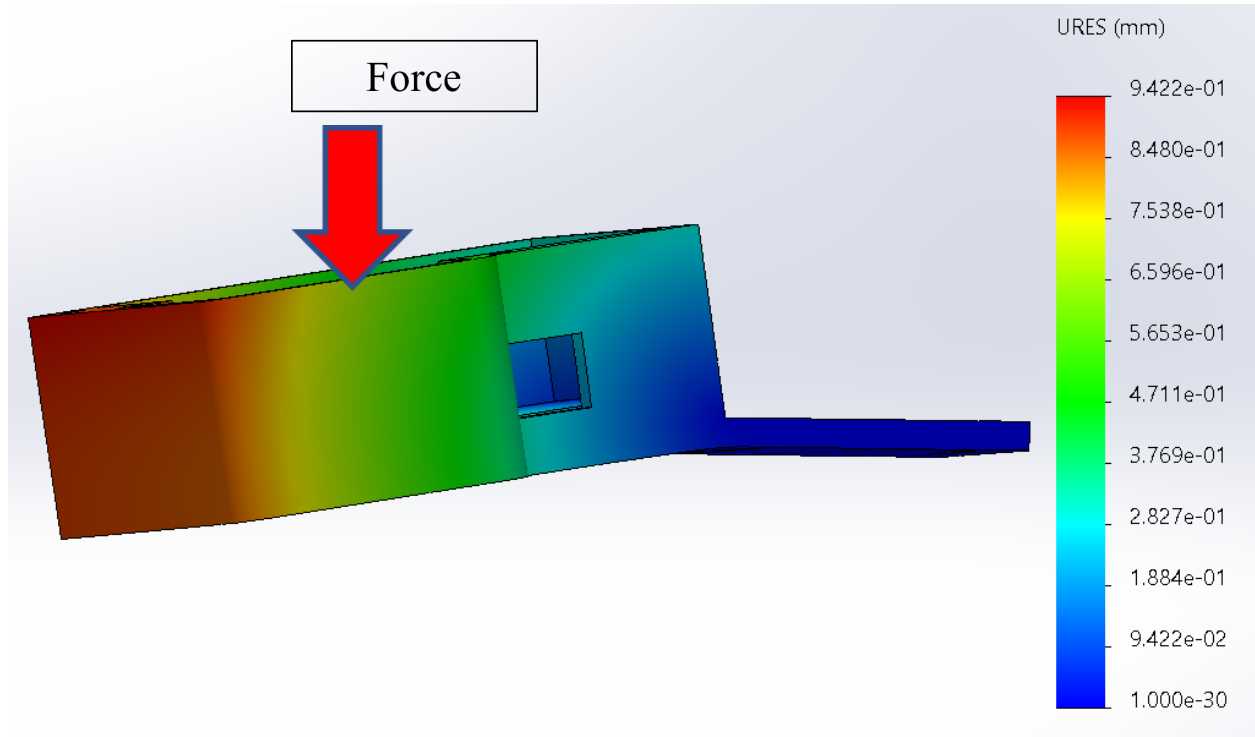
**Figure 7. Antler Adaptive Side Deformation.** The antler deflects almost 30 mm towards the adaptive side of the rower when subject to a very high and extreme load.



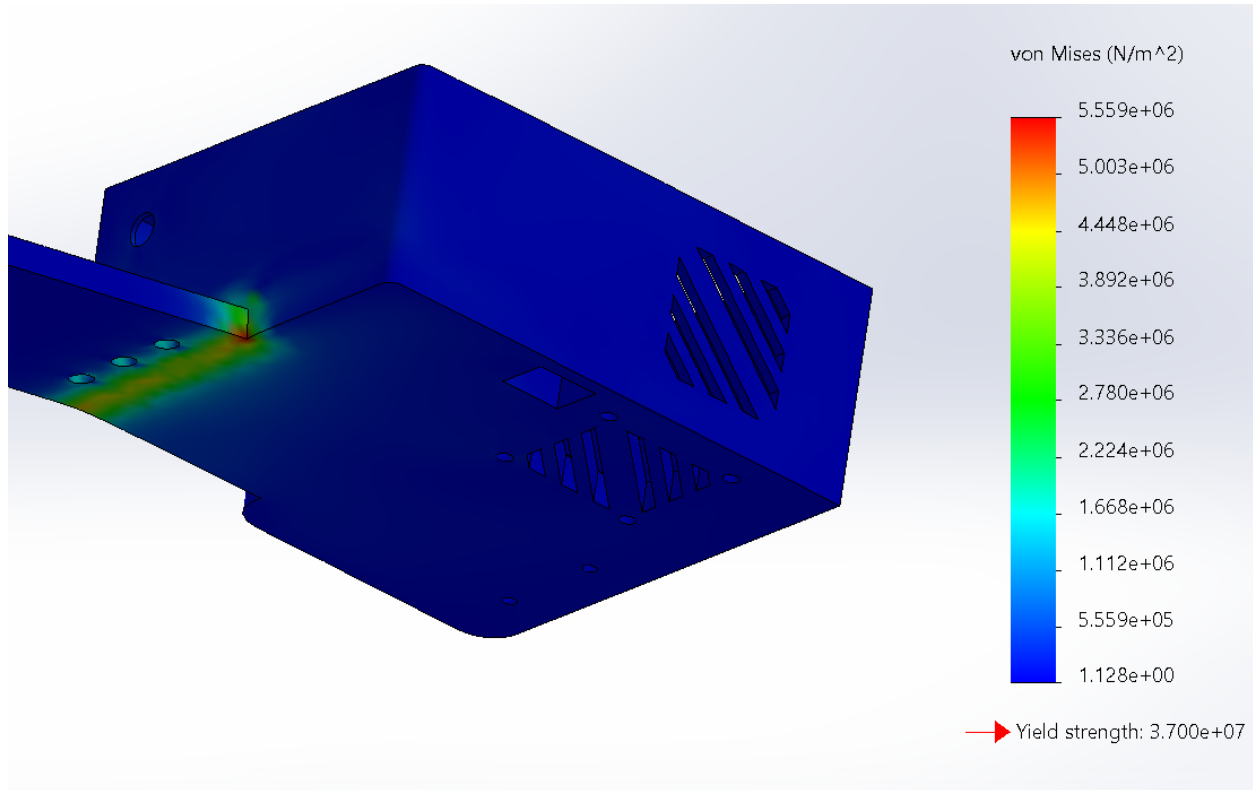
**Figure 8. Antler Adaptive Side Max Stress.** The antler develops significant stress in the arm of the antler support under extremely high and excessive loading, causing the structure to fail under this given loading scenario.

After completing the SolidWorks simulation testing on the electronics box, the resulting stresses and displacements were analyzed to determine the strength of the Tough PLA material and the designed geometries. After applying a 50 N load to the bottom surface of the box, a maximum displacement of 0.9422 mm occurred on the left side of the box (**Figure 9**). This was expected because since the box is rigidly connected to the underside of the pulley plates, it is likely to bend more the further the material is away from this fixed location. Thus, the left side of the box deflected the most. Throughout the rest of the plate, displacements were less than 0.9422 mm, proving that the geometry of the box will be strong enough to withstand typical external loads. Additionally, the maximum stress that developed under this maximum load was 5.559 MPa (**Figure 10**), which is much less than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed along the edge where the box is no longer rigidly connected to the underside of the pulley plates. This was expected because when the load is applied, the box will begin to kink at this location. Loading with a safety factor of 2.25 shows that the electronics box

will be able to withstand loads of the console, electronics, and extra downward directed forces, such as from the user pressing down slightly on the console when pressing a button, without fracturing or deforming excessively.



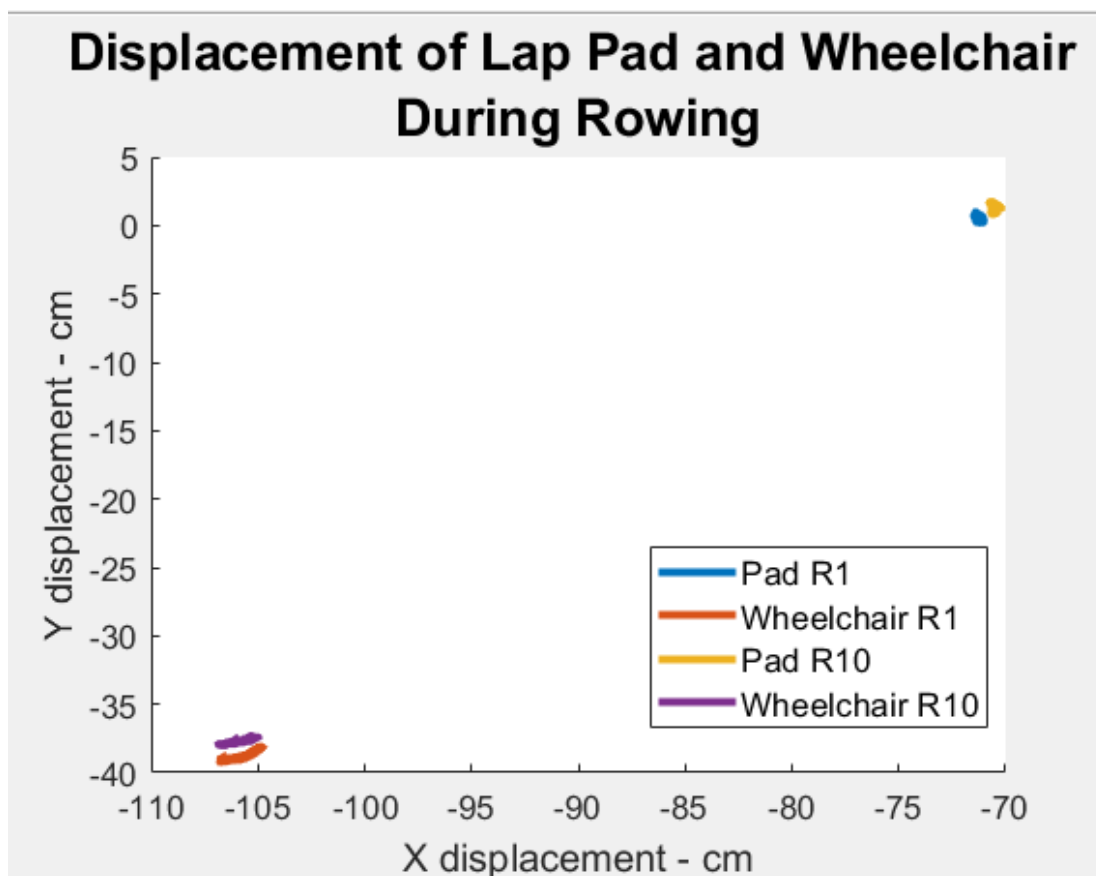
**Figure 9. Electronics Box Deformation.** The electronics box deflects less than 1 mm under a worst case loading, proving it is likely to succeed in holding the weight of the designed circuit.



**Figure 10. Electronics Box Max Stress.** The electronics box has a higher likelihood to fail right at the location where it begins to bend and is no longer rigidly connected to the underside of the pulleys. However, these developed stresses are much less than the yield stress of Tough PLA, so the box is not predicted to actually fracture.

### C. Kinovea Analysis

The completion of motion analysis in Kinovea and MATLAB shows that there was movement of the lap pad and the wheelchair during the rowing trials. When rowing on the maximum resistance level, the wheelchair experienced an overall max displacement of 1.93 cm, and the lap pad experienced an overall max displacement of 0.99 cm. When rowing on the minimum resistance level, the wheelchair experienced an overall max displacement of 2.06 cm, and the lap pad experienced an overall max displacement of 0.79 cm. Greater lap pad displacements were seen during the maximum resistance trial in both the x and y directions, and the wheelchair moved more during the minimum resistance trial. The motion of both the wheelchair and lap pad during both trials is shown in **Figure 11**. The complete breakdown of the lap pad and wheelchair displacements can be found in **Table 3**. In terms of safety, reducing displacement in the y direction is the main focus since movement in the y direction represents tipping of the wheelchair. The maximum displacement in the y direction for the wheelchair was 1.19 cm. While this value disputes the zero movement criterion set in the PDS, the stability frame is successful in securing the user.



**Figure 11. Diagram of Lap Pad and Wheelchair Motion.** Motion of the wheelchair and lap pad during the rowing trials are represented with the four different lines. The axes are not centered at 0, due to the coordinate system originating from the calibration line.

**Table 3. Max Displacements of Lap Pad and Wheelchair.** Displacements for lap pad and wheelchair from maximum and minimum resistance trials.

	Lap Pad		Wheelchair	
	R1	R10	R1	R10
x (cm)	0.48	0.58	2.06	1.93
y (cm)	0.79	0.99	1.19	0.69

References for Appendix G:

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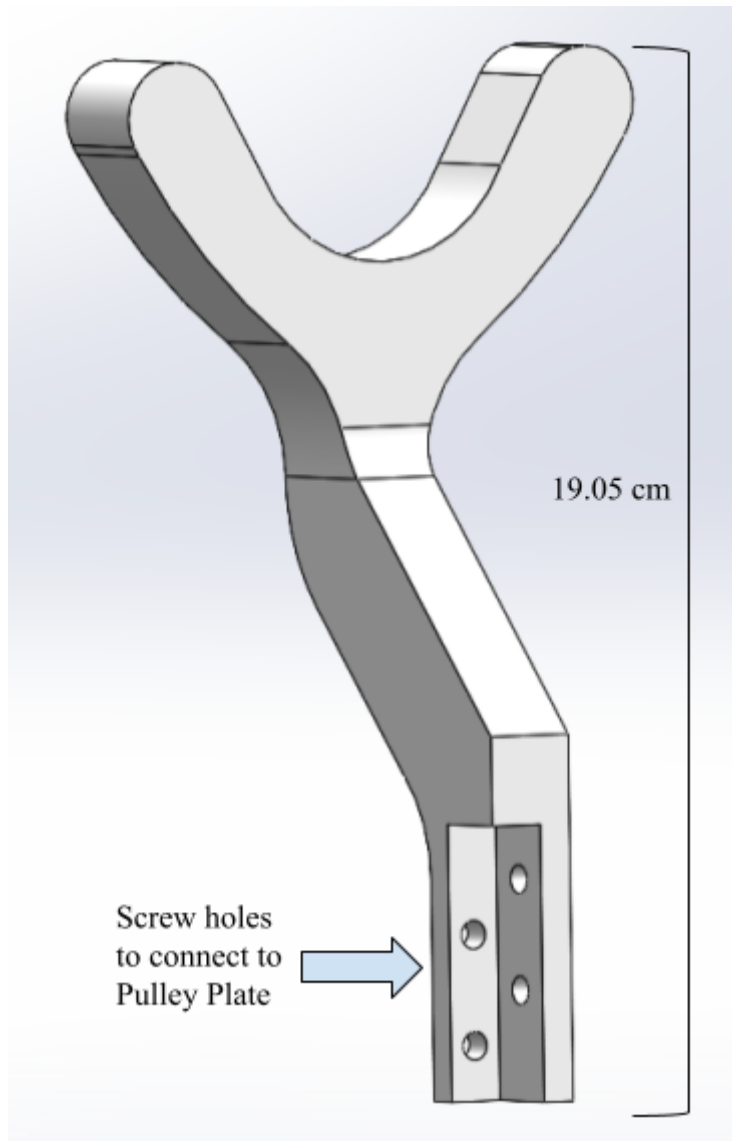


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[https://www.amazon.com/gp/product/B07GFFG1BQ/ref=ppx\\_yo\\_dt\\_b\\_asin\\_title\\_o00\\_s00?ie=UTF8&psc=1](https://www.amazon.com/gp/product/B07GFFG1BQ/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1) (accessed Dec. 11, 2022).
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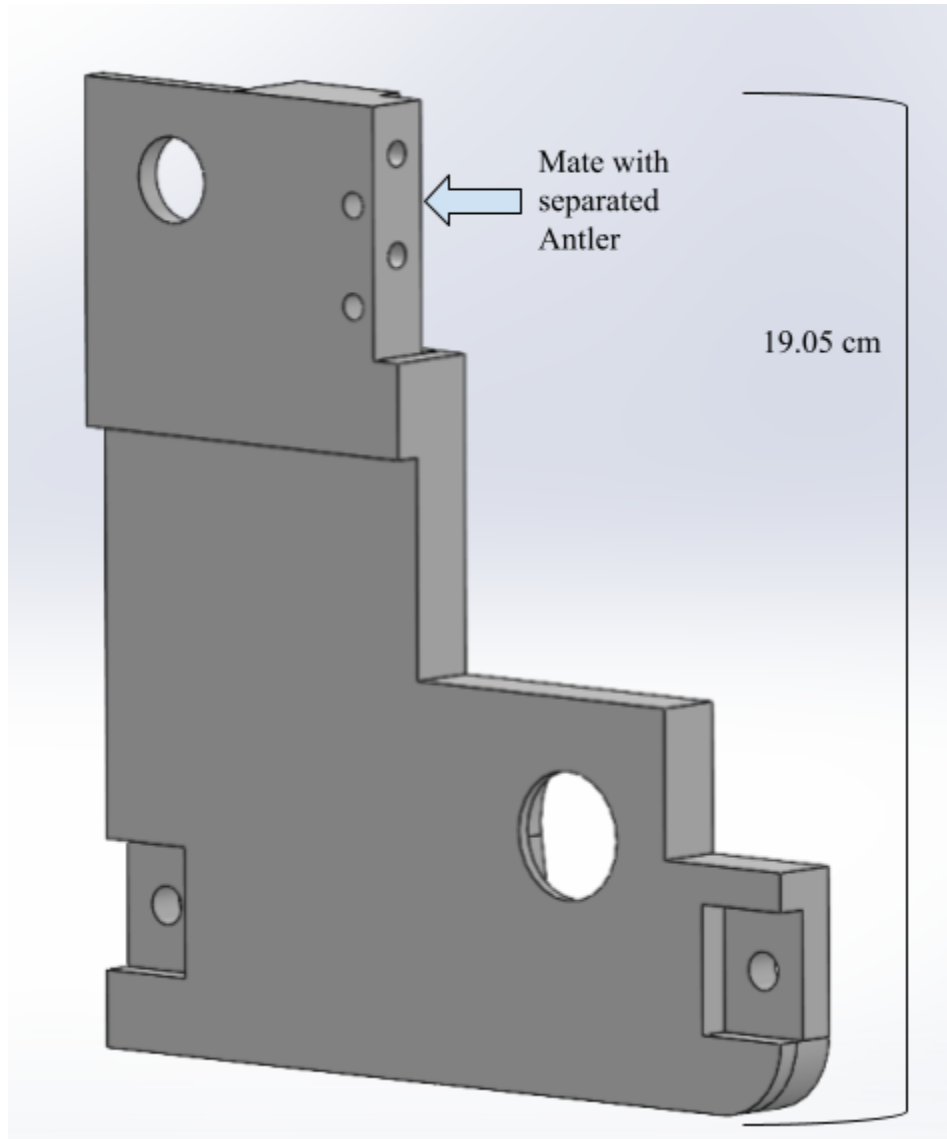
## **Appendix J: BME 402 Updates to Pulley Plates and Antlers**

This semester, one of the main goals was to modify the Pulley Plate and Antler design to make them more manufacturable so that Johnson Health Tech could fabricate the parts out of metal, specifically Plain Carbon Steel. This would help to give the adaptive rower a more professional look while also increasing the strength of the parts, since metal is stronger and more durable than 3D printed Tough PLA. To begin the process of modifying the Pulley Plates and Antlers for manufacturability, the first proposed design was to split the component into two separate pieces. If the design stayed as one piece, the metal fabrication would waste a lot of unused material. This is because Johnson Health Tech would have to start with one large rectangular prism of metal and essentially cut out the shape of the Pulley Plate and Antler. To split the part into two separate pieces, the antler was cleaved from the side of the Pulley Plate and made a separate part in SolidWorks. Then, screw holes were made that would rigidly attach the Antler to the Pulley Plate. The thickness of all the parts remained the same as the final BME

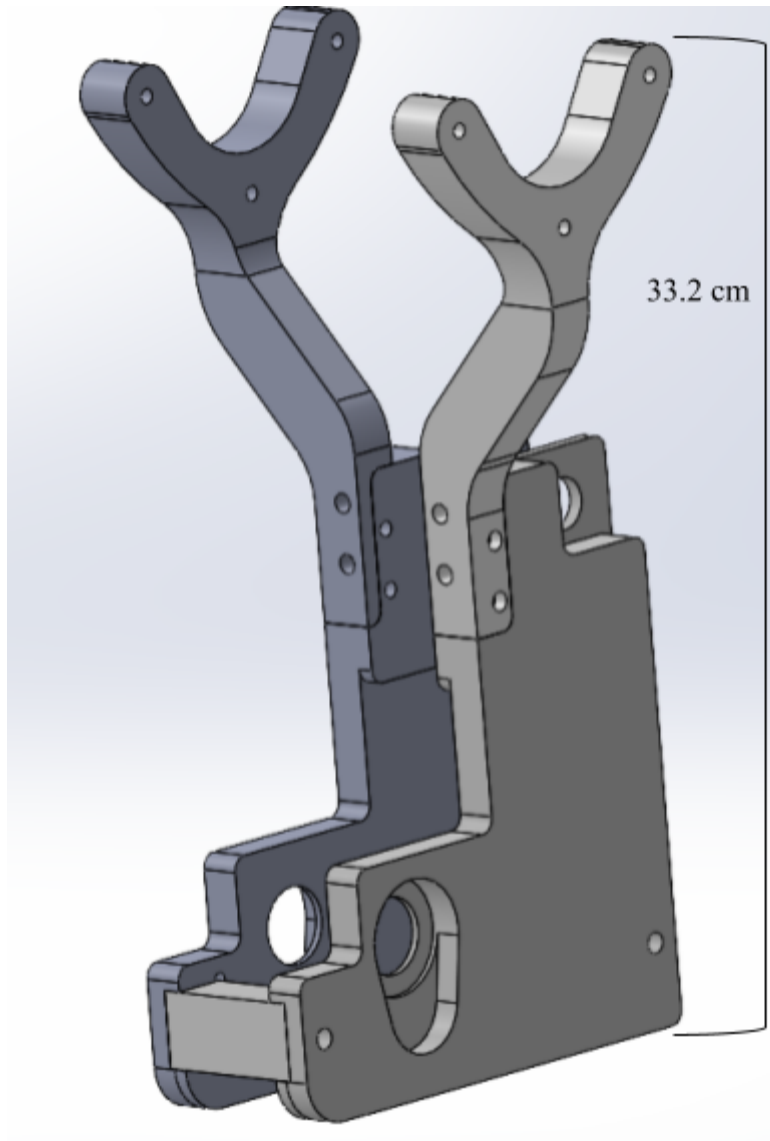
400 concept. The separated Antler (**Figure 1**) and Pulley Plate (**Figure 2**) can be seen below. These models were sent to Johnson Health Tech for slight modifications that included adding fillets to all corners capable of what their machines could create (**Figure 3**).



**Figure 1. Separated Antler.** The separated Antler has four screw holes that can rigidly connect to the Pulley Plate via the corner crevice that will mate with the corresponding corner on the Pulley Plate.



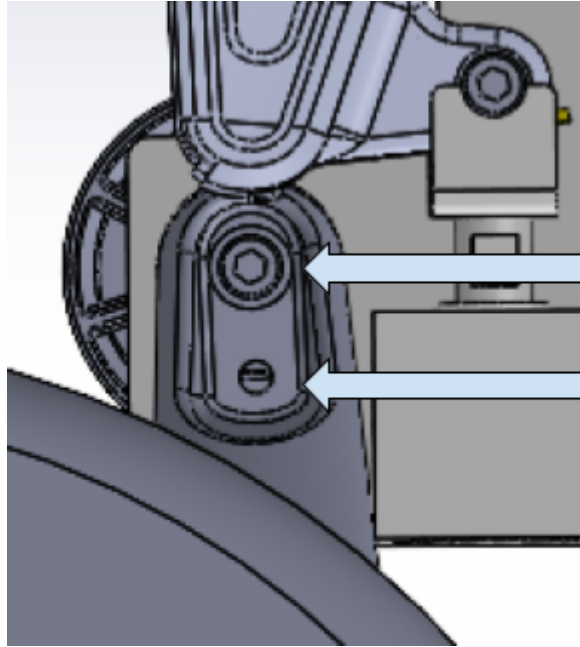
**Figure 2. Separated Pulley Plate.** The separated Pulley Plate has a mating corner with screw holes that will fit snugly with the separated Antler. No other features on the Pulley Plate were modified.



**Figure 3. Johnson Health Tech modified Two-Piece Initial Design Assembly.** Johnson Health Tech added fillets to all the sharp corners on the antlers and pulley plate based on what dimension of fillet their machines can create. Johnson Health Tech also added three mounting holes to each antler to secure it to machines while cutting.

After developing this initial design, Johnson Health Tech realized that the cost to fabricate the separated Antler and Pulley Plate for both the right and left sides would be over \$430. This is too expensive, and would again result in a lot of wasted material. To create a more robust design that is cheaper to fabricate yet still achieves the design requirements, a new approach was taken. To create this new design, the Pulley Plate and Antler were once again modeled as a single component, rather than two separate pieces. One of the main changes for the new design was how the components attached to the rower neck support arms. In the prior design, the Pulley Plates sat on the rower neck support arms with the layered cavity designed in BME 400 to prevent translation or rotation while rowing. However, the new design uses a different mechanism to prevent this movement. Rather than making a layered cavity, the new

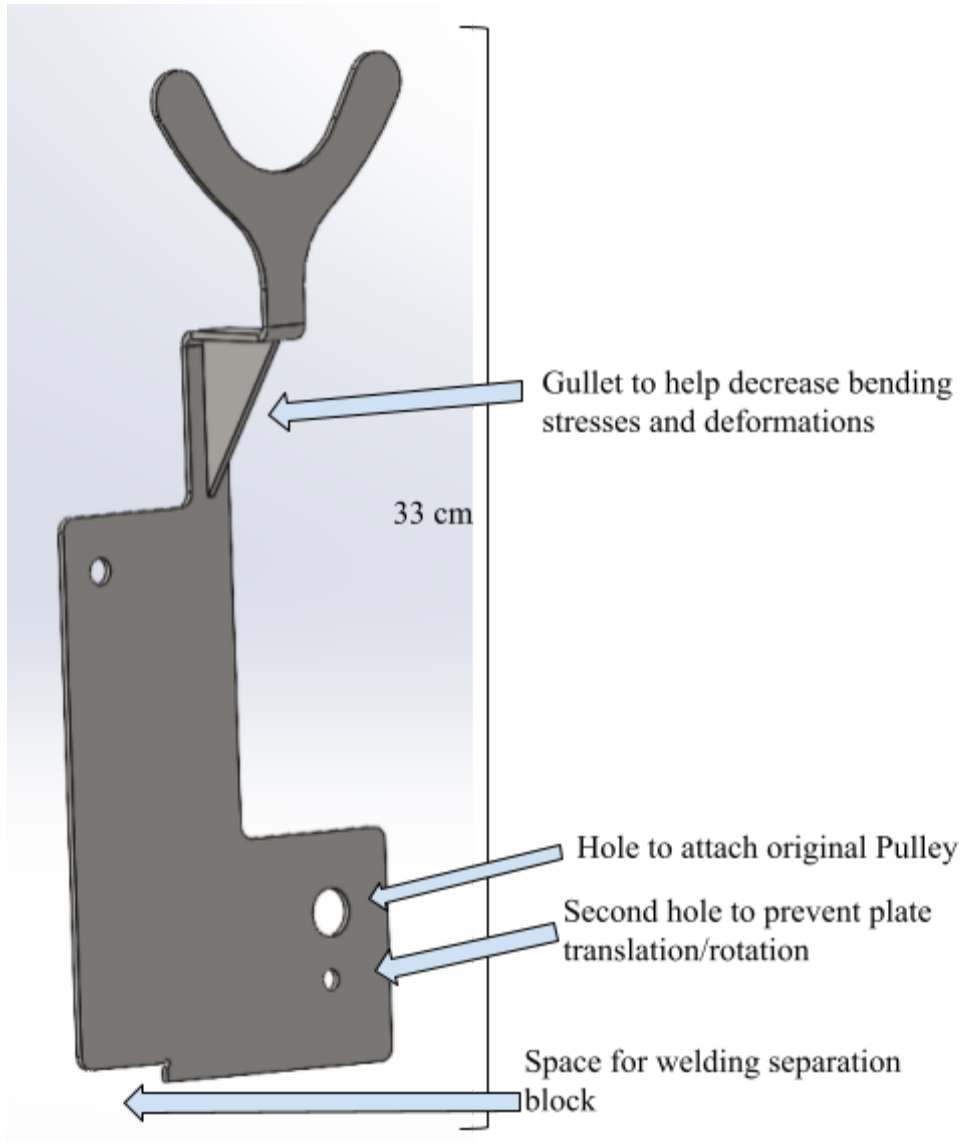
design aims to have the entire Pulley Plate and Antler be one piece of sheet metal with a thickness of 0.104 inches (12-gage). To attach the plates to the rower support arms, two holes will be drilled in the side of the plates that will align with the two holes on the rower neck support arms. Currently, only the top hole has ever been used, as this is the hole that the original pulley is rigidly attached to. On the rower neck support arms, there is a second unused hole directly below the pulley attachment hole. To attach the new plates to the rower neck support arms, this second hole will be utilized. Thus, by having two rigid connection points (**Figure 4**), the plate will not be able to rotate or translate once attached.



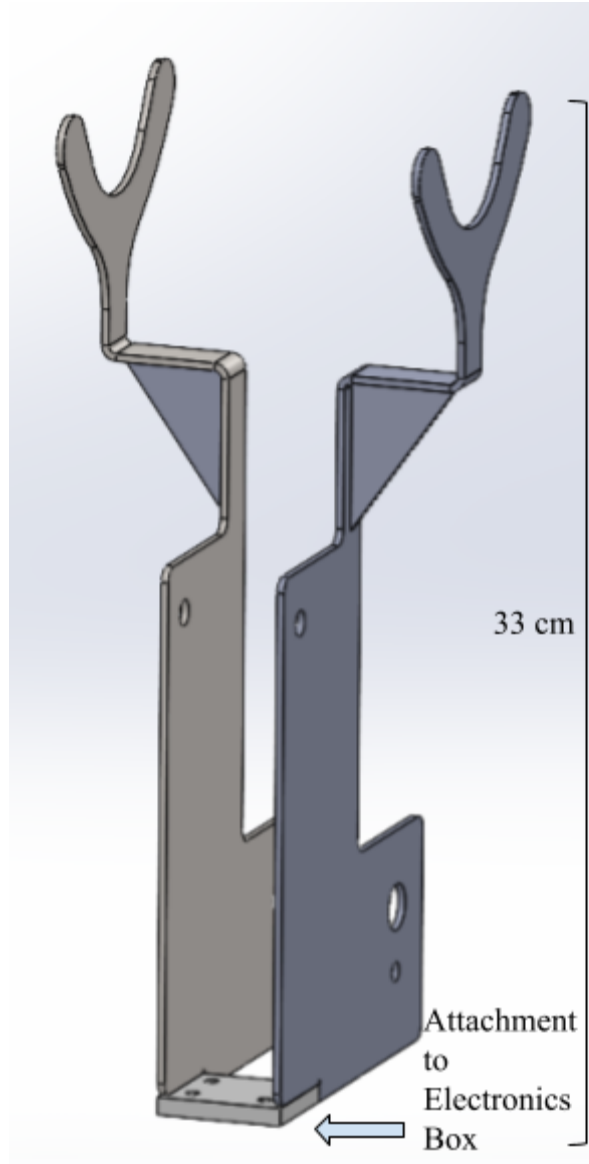
**Figure 4. New Pulley Plate Connection to Rower Neck Support Arms.** The Pulley Plate will now be screwed into both holes on each of the rower neck support arms to prevent rotations and translations during rowing.

A second difference between the prior design and this new design is the concept of the separation blocks. In the prior design, two separation blocks were used to push the Pulley Plates apart to counteract the slight improper fit of the layered cavity on the rower neck support arms. However, now that the thinned plates will be able to sit flat and flush on the inner surface of the rower neck support arms, these blocks are no longer required. A third difference between the prior and new design is the connection mechanism between the Pulley Plates and the console rotation electronics box. Since the plates are now much thinner than the prior design, a new method of attaching the motor box to the Pulley Plates was required. This is because the plates are too thin to screw in a screw from the bottom face. To fix this issue, a rectangular cut will be made in the bottom front corner of each plate. Then, a block of metal will be welded to the two plates. Within this block, four corner screws will be placed that will secure the box containing the stepper motor and console for console rotation to the Pulley Plate assembly.

The fourth difference between the prior and new design are the angles of the antlers. In the prior design, Johnson Health Tech had suggested making the antlers come up at some arbitrary angle rather than having two 90° bends because the 3D printed Tough PLA material would be able to better withstand loads in the angled formation rather than the 90° bend formation. However, since Steel is much stronger than plastic, Johnson Health Tech suggested a return to the 90° bend concept. This will also make it easier to fabricate, as 90° bends are easier to control with their metal bending equipment as opposed to bends of other angles. The fifth difference is the addition of the triangular gullet. This gullet serves to better support the arm of the antler under drastic bending loads to prevent yielding or failure from occurring. The final difference between the prior and new design is that the antlers are now slightly taller. At the conclusion of BME 400, the antlers sat too low on the rower, which prohibited the console from being able to rotate under the handlebar when completely vertical. To fix this problem, the antlers have been made to be around 1.5 inches taller than the original design. The updated thinned Pulley Plate and Antler part (**Figure 5**), assembly (**Figure 6**), and full rower assembly (**Figure 7**) can be seen below.

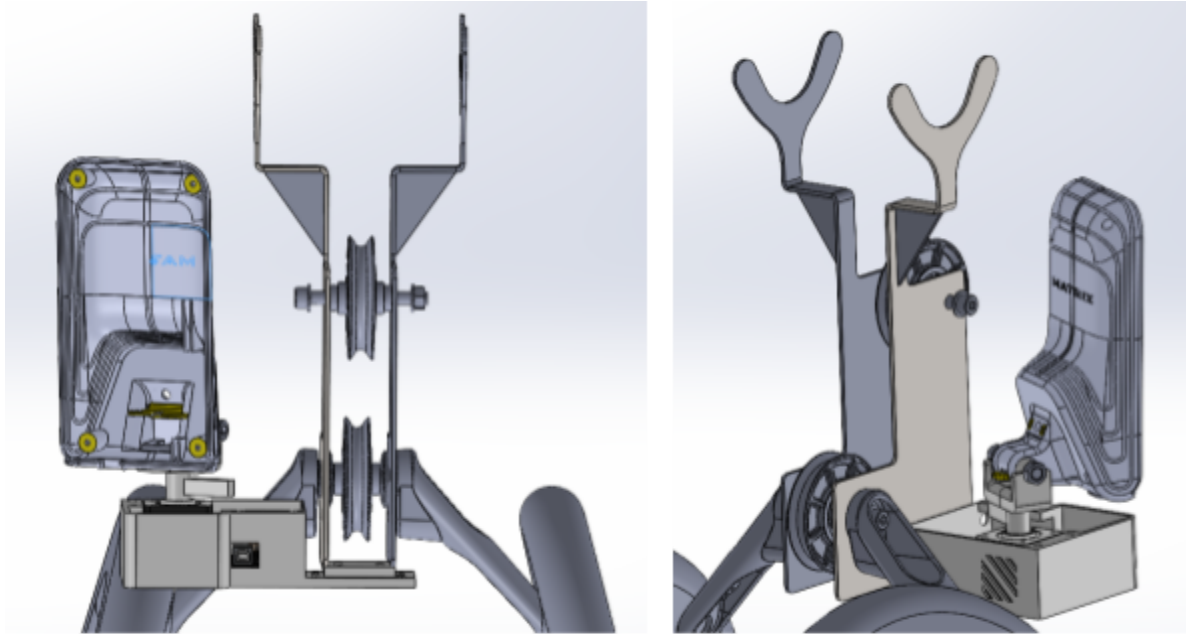


**Figure 5. Tinned Pulley Plate and Antler Part.** The Pulley Plate and Antler are thinned and combined as one part. The Antler has two 90° bends and is 1.5 inches taller than the original Antler design. Two holes will be drilled in the plates to rigidly attach the rower neck support arms to prevent any translation or rotation.



**Figure 6. Tinned Pulley Plate and Antler Assembly.** The Pulley Plate and Antler assembly will replace the current 3D printed design. A front block welded to the bottom of both plates will allow for a new connection mechanism to the electronics box for console rotation.





**Figure 7. Tinned Pulley Plate and Antler Assembly on Rower.** The front (left) and back (right) views of the updated and thinned Pulley Plate and Antler assembly show the new design on the rower. This new design will allow for complete rotation of the console under the handlebar and still allow for attachment to the console rotation electronics box.

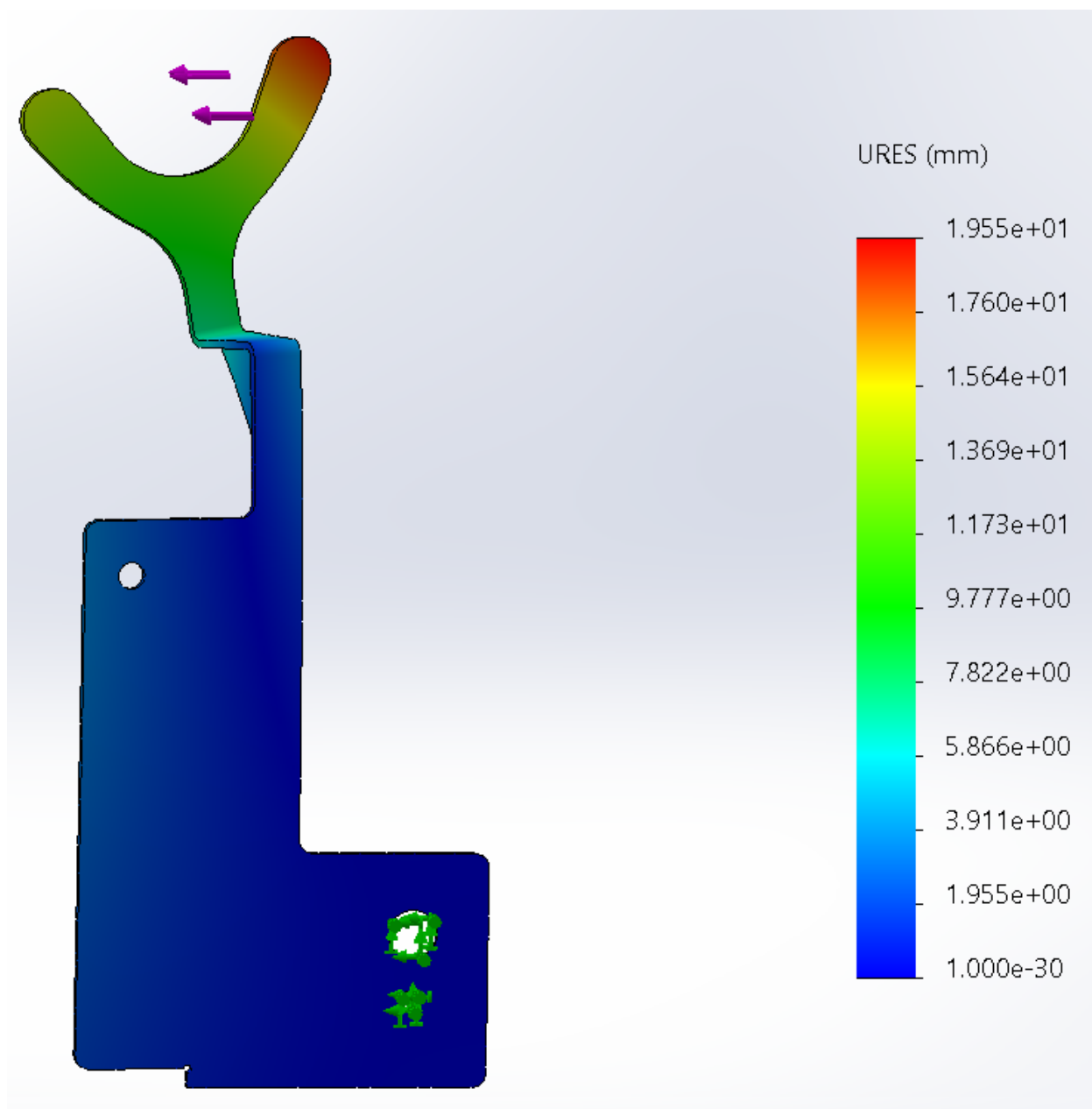
The manufacturing process for this updated design will be much easier and more cost effective. To create this part, Johnson Health Tech will use a laser cutter to cut out the flattened profile of the Pulley Plate and Antler. Then, they will use a machine to bend the Antler to give it its two 90° bends. Lastly, the front block will be welded to the underside cavity of the two plates to allow connection of the console rotation electronics box. After fabrication, this assembly will be integrated with the rest of the rower. Additionally, once the parts are completely finalized, a final SolidWorks Simulation will be run using the correct material to confirm the improved strength and rigidity for typical use cases.

### **Appendix K: BME 402 Pulley Plate & Antler Simulation**

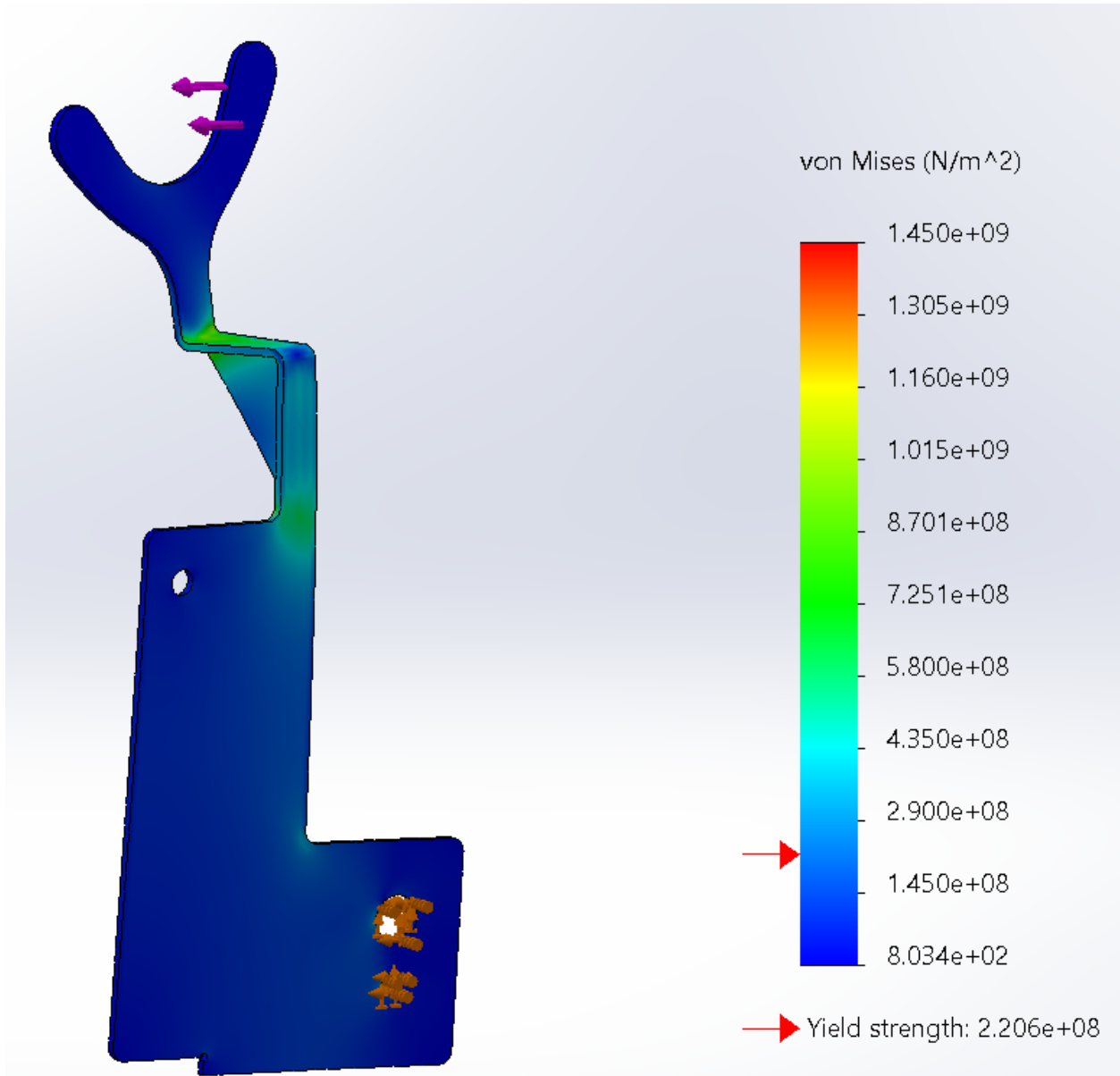
After completing the SolidWorks models of the final versions of the Pulley Plate and Antlers with the client's advice, SolidWorks simulations were run on the single component plate/antler under four loading conditions. The component was modeled as one piece of Plain Carbon Steel Sheet metal, as this is what they will physically be fabricated from. In BME 301 and BME 400 simulations, loads of 1050 N were used for all simulations. This was because this was determined to be the maximum force a human could apply to a rowing machine. However, after discussion with the client, it was determined that this load is really describing the maximum load that would be applied to the rower itself, and not to the handlebar-antler interface.

Therefore, it was determined that this load value was an inappropriate choice for running simulations on the manufactured plate/antler. This was confirmed when running simulations with the 1050 N load. Stresses would be several orders of magnitudes larger than the yield strength of Plain Carbon Steel and deformations would be close to 30 cm. So, as a proxy, the tension data collected in BME 301 was used instead. From this data, the maximum tension developed on the adaptive side while rowing never exceeded 300 N. Therefore, a simulation was run with a 300 N load placed at the distal tip of the antler facing the adaptive side to assess the deformation (**Figure 1**) and stress (**Figure 2**). Similarly, the BME 301 tension data showed that the maximum tension that developed on the standard side while rowing never exceeded 400 N. Therefore, a simulation was run with a 400 N load placed at the distal tip of the antler facing the standard side to assess the deformation (**Figure 3**) and stress (**Figure 4**). Both of these pairs of simulations have a safety factor of 2, since ideally this load would be distributed equally between both the right and left pulley plate and antlers. Next, a simulation was run in which each of these loads were cut in half. This was done to simulate the expected stresses and deformations that each plate/antler would endure under a maximum load. Therefore, a simulation was run with a 150 N load placed at the distal tip of the antler facing the adaptive side to assess the deformation (**Figure 5**) and stress (**Figure 6**). Similarly, a simulation was run with a 200 N load placed at the distal tip of the antler facing the standard side to assess the deformation (**Figure 7**) and stress (**Figure 8**).

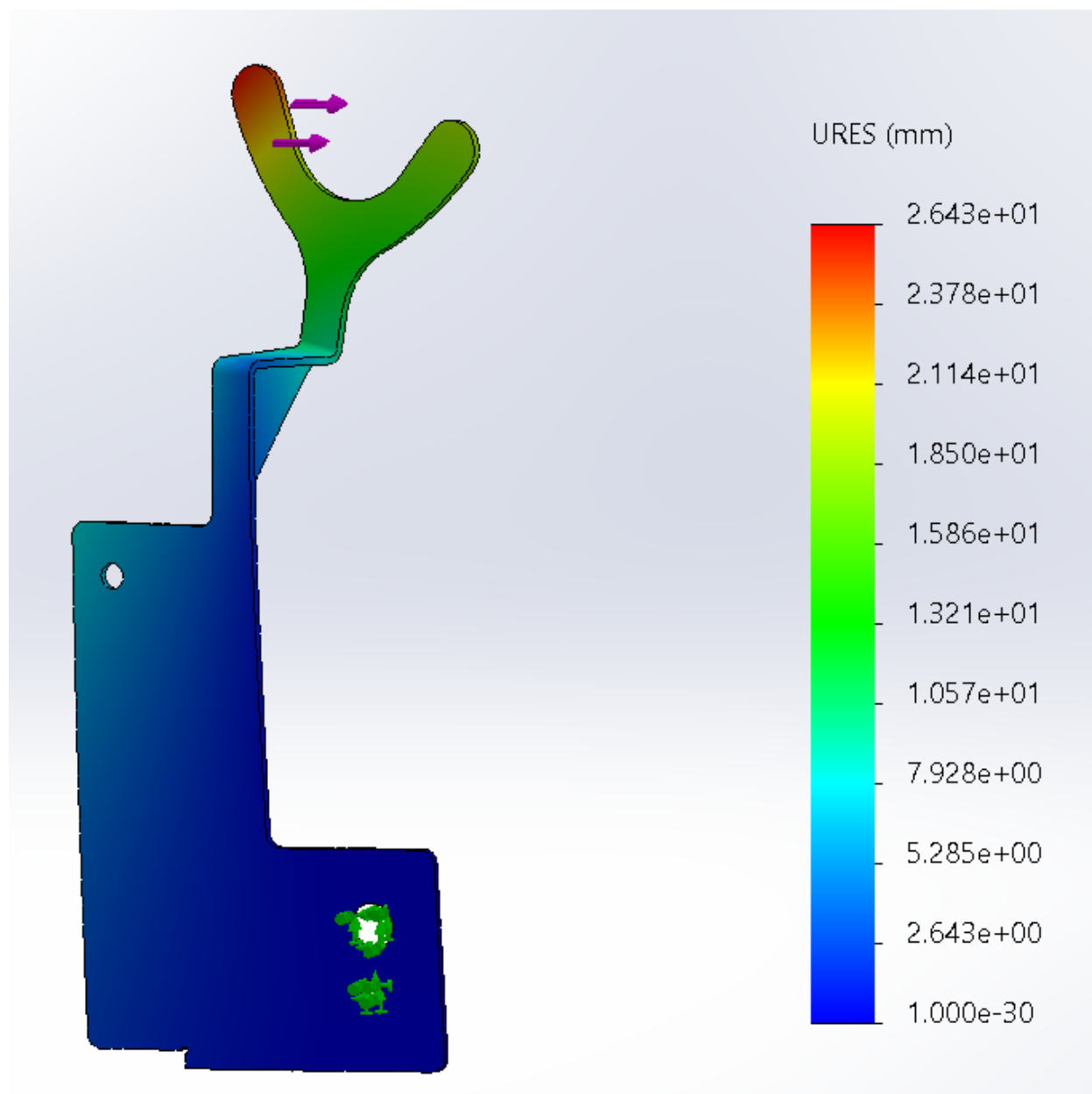
As can be seen in the figures below, the maximum displacement of 2.643 cm occurs when a 400 N load is applied towards the standard side of the rower. However, this describes a safety factor of two. When looking at the 150 N and 200 N loading scenarios (which describe how much force one pulley plate and antler would truly be expected to endure), the max displacement of 1.167 cm occurs when a 200 N load is applied towards the standard side of the rower. After discussing these results with the client, the client is confident that the physical steel sheet metal part will not deform. Additionally, it is very unlikely that the plates themselves will actually ever experience loading of this magnitude. These forces are the forces that develop while rowing at the highest resistance level. It is very unlikely for someone to pull on the handlebar while it is still in the antler cavities. Therefore, although these loading conditions predict a little bit of displacement and slight yielding, it is likely that loads much less than these will actually be applied to the component and thus no displacement or yielding should occur. A person who is using the rower will understand that they must first lift the handlebar out of the cavity prior to rowing. This will be ensured via the addition of warning labels to the machine to indicate how to grab and remove the handlebar from the antlers. Any slight loads felt by the pulley plate and antlers would be from the user lifting the handlebar out of the cavity at a slight angle, which would apply slight pressure to the inner surface of the antler cavity. These slight loads are not predicted to cause yielding or failure. Once the parts are fabricated and attached to the rower, a physical test will be performed in which the handlebar will be pulled back and let go to fly towards the pulley plate and antlers to determine if it causes them to break.



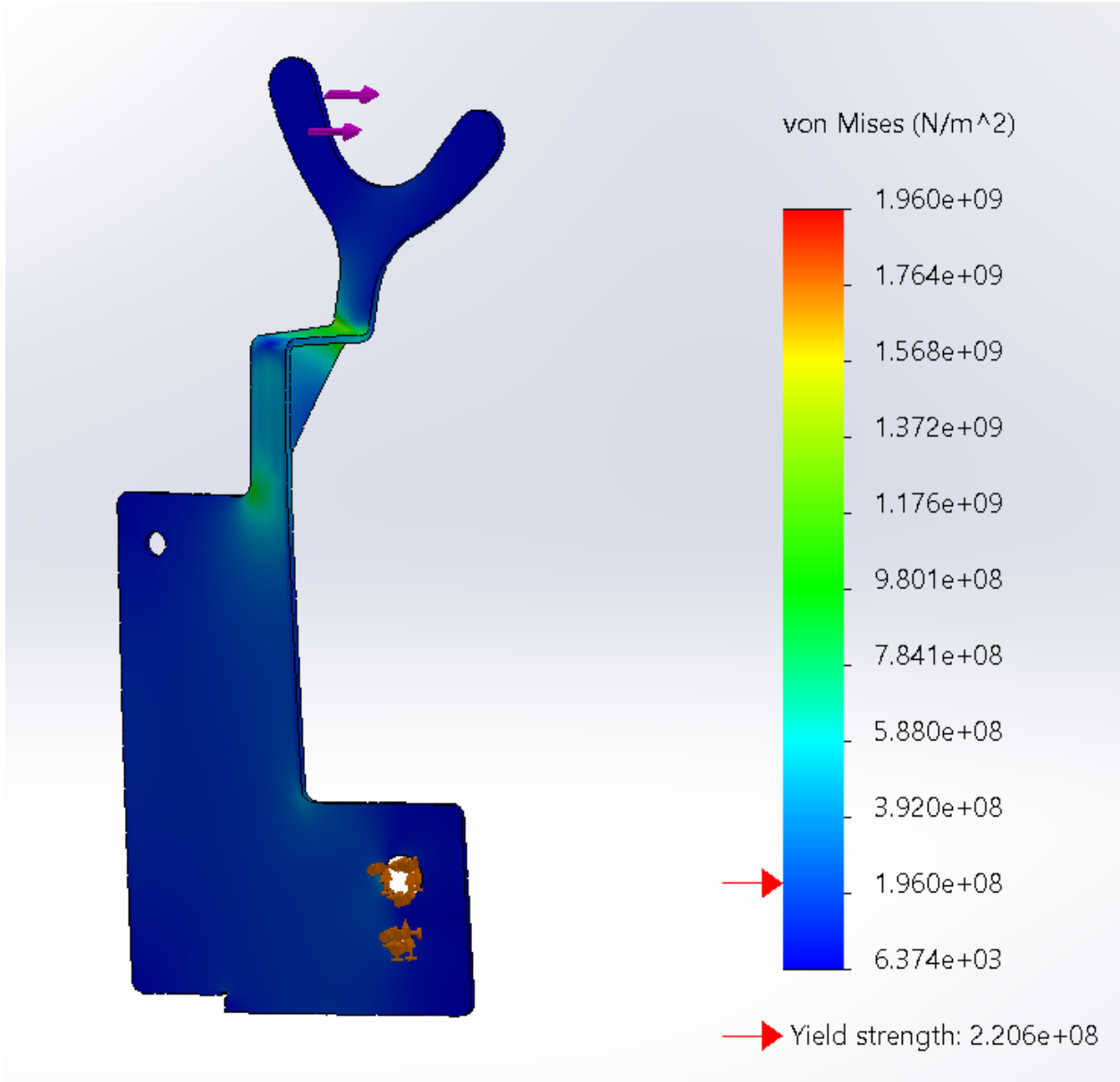
**Figure 1. 300 N Load Adaptive Side Deformation.** Under a 300 N load applied towards the adaptive side of the rower, the Pulley Plate and Antler experience a max displacement of 1.955 cm at the distal tip of the Antler.



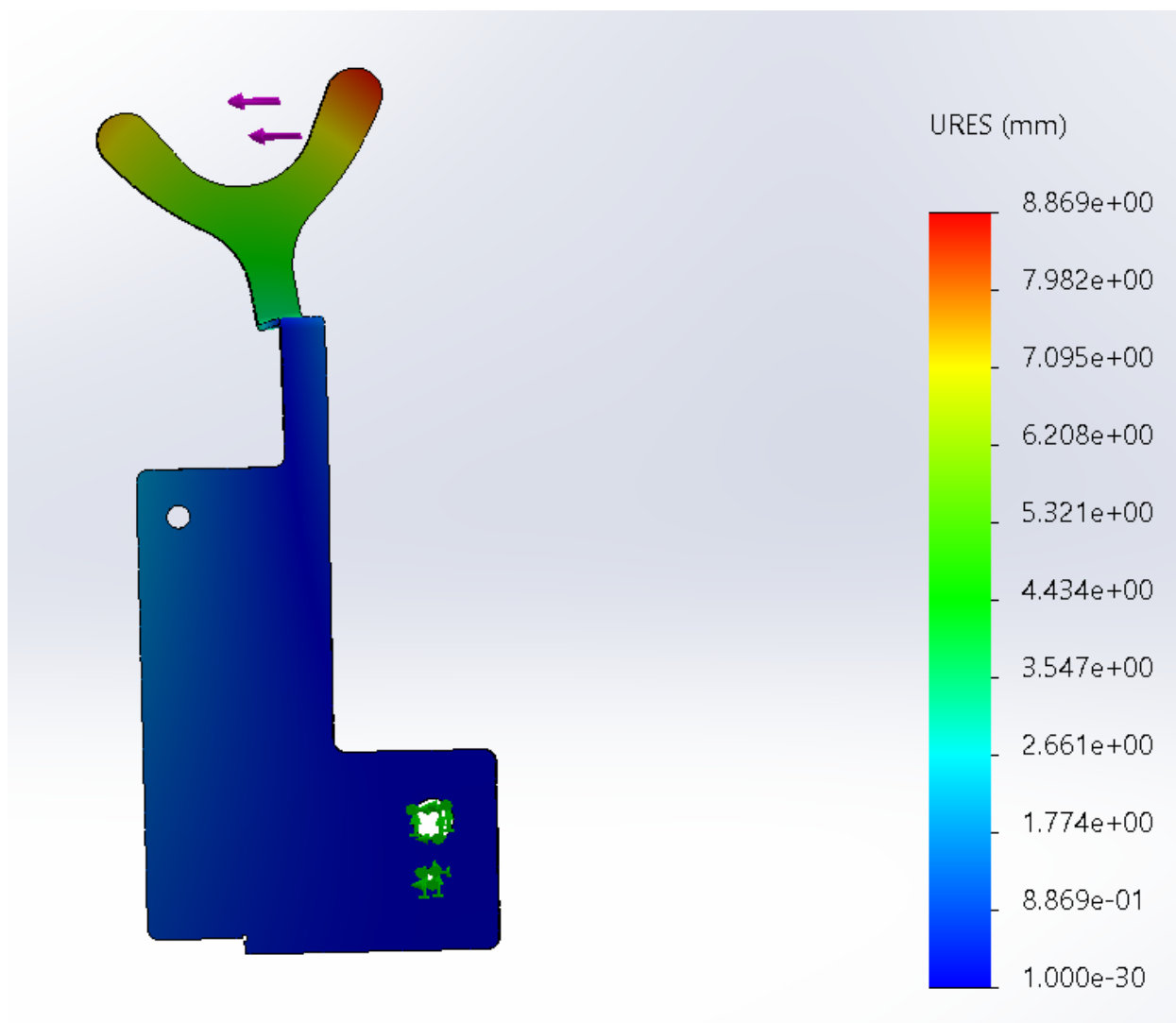
**Figure 2. 300 N Load Adaptive Side Stress.** Under a 300 N load applied towards the adaptive side of the rower, the Pulley Plate and Antler experience a max stress of 1450 MPa at the corner between the gullet and the vertical portion of the Antler.



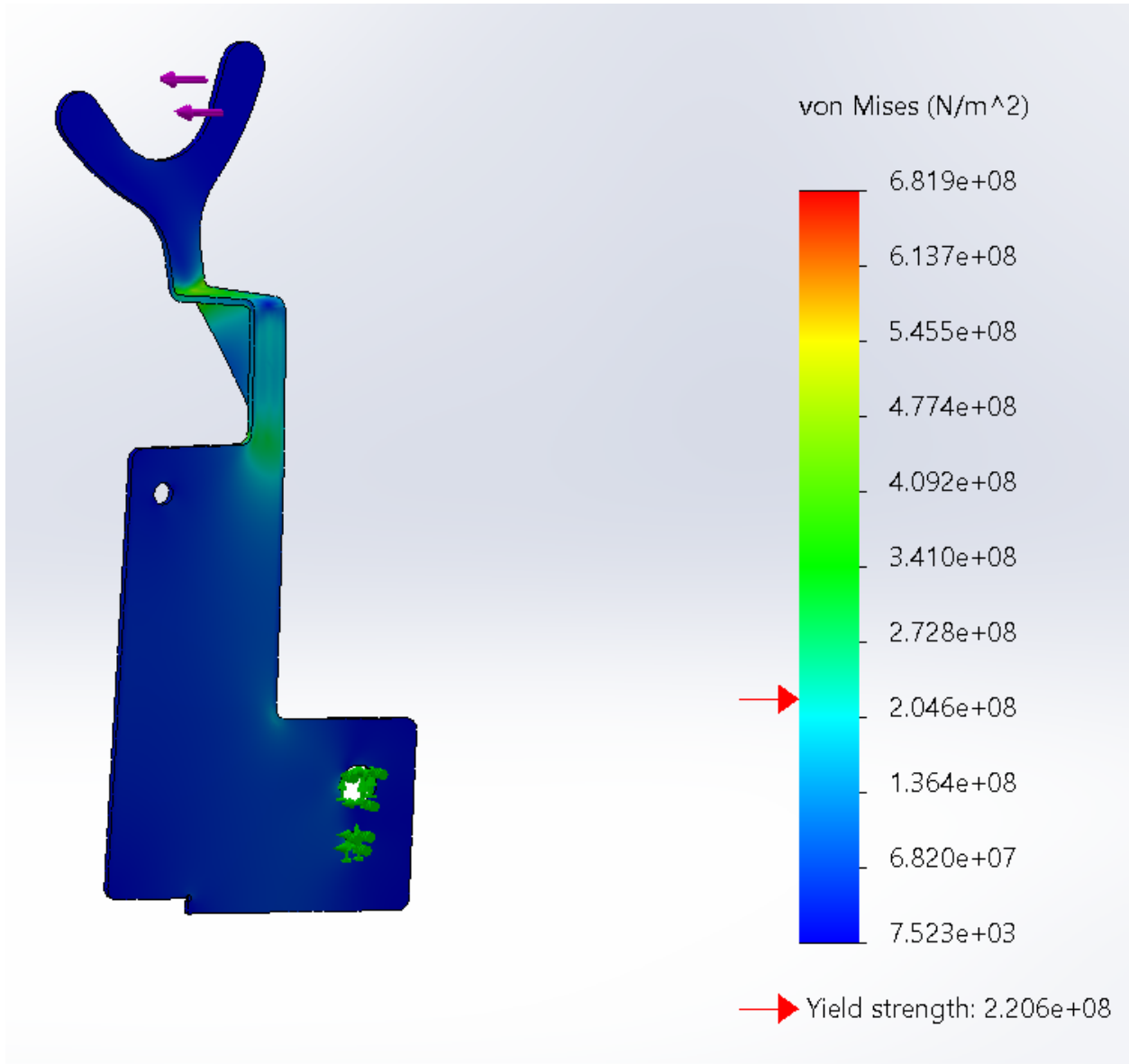
**Figure 3. 400 N Load Standard Side Deformation.** Under a 400 N load applied towards the standard side of the rower, the Pulley Plate and Antler experience a max displacement of 2.643 cm at the distal tip of the Antler.



**Figure 4. 400 N Load Standard Side Stress.** Under a 400 N load applied towards the standard side of the rower, the Pulley Plate and Antler experience a max stress of 1960 MPa at the corner between the gullet and the vertical portion of the Antler.

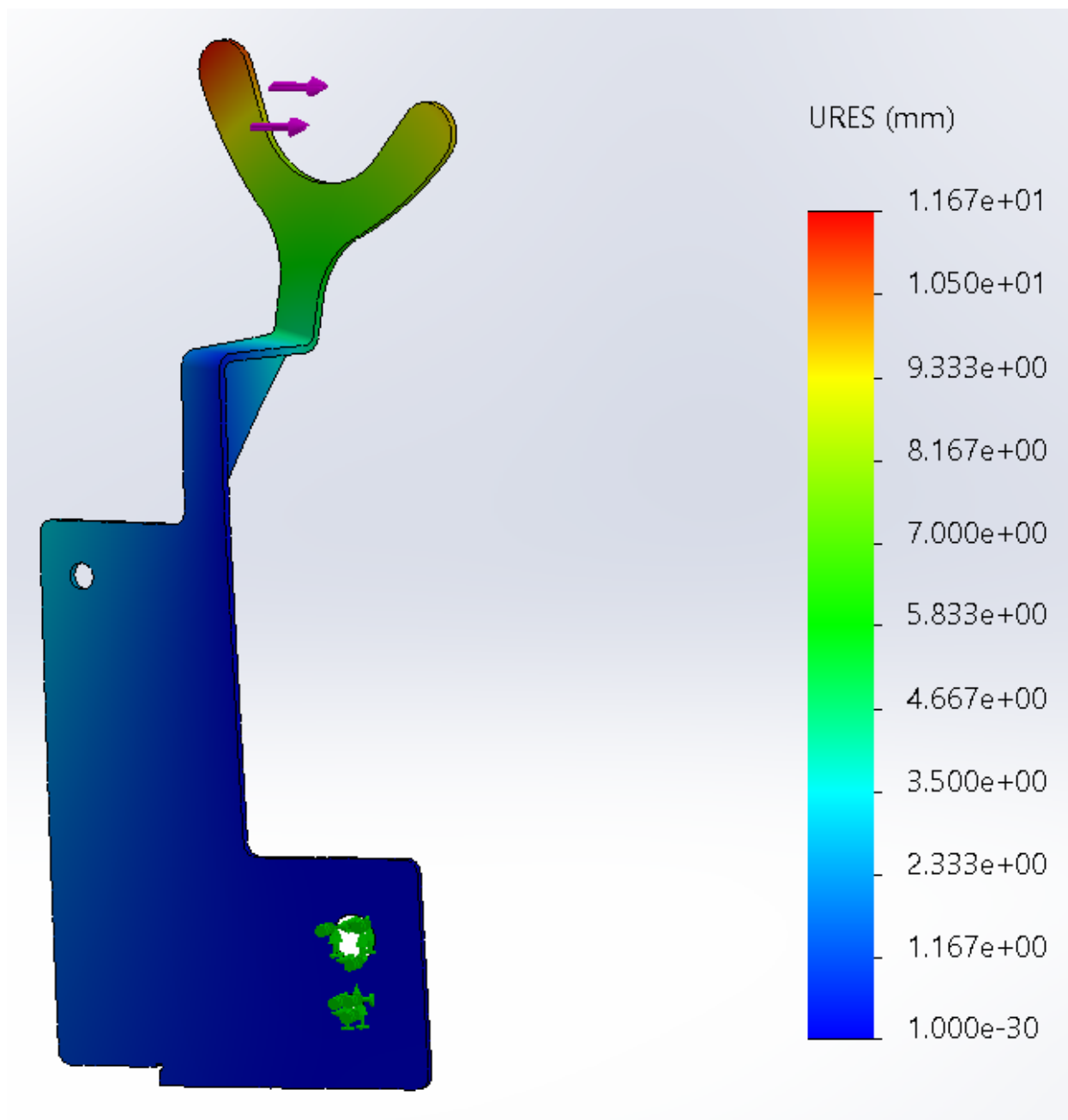


**Figure 5. 150 N Load Adaptive Side Deformation.** Under a 150 N load applied towards the adaptive side of the rower, the Pulley Plate and Antler experience a max displacement of 0.8869 cm at the distal tip of the Antler.

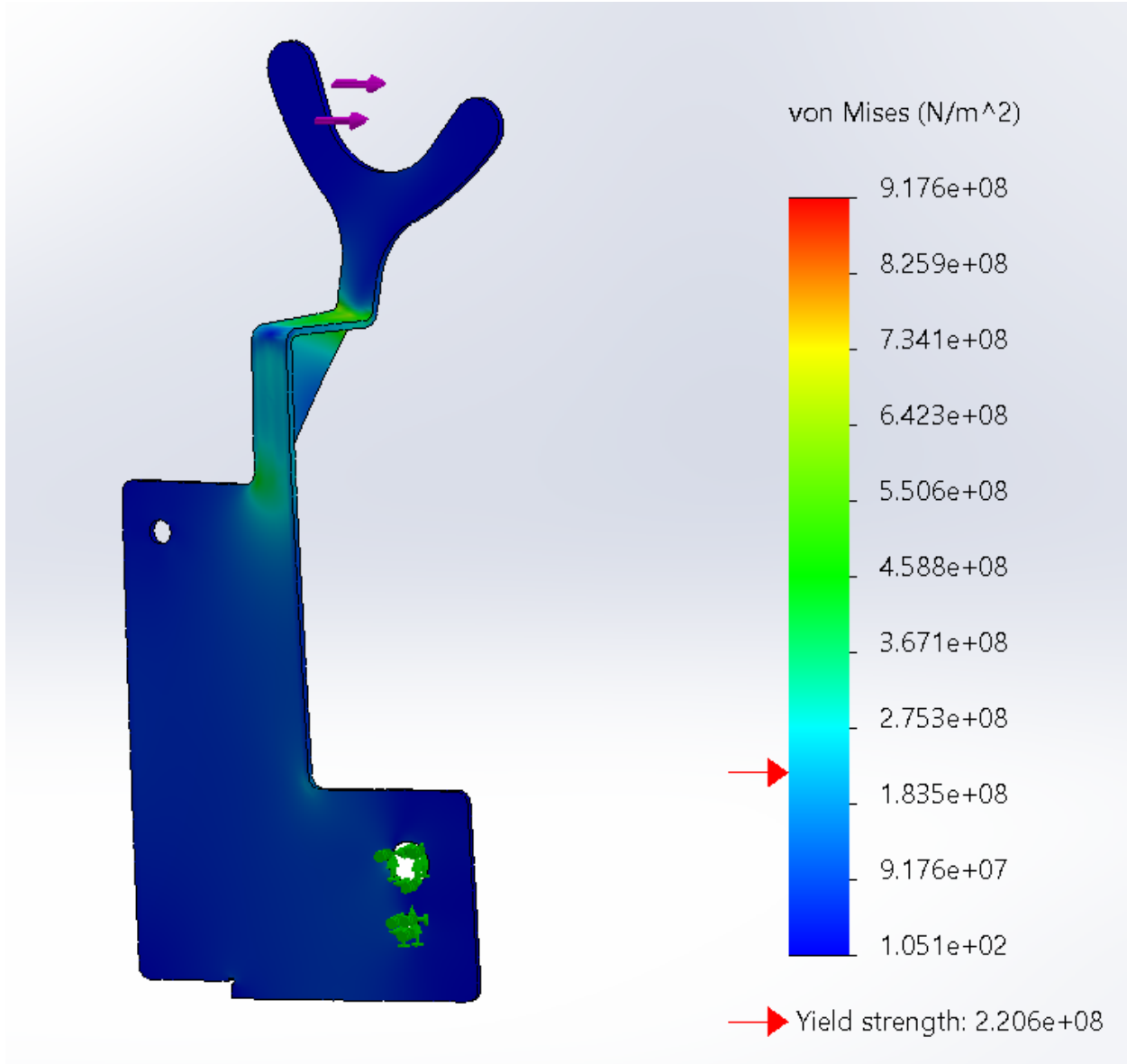


**Figure 6. 150 N Load Adaptive Side Stress.** Under a 150 N load applied towards the adaptive side of the rower, the Pulley Plate and Antler experience a max stress of 681.9 MPa at the corner between the gullet and the vertical portion of the Antler.





**Figure 7. 200 N Load Standard Side Deformation.** Under a 200 N load applied towards the standard side of the rower, the Pulley Plate and Antler experience a max displacement of 1.167 cm at the distal tip of the Antler.

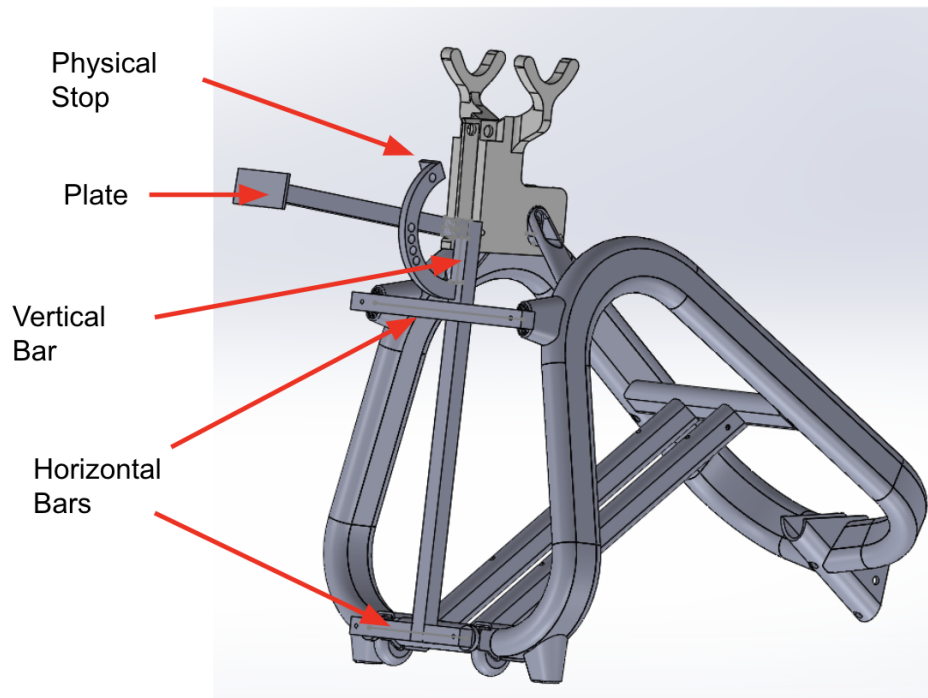


**Figure 8. 200 N Load Standard Side Stress.** Under a 200 N load applied towards the standard side of the rower, the Pulley Plate and Antler experience a max stress of 917.6 MPa at the corner between the gullet and the vertical portion of the Antler.

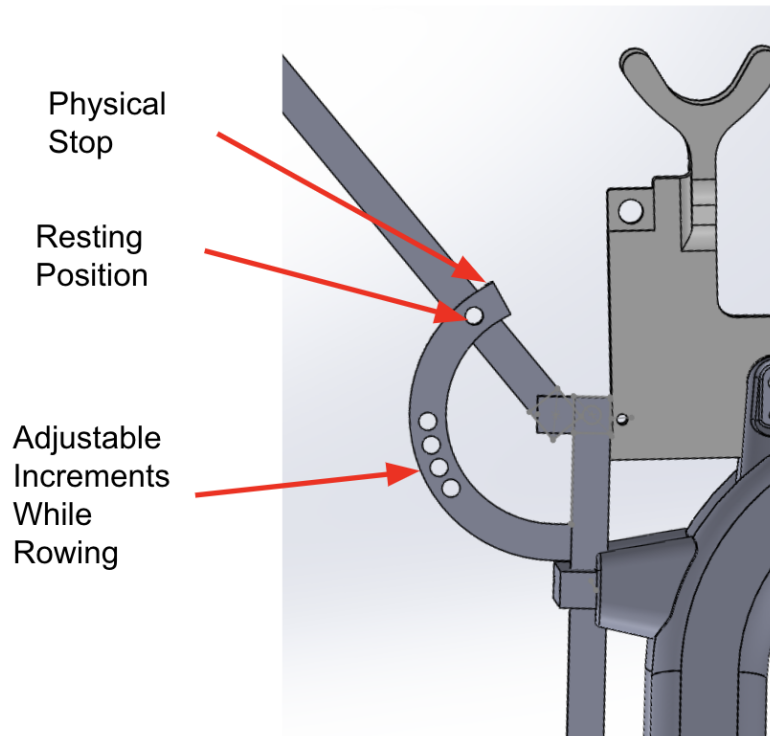
### Appendix L: BME 402 Updates to Stabilization Frame

The main goal for the stabilization frame this semester was to modify it to be manufacturable and to attain a more professional look. To achieve this goal, unnecessary segments of the frame were removed, and the material of the frame was changed from perforated to non-perforated steel bars to improve the strength and aesthetic of the part. The vertical support bar is shifted to now be in plane with the two horizontal support bars (**Figure 1**). This change

increases the strength of the frame in addition to improving its silhouette. The previous method for providing rotation to the lap pad restraint, which was a bolt and screw stop, is replaced by a metal arc with holes at specific increments and a spring-loaded pin (**Figure 2**). This is a common adjustment mechanism for exercise equipment. This change resolves the issue of the lap pad restraint hinge being too firm to move or too loose such that it would rotate too quickly and potentially fall on the user. The metal arc/plate contains a physical stop to control the stowing position of the lap pad restraint. In order to attach the lap pad, a plate was added to the end of the lap pad extension bar.



**Figure 1. SolidWorks Model of Updated Stabilization Frame.** The updated stabilization frame has the vertical bar in plane with the horizontal support bars. Additionally, the pin-adjustment mechanism has been incorporated to limit the lap pad movement to discrete increments.



**Figure 2. Pin-adjustment Mechanism.** The pin-adjustment mechanism allows for the lap pad bar to rotate and lock into discrete positions along the arc. The top hole is the resting position for the lap pad while the other holes are positions that the user can utilize to lock the lap during the rowing exercise. The pin-adjustment mechanism also includes a physical stop at the top of the arc.

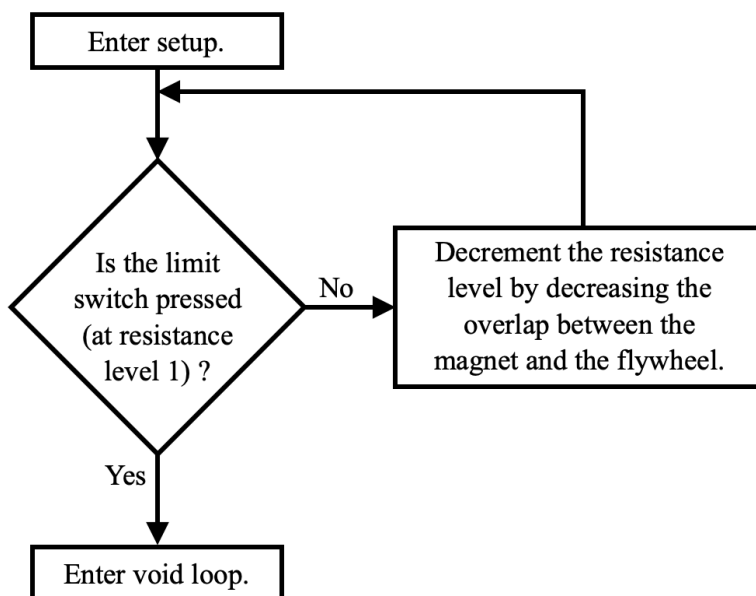
## Appendix M: BME 402 Adaptive Resistance Mechanism

### *Circuit and Code*

Because individuals who require the use of wheelchairs operate the Adaptive Rowing Machine from the side opposite the machine's original intended use, these individuals are unable to adjust the resistance level of the flywheel during their workout. A user would need to change the resistance level before securing themselves with the lap bar of the stabilization frame, which is inconvenient both in terms of accessibility and workout disruption. To improve the ergonomics of the rowing machine for individuals who require the use of wheelchairs, an adaptive resistance mechanism will be added to the existing design.

To increment/decrement the resistance level from either the standard or adaptive sides of the machine, the current cable mechanism will be replaced with an electrical design. A NEMA 17 stepper motor will adjust the overlap between the magnet and the flywheel by rotating clockwise to increment the resistance level and counterclockwise to decrement the resistance

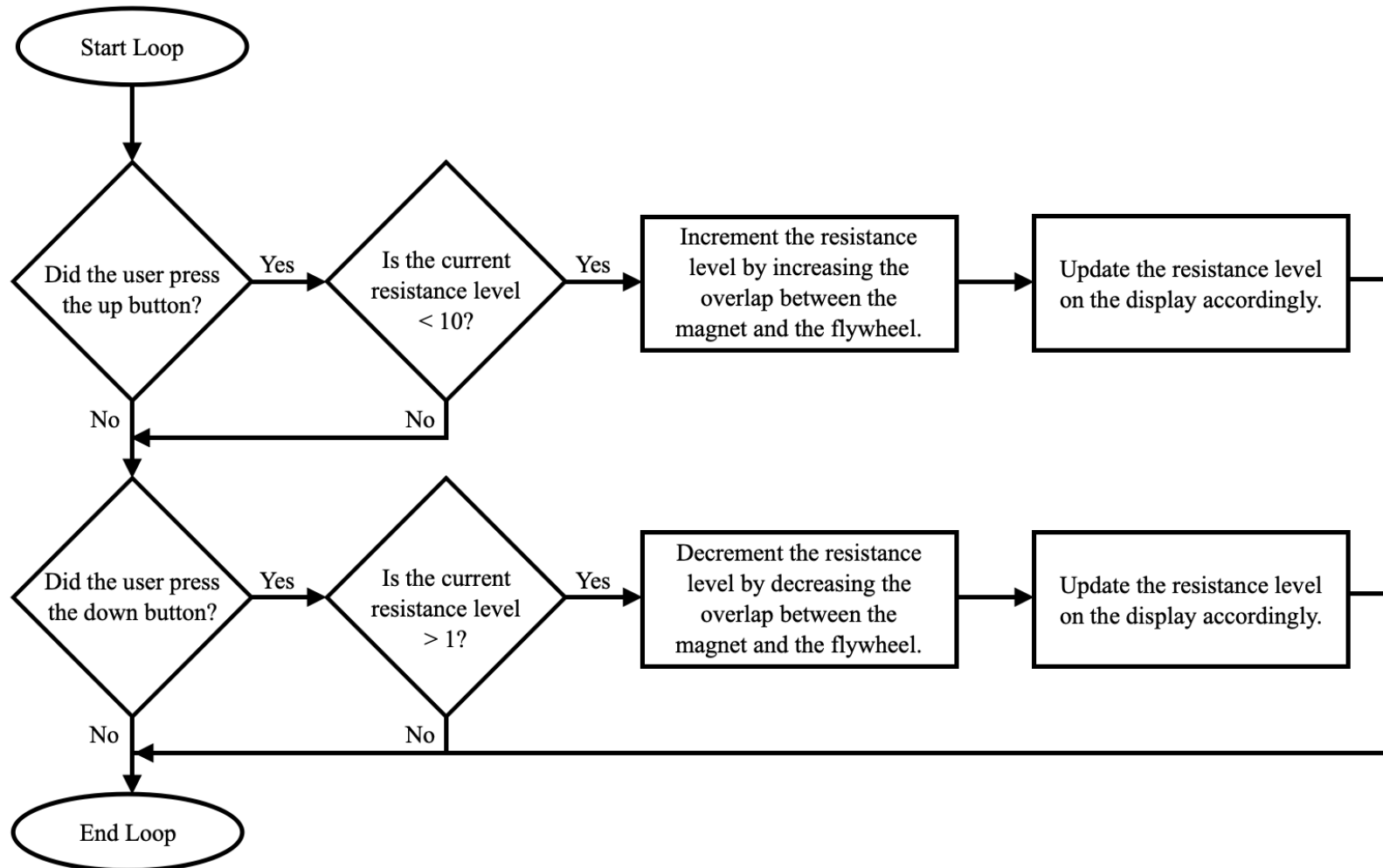
level. An Arduino Mega, DRV8825 motor driver, and +12 Volt power supply will control the stepper motor's position according to feedback from several switches within the circuit. Each side of the machine will have a set of up/down arrow buttons that allow the user to increment/decrement the resistance level, respectively. A limit switch placed near the magnet fixture will serve to orient the system at the onset of power application. The first task that the program will complete is to rotate the stepper motor in the counterclockwise direction until the limit switch is depressed. The position of the limit switch will be such that the resistance level is set to one, the lowest resistance, when the magnet fixture depresses the limit switch. Calibrating the resistance level to a known value at the start of the program ensures that the overlap between the magnet and the flywheel accurately portrays the intended resistance level. This setup logic is illustrated in **Figure 1**.



**Figure 1. Resistance Dial Setup Coding Flowchart.** At the beginning of the program (i.e., when the device is first powered on), check the state of the resistance dial limit switch. If it is not depressed, rotate the stepper motor that controls the overlap between the magnet and the flywheel such that the resistance level is decreased. Continue to decrement the resistance level until the limit switch is depressed, indicating that the resistance level is 1. Once at the base resistance level, enter the void loop.

Once the resistance level is calibrated to a known starting point, a user, from either side of the machine, can adjust the resistance level by using the up/down arrow buttons. If the up button is pressed and the current resistance level is less than the maximum value of 10, the stepper motor will rotate clockwise by a set number of degrees that correlate to one increment in the resistance level. Similarly, if the down button is pressed and the current resistance level is more than the minimum value of 1, the stepper motor will rotate counterclockwise by a set number of degrees that correlate to one decrement of the resistance level. The number of degrees

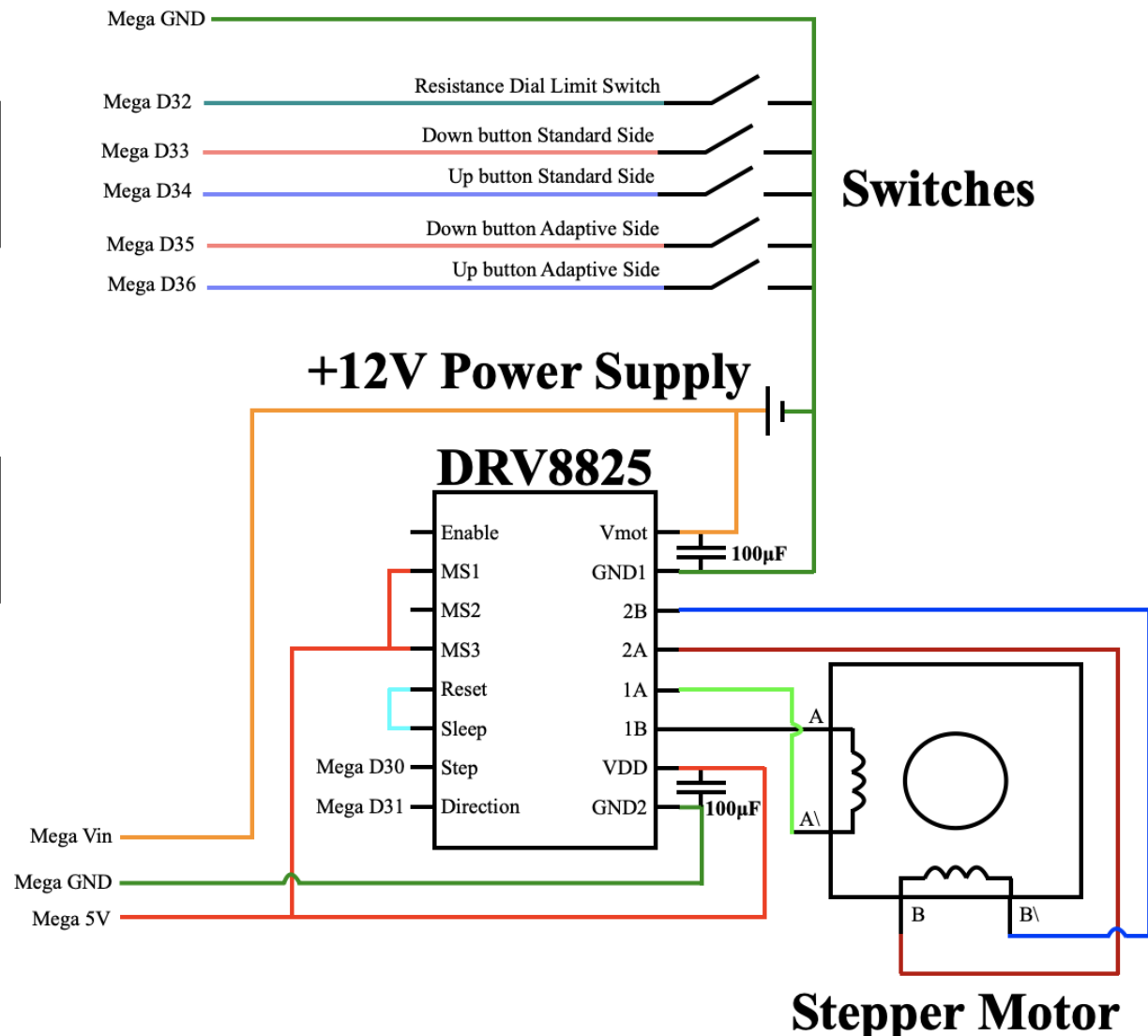
required to change the resistance level by one value will be measured using the current cable mechanism before it is disassembled and replaced by the electronic system. A two digit seven segment LED display will be present on both sides of the machine to display the current resistance level to the user. After each press of a button, the display will be automatically updated to reflect the new resistance level. **Figure 2** depicts the coding flowchart for the void loop of the program, which runs continuously until power is disconnected.



**Figure 2. Resistance Dial Void Loop Coding Flowchart.** Each loop iteration, the code checks the state of the up and down resistance level buttons. If the up button is pressed and the current resistance level is less than 10, rotate the stepper motor that controls the overlap between the magnet and the flywheel such that the resistance level is incremented by one. If the down button is pressed and the current resistance level is greater than 1, rotate the stepper motor that controls the overlap between the magnet and the flywheel such that the resistance level is decremented by one. After rotation, update the display to accurately portray the current resistance level. The loop continuously repeats to ensure that the resistance level is at the correct setting according to user preference.

The circuit will be constructed according to the schematic shown in **Figure 3**. An Arduino Mega is necessary because the Arduino Uno does not have enough digital pins to implement the proposed design. The Arduino Mega will be purchased from the MakerSpace at the University of Wisconsin-Madison. An Arduino Mega screw terminal board will also be purchased to strengthen the connections within the design and improve durability [1]. The NEMA 17 stepper motor will be purchased from the same vendor that sold the one used in the console rotation mechanism [2]. The DRV8825 will be taken from the set of five purchased last semester for the console rotation mechanism. Two 100  $\mu\text{F}$  capacitors required to protect the DRV8825 from power surges will be sourced from the BME storage closet. The limit switch will be taken from materials supplied by JHT. Two sets of up/down arrow buttons [3] and 2 two digit seven LED [4] displays will be purchased from online vendors. The power supply and Arduino Mega will ultimately be shared between the console rotation mechanism and the adaptive resistance mechanism. Therefore, the final stage of the circuit design will be to integrate each individual circuit into a larger, single circuit design.





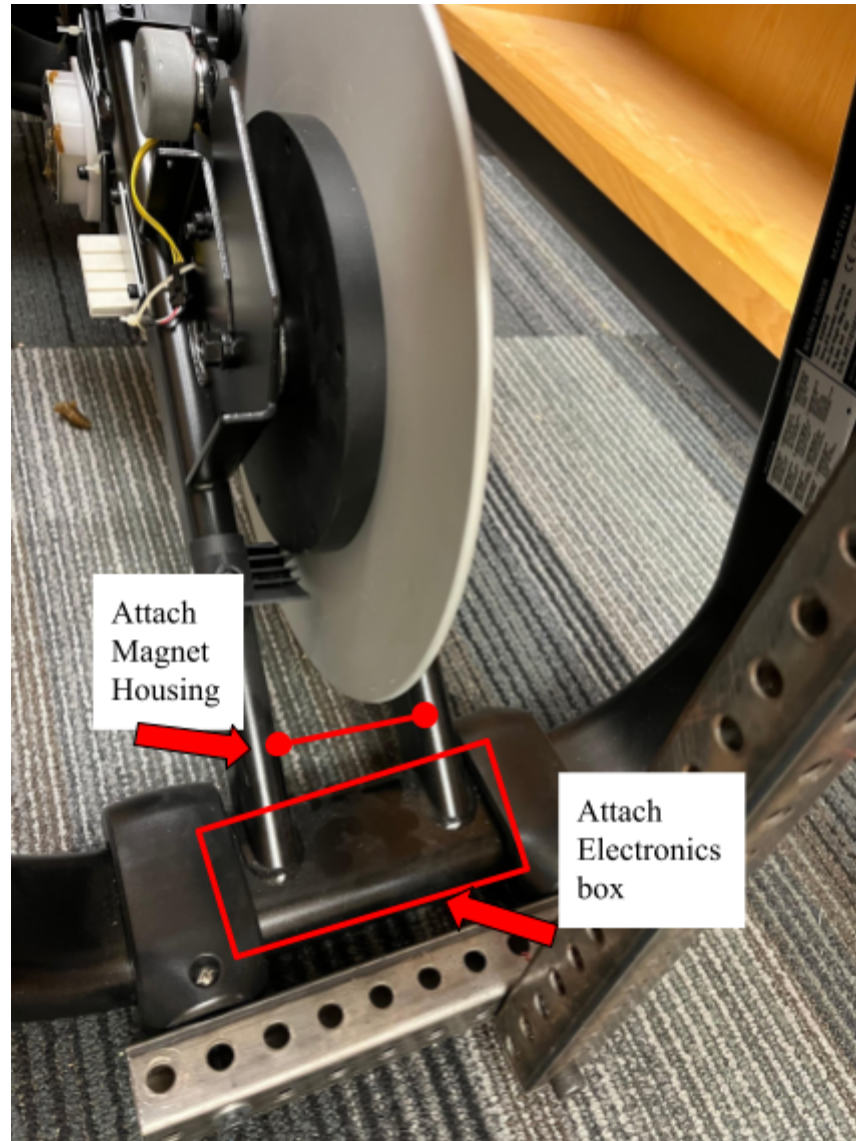
**Figure 3. Resistance Dial Circuit Schematic.** The resistance dial circuit consists of an Arduino Mega, DRV8825, NEMA17 stepper motor, +12V power supply, two 100 µF capacitors, two 2 digit 7 segment displays, four press buttons, and one NO limit switch. The colored lines represent the wire connections present between each physical component. The Arduino Mega is not explicitly shown to improve the readability of the schematic.

### *Assembly Integration with Matrix Rower*

The stepper motor and associated housing will be placed within the plastic housing that contains all the internal components of the rower (flywheel, rope, supports, etc.). The resistance level changes by rotating a pair of magnets around the internal flywheel of the rower. When the magnets have increased overlap with the flywheel, it produces more Eddy currents which increases the resulting resistance felt by the user while rowing. As long as the magnets can rotate about the flywheel to the same degree that they rotate in their current position within the rower, the same resistance levels can be achieved. Given this fact, the proposed design includes moving the magnets to a location within the plastic housing of the rower that has room to fit the stepper motor. Currently, the proposed design aims to move the magnets to the base of the rower and screw in the stepper motor to the rigid base. This will be done by simply unscrewing the current housing of the magnets from the two angled support bars (**Figure 4**), flipping it 180°, and re-screwing it into the same two angle support bars, but near the base of the rower (**Figure 5**). Prior to unscrewing the magnet housing, a calibration will be done to determine how much the magnets rotate between each change in resistance level. Given this degree of rotation, the stepper motor can be calibrated to produce the same amount of rotation once connected with the magnet housing.



**Figure 4. Current location of magnet housing.** The magnet housing is currently screwed into the support portion of the two angled support bars that are within the plastic housing of the rower. The housing is one large piece of plastic that rotates about the central bolt shown above. The proposed resistance dial mechanism will keep this entire structure intact, but move it to another location within the inside of the rower.



**Figure 5. Proposed location of magnet housing.** The proposed resistance dial design will aim to move the location of the magnet housing to a location where there is enough space to add a stepper motor. In the above figure, the magnet housing would be flipped 180° and screwed into the two angled support bars where the line is drawn connecting them. The stepper motor and associated electronics containing structure will most likely be screwed into the flat portion of the rower base, shown within the red box above.

To physically attach the magnet housing to the stepper motor, a mechanism will be developed that essentially fits between the shaft of the stepper motor and the bolt through hole in the magnet housing. The bolt through hole is the magnet housing's rotation point. To keep this same rotation point, a mechanism that connects this region to the stepper motor will be developed. This will most likely be some sort of tube that fits over the stepper motor shaft and fits within the bolt through hole. An additional attachment point will be required, such as creating a flat face parallel to a flat face on the magnet housing to screw together. This will make sure that the magnet housing stays rigidly connected to the stepper motor. Then, whenever the

stepper motor rotates, it will rotate the magnet housing, thus rotating the magnets about the flywheel and changing the resistance. The last component of the design will be to develop a structure to hold all the electronics, similar to the motor box that was designed for console rotation. This box will most likely be rigidly screwed into the flat portion of the rower base (**Figure 5**). This new electronics box will likely hold both the electronics for the resistance dial mechanism and those for console rotation. Thus, the console rotation electronics box will only contain the stepper motor and console. This change will help to consolidate the electronics and put them in a safer location. The SolidWorks models of the magnet housing and rower based were just recently received, and developing the SolidWorks models of both the attachment mechanism between the stepper motor and the magnet housing, along with the structure to contain all the electronic components will be the next focus of the project.

### References:

- [1] Electronics-Salon, “Electronics-Salon Prototype Screw/Terminal Block Shield Board Kit for Arduino MEGA-2560 R3.: Amazon.com: Industrial & Scientific,” *Amazon*.  
<https://www.amazon.com/Electronics-Salon-Prototype-Terminal-Arduino-MEGA-2560/dp/B00UT13YXA> (accessed Feb. 26, 2023).
- [2] “Amazon.com: STEPPERONLINE Stepper Motor Nema 17 Bipolar 40mm 64oz.in(45Ncm) 2A 4 Lead 3D Printer Hobby CNC : Industrial & Scientific.”  
[https://www.amazon.com/gp/product/B00PNEQI7W/ref=ppx\\_yo\\_dt\\_b\\_asin\\_title\\_o00\\_s00?ie=UTF8&psc=1](https://www.amazon.com/gp/product/B00PNEQI7W/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1) (accessed Dec. 11, 2022).
- [3] Billet Automotive Buttons, “19mm Pair ‘ARROW SYMBOLS 2’ Billet Push Buttons Switches Power Windows Turn Signals etc,” *Billet Automotive Buttons*.  
<https://billetautomotivebuttons.com/products/19mm-pair-arrows-symbols-v2-billet-push-buttons-switches-power-windows-turn-signals-etc> (accessed Feb. 26, 2023).
- [4] uxcell, “Amazon.com: uxcell Common Anode 10 Pin 2 Bit 7 Segment Display 0.59 x 0.55 x 0.28 Inch 0.35" Red LED Display Digital Tube 5pcs : Industrial & Scientific,” *Amazon*.  
<https://tinyurl.com/4s8rsexk> (accessed Feb. 26, 2023).

### Appendix N: BME 402 Preliminary Arduino Code

// Written by: Annabel Frake

// Class: BME 402

// Purpose: Code for changing the display output (between 1 and 10 resistance levels) using up and down buttons.

// Include necessary libraries.

```
#include "SevSeg.h"
```

```
#include <ezButton.h>;
```

// Declare pins for the buttons.

```
byte const upButtonPin = 10;
```

```
byte const downButtonPin = 11;
```

// Create ezButton objects for the up and down buttons.

```
ezButton upButton(upButtonPin);
```

```
ezButton downButton(downButtonPin);
```

// Create a SevSeg object for the display.

```
SevSeg sevseg;
```

// Define digital pins for the DIR and STEP features of the stepper motor.

```
byte const dirPin = 8; // need to update once have Mega
```

```
byte const stepPin = 9; // need to update once have Mega
```

// Define the time delay that defines the rotation degree for one increment of the resistance dial.

```
int incrementDelay = 1000; // microseconds
```

// Declare variable for resistance level

int resistanceLevel = 1; // Will need to discern what this is based on the location of the stepper motor in later code. Maybe set the resistance level manually to 1 every time the program starts.

```
void setup()
{
  // Initialize the serial port.
  Serial.begin(9600);

  // Set the stepper pinmodes to OUTPUT.
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);

  byte numDigits = 2;
  byte digitPins[] = {12, 13}; // {D3, D4}
  byte segmentPins[] = {9, 2, 3, 5, 6, 8, 7, 4}; // {A, B, C, D, E, F, G, DP}

  bool resistorsOnSegments = true;
  bool updateWithDelaysIn = true;
  byte hardwareConfig = COMMON_ANODE;
  sevseg.begin(hardwareConfig, numDigits, digitPins, segmentPins, resistorsOnSegments);
  sevseg.setBrightness(90);

  // Assign the up and down buttons with a debounce time of 50 milliseconds
  upButton.setDebounceTime(50);
  downButton.setDebounceTime(50);
}
```

```
void loop()
{
  // Call the loop() function for the up and down buttons.
  upButton.loop();
  downButton.loop();

  if (upButton.isPressed() && resistanceLevel < 10)
  {
    // If the up button is pressed, increment the resistance level.
    resistanceLevel += 1;

    // Increment the position of the magnet over the flywheel using a stepper motor.
    increment();

    Serial.print("Resistance level incremented to: ");
    Serial.println(resistanceLevel);
  }

  if (downButton.isPressed() && resistanceLevel > 1)
  {
    // If the down button is pressed, decrement the resistance level.
    resistanceLevel -= 1;

    // Decrement the position of the magnet over the flywheel using a stepper motor.
    decrement();
```



```
Serial.print("Resistance level decremented to: ");
Serial.println(resistanceLevel);
}

sevseg.setNumber(resistanceLevel);
sevseg.refreshDisplay();
}

// A function to rotate the magnet such that the resistance level is incremented once.
void increment()
{
    // Specify the direction the motor will rotate: clockwise.
    digitalWrite(dirPin, HIGH);

    digitalWrite(stepPin, HIGH);
    delayMicroseconds(incrementDelay); // rotate X degrees
    digitalWrite(stepPin, LOW);
}

// A function to rotate the magnet such that the resistance level is decremented once.
void decrement()
{
    // Specify the direction the motor will rotate: counterclockwise.
    digitalWrite(dirPin, LOW);
```

```

digitalWrite(stepPin, HIGH);

delayMicroseconds(incrementDelay); // rotate X degrees

digitalWrite(stepPin, LOW);

}

```

## Appendix O: BME 402 Testing Protocols

### Adaptive Side Protocol - EMG:

Test Subjects: Users that do not require wheelchairs, but will be provided with one during testing

1. Have the user approach the adaptive side of the rower slowly.
2. Have the user ensure that the stabilization pad is lifted enough in reference to the horizontal plane to properly roll as close to the rower as possible so that they can comfortably reach the rower handlebar in its resting position.
3. Once positioned at a comfortable reach, the user should lower the stabilization pad onto their lap to secure themselves in place and prevent backwards tipping. The pad should be placed at the crease between the lower abdomen and upper lap. The console should turn to face the adaptive side during this portion.
4. Lock wheelchair wheels in place to prevent translation forwards and/or backwards.
5. Plug the power cord of the Delysis Trigno EMG machine into a power source/outlet. Plug two electrodes into the Delysis Trigno EMG machine.
6. Have the user clean their skin where the electrodes will be placed with an alcohol sterilization wipe.
7. Remove the plastic from the EMG electrode. Place a pea-sized amount of electrode gel on top of the electrode. Spread the gel over the entire electrode surface evenly.
8. Have the user hold their left hand and left arm in a supine position. Place one of the electrodes on the skin distal to the user's shoulder. Place the other electrode on the skin proximal to the user's elbow crease.
9. Adjust the settings on the console to display stroke rate.
10. Turn on the Delysis Trigno EMG.
11. Have the user turn the resistance dial to level 1.
12. Have the user grab the handlebar with both hands and lift vertically upward to remove the handlebar from the supports.
13. Next, the user should pull the handlebar towards the middle of their chest, pause for 0.5 seconds, and then extend the arms forward again. The user can slightly lean forward upon this extension to achieve a longer rowing pull stroke if desired. Repeat this motion for one minute.

- a. The user should try to maintain a constant and steady stroke rate between 25-30 rpm, or at a level deemed comfortable for the individual.
14. Once the minute trial is complete, slowly and gently place the handlebar back within the supports.
15. Rest for two minutes.
16. Repeat steps 11-15 at resistance levels 5 and 10.
17. Have the user remove the electrodes from their skin carefully. Place the electrodes back on to the plastic and return all materials to the researcher.
18. Repeat steps 6-17. For step 8, instead of placing the electrodes on the users left bicep, place one electrode on the user's left middle deltoid and the other electrode on the center of the user's left latissimus dorsi muscle.
19. Turn off the EMG machine and unplug from the power supply.
20. To remove themselves from the rower, the user should slowly lift the stabilization pad until it is completely vertical in orientation. The console should turn to face the standard side during this portion.
21. Unlock the wheelchair wheels and have the user slowly roll away from the rower.
22. Have the user complete the survey(s).

## Adaptive Side Protocol - NO EMG:

Test Subjects: Users that require a wheelchair

1. Have the user approach the adaptive side of the rower slowly.
2. Have the user ensure that the stabilization pad is lifted enough in reference to the horizontal plane to properly roll as close to the rower as possible so that they can comfortably reach the rower handlebar in its resting position.
3. Once positioned at a comfortable reach, the user should lower the stabilization pad onto their lap to secure themselves in place and prevent backwards tipping. The pad should be placed at the crease between the lower abdomen and upper lap. The console should turn to face the adaptive side during this portion.
4. Lock wheelchair wheels in place to prevent translation forwards and/or backwards.
5. Adjust the settings on the console to display the stroke rate.
6. Have the user turn the resistance dial to level 1.
7. Have the user grab the handlebar with both hands and lift vertically upward to remove the handlebar from the supports.
8. Next, the user should pull the handlebar towards the middle of their chest, pause for 0.5 seconds, and then extend the arms forward again. The user can slightly lean forward upon this extension to achieve a longer rowing pull stroke if desired. Repeat this motion for one minute.
  - a. The user should try to maintain a constant and steady stroke rate between 25-30 rpm, or at a level deemed comfortable for the individual.

9. Once the minute trial is complete, slowly and gently place the handlebar back within the supports.
10. Rest for two minutes.
11. Repeat steps 6-10 at resistance levels 5 and 10.
12. To remove themselves from the rower, the user should slowly lift the stabilization pad until it is completely vertical in orientation. The console should turn to face the standard side during this portion.
13. Unlock the wheelchair wheels and have the user slowly roll away from the rower.
14. Have the user complete the survey(s).

## Standard Side Protocol- EMG:

Test Subjects: Users that do not require the use of a wheelchair

1. Approach the standard side of the rower slowly.
2. Have the user grab the handlebar with both hands and remove it from the handlebar supports, placing it in the original Matrix rower handlebar resting position.
3. Have the user sit on the sliding seat on the standard side of the rowing machine and strap their feet into place using the foot straps.
4. Plug the power cord of the Delysis Trigno EMG machine into a power source/outlet. Plug two electrodes into the Delysis Trigno EMG machine.
5. Have the user clean their skin where the electrodes will be placed with an alcohol sterilization wipe.
6. Remove the plastic from the EMG electrode. Place a pea-sized amount of electrode gel on top of the electrode. Spread the gel over the entire electrode surface evenly.
7. Have the user hold their left hand and left arm in a supine position. Place one of the electrodes on the skin distal to the user's shoulder. Place the other electrode on the skin proximal to the user's elbow crease.
8. Adjust the settings on the console to display the stroke rate.
9. Turn on the Delysis Trigno EMG machine.
10. Set resistance dial to 1.
11. Have the user lean forward to grab the handlebar with two hands from its position in the original Matrix rower handlebar resting position.
12. Have the user pull the handlebar towards the middle of their chest while extending their legs as far as possible without locking them out. The user should try to keep their torso vertical while pulling the handlebar backward. Have them pause for 0.5 seconds. Then, the user should extend their arms forward again while bending their legs to reorient back to the original position. Repeat this motion for one minute.
  - a. The user should try to maintain a constant and steady stroke rate between 25-30 rpm, or at a level deemed comfortable for the individual.

13. Once the minute trial is complete, slowly and gently place the handlebar back in the supports.
14. Rest for two minutes.
15. Repeat steps 10-14 at resistance levels 5 and 10.
16. Have the user remove the electrodes from their skin carefully. Place the electrodes back on to the plastic and return all materials to the researcher.
17. Repeat steps 5-17. For step 7, instead of placing the electrodes on the users left bicep, place one electrode on the user's left middle deltoid and the other electrode on the center of the user's left latissimus dorsi muscle.
18. Turn off the EMG machine and unplug from the power supply.
19. After placing the handlebar back in the original Matrix rower handlebar resting position, have the user undo the straps that secure their feet in place. The user should stand up from the sliding seat on the rowing machine.
20. Have the user grab the handlebar with both hands, remove it from the Matrix rower handlebar resting position and place it back in the handlebar supports.
21. Have the user complete the survey.

### Standard Side Protocol - NO EMG:

Test Subjects: Users that do not require the use of a wheelchair

1. Have the user approach the standard side of the rower slowly.
2. Have the user grab the handlebar with both hands and remove it from the handlebar supports, placing it in the original Matrix rower handlebar resting position.
3. Have the user sit on the sliding seat on the standard side of the rowing machine and strap their feet into place using the foot straps.
4. Adjust the settings on the console to display the stroke rate.
5. Set resistance dial to 1.
6. Have the user lean forward to grab the handlebar with two hands from its position in the original Matrix rower handlebar resting position.
7. Have the user pull the handlebar towards the middle of their chest while extending their legs as far as possible without locking them out. The user should try to keep their torso vertical while pulling the handlebar backward. Have them pause for 0.5 seconds. Then, the user should extend their arms forward again while bending their legs to reorient back to the original position. Repeat this motion for one minute.
  - a. The user should try to maintain a constant and steady stroke rate between 25-30 rpm, or at a level deemed comfortable for the individual.
8. Once the minute trial is complete, slowly and gently place the handlebar back in the supports.
9. Rest for two minutes.
10. Repeat steps 5-9 at resistance levels 5 and 10.

11. After placing the handlebar back in the original Matrix rower handlebar resting position, have the user undo the straps that secure their feet in place. The user should stand up from the sliding seat on the rowing machine.
12. Have the user grab the handlebar with both hands, remove it from the Matrix rower handlebar resting position and place it back in the handlebar supports.
13. Have the user complete the survey.

## Appendix P: BME 402 Testing Surveys

### 1. Adaptive Side only Survey

#### Johnson Health Tech Adaptive Rowing Machine Survey Evaluation of the Adaptive Side by Individuals Using a Wheelchair

1. Have you previously used a rowing machine?

Yes

No

2. If you answered “Yes” to question 1, did you use a standard rowing machine or an adapted rowing machine? If you answered “No” to question 1, answer with “N.A.”.

I used a standard rowing machine before this study.

I used a rowing machine adapted for wheelchair accessibility before this study.

N.A.

Other

If you answered with “Other”, please describe the type of rowing machine you used below:

3. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience grabbing the rowing handle to start your exercise?

Very Difficult

Moderately Difficult

Neutral

Moderately Easy

Very Easy

1

2

3

4

5

Comments:

4. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience putting the rowing handle back in its resting place after finishing the exercise?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

5. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience interacting with the console?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

6. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience changing the resistance level?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

7. On a scale of 1 to 5 (1 = very poor, 5 = very good), how would you rate your experience changing the resistance level between the adaptive and standard sides of the machine?

Very Poor	Moderately Poor	Neutral	Moderately Good	Very Good
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

8. On a scale of 1 to 5 (1 = not intuitive at all, 5 = very intuitive), how intuitive was it to use the rowing machine?

Very Unclear	Moderately Unclear	Neutral	Moderately Intuitive	Very Intuitive
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

9. On a scale of 1 to 5 (1 = unsafe, 5 = very safe), how safe did you feel using the rowing machine?

Very Unsafe	Moderately Unsafe	Neutral	Moderately Safe	Very Safe
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

10. Did you feel as though the wheelchair would tip backwards at any point during the workout?

Yes  No

If you answered with “Yes”, please describe when (i.e., what phase of the rowing motion) and how often you felt the wheelchair would tip backwards below:

11. On a scale of 1 to 5 (1 = insecure, 5 = very secure), how secure did you feel in the wheelchair during the rowing motion?

Very Insecure	Moderately Insecure	Neutral	Moderately Secure	Very Secure
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:



12. On a scale of 1 to 5 (1 = very uncomfortable, 5 = very comfortable), how would you rate your discomfort level during use?

Very Uncomfortable	Moderately Uncomfortable	Neutral	Moderately Comfortable	Very Comfortable
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

13. Do you have any suggestions for improving the rowing experience (e.g., ergonomics, material use, stability issues, etc.)? If yes, please describe your suggestions below. If not, please leave this question blank.

14. On a scale of 1 to 5 (1 = not likely, 5 = very likely), how likely are you to use a similar machine again in the future?

Very Unlikely	Moderately Unlikely	Neutral	Moderately Likely	Very Likely
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

15. In the space below, provide any additional comments you would like to share.

## 2. Comparison between Adaptive and Standard Sides Survey

### Johnson Health Tech Adaptive Rowing Machine Survey

Comparison of the Standard and Adaptive Sides by Individuals not Using a Wheelchair

#### Standard Side:

1. Have you previously used a rowing machine?

Yes

No

2. If you answered “Yes” to question 1, did you use a standard machine or an adapted machine?  
If you answered “No” to question 1, answer with “N.A.”.

I used a standard rowing machine before this study.

I used a rowing machine adapted for wheelchair accessibility before this study.

N.A.

Other

If you answered with “Other”, please describe the type of machine you used below:

3. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience grabbing the rowing handle to start your exercise?

Very Difficult

Moderately Difficult

Neutral

Moderately Easy

Very Easy

1

2

3

4

5

Comments:

4. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience putting the rowing handle back in its resting place after finishing the exercise?

Very Difficult

Moderately Difficult

Neutral

Moderately Easy

Very Easy

1

2

3

4

5

Comments:

5. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience interacting with the console?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

6. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience changing the resistance level?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

7. On a scale of 1 to 5 (1 = very unclear, 5 = very intuitive), how intuitive was it to use the rowing machine?

Very Unclear	Moderately Unclear	Neutral	Moderately Intuitive	Very Intuitive
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

8. On a scale of 1 to 5 (1 = very unsafe, 5 = very safe), how safe did you feel using the rowing machine?

Very Unsafe	Moderately Unsafe	Neutral	Moderately Safe	Very Safe
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

9. On a scale of 1 to 5 (1 = very uncomfortable, 5 = very comfortable), how would you rate your discomfort level during use?

Very Uncomfortable	Moderately Uncomfortable	Neutral	Moderately Comfortable	Very Comfortable
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

10. Do you have any suggestions for improving the rowing experience (e.g., ergonomics, material use, stability issues, etc.)? If yes, please describe your suggestions below. If not, please leave this question blank.

11. In the space below, provide any additional comments you would like to share.

### **Adaptive Side:**

1. Have you previously used a rowing machine?

Yes  No

2. If you answered “Yes” to question 1, did you use a standard rowing machine or an adapted rowing machine? If you answered “No” to question 1, answer with “N.A.”.

- I used a standard rowing machine before this study.
- I used a rowing machine adapted for wheelchair accessibility before this study.
- N.A.
- Other

If you answered with “Other”, please describe the type of rowing machine you used below:

3. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience grabbing the rowing handle to start your exercise?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

4. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience putting the rowing handle back in its resting place after finishing the exercise?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

5. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience interacting with the console?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

6. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience changing the resistance level?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

7. On a scale of 1 to 5 (1 = very poor, 5 = very good), how would you rate your experience changing the resistance level between the adaptive and standard sides of the machine?

Very Poor	Moderately Poor	Neutral	Moderately Good	Very Good
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

8. On a scale of 1 to 5 (1 = very unclear, 5 = very intuitive), how intuitive was it to use the rowing machine?

Very Unclear	Moderately Unclear	Neutral	Moderately Intuitive	Very Intuitive
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

9. On a scale of 1 to 5 (1 = very unsafe, 5 = very safe), how safe did you feel using the rowing machine?

Very Unsafe	Moderately Unsafe	Neutral	Moderately Safe	Very Safe
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

10. Did you feel as though the wheelchair would tip backwards at any point during the workout?

Yes  No

If you answered with “Yes”, please describe when (i.e., what phase of the rowing motion) and how often you felt the wheelchair would tip backwards below:

11. On a scale of 1 to 5 (1 = very insecure, 5 = very secure), how secure did you feel in the wheelchair during the rowing motion?

Very Insecure	Moderately Insecure	Neutral	Moderately Secure	Very Secure
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

12. On a scale of 1 to 5 (1 = very uncomfortable, 5 = very comfortable), how would you rate your discomfort level during use?

Very Uncomfortable	Moderately Uncomfortable	Neutral	Moderately Comfortable	Very Comfortable
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

13. On a scale of 1 to 5 (1 = very unlikely, 5 = very likely), how likely are you to use a similar machine again in the future?

Very Unlikely	Moderately Unlikely	Neutral	Moderately Likely	Very Likely
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

14. Do you have any suggestions for improving the rowing experience (e.g., ergonomics, material use, stability issues, etc.)? If yes, please describe your suggestions below. If not, please leave this question blank.

15. In the space below, provide any additional comments you would like to share.

## Comparison Between Sides:

1. On a scale of 1 to 5 (1 = very poor, 5 = very well), how well did the adaptive side emulate the action of rowing?

Very Poor	Moderately Poor	Neutral	Moderately Well	Very Well
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

2. On a scale of 1 to 5 (1 = very difficult, 5 = very easy), how would you describe your experience transitioning between the standard and adaptive sides of the machine?

Very Difficult	Moderately Difficult	Neutral	Moderately Easy	Very Easy
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:

3. Do you have any suggestions for improving the transition between the standard and adaptive sides of the machine (e.g., ergonomics, material use, stability issues, etc.)? If yes, please describe your suggestions below. If not, please leave this question blank.

4. On a scale of 1 to 5 (1 = very poor, 5 = very good), how would you rate the console's transition between the adaptive and standard sides of the machine?

Very Poor	Moderately Poor	Neutral	Moderately Good	Very Good
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

Comments:



5. Do you have any suggestions for improving the console's transition between the standard and adaptive sides of the machine (e.g., ergonomics, material use, stability issues, etc.)? If yes, please describe your suggestions below. If not, please leave this question blank.

6. Which side of the machine were you more comfortable using?

- Standard side
- Adaptive side
- I was equally comfortable using both sides of the machine.

Please explain why in the space below:

7. In the space below, provide any additional comments you would like to share.

## **Appendix Q: BME 402 IRB Miscellaneous Documents**

### **1. Consent Form**

#### **TITLE OF STUDY**

Matrix Adaptive Rowing Assessment

#### **PRINCIPAL INVESTIGATOR**

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#### **PURPOSE OF STUDY**

You are being asked to participate in a research study as part of the BME 402 Spring 2023 design course at UW-Madison. Before deciding to take part in this study, please read the following information carefully and ask the researchers if you have any questions or need more information. Additionally, please read all procedures provided by the researchers thoroughly before signing the consent form.

The purpose of this study is to assess the ease of use and effectiveness of an adapted Matrix rowing machine made accessible to wheelchair users. As part of this study, you will be asked to interact with the standard and/or adaptive sides of the modified machine and provide feedback on the experience via a survey.

#### **CONFIDENTIALITY**

Your survey feedback will be anonymous. Please refrain from writing identifying information on your survey. You reserve the right to decline to answer any questions on the survey, and you are free to withdraw from participation at any time.

#### **CONTACT INFORMATION**

If you have any questions or you wish to further discuss any aspect of this study at any time, you may contact the principal investigator and/or researchers listed at the beginning of this document. If you have any questions about your rights as a research participant, or if anything arises which you do not feel comfortable discussing with the principal investigator, please reach out to the Institutional Review Board by phone at (608) 263-2362 or by email at asktheirb@hsirb.wisc.edu.

## **VOLUNTARY PARTICIPATION**

Participation in this research study is voluntary, and it is your choice whether or not to take part in this research. To participate, you must sign the consent form. However, you may withdraw at any point during the study without providing reasoning. If withdrawal occurs, your data will be returned to you or destroyed.

## **CONSENT**

I have fully and thoroughly read the information on this document, as well as the procedures used in the study, and I have had the opportunity to ask clarifying questions or obtain additional information from the researchers and principal investigator. By signing this document, I understand that participation in this study is voluntary, and I have the right to withdraw from the study at any point in time without providing a reason. I voluntarily agree to participate in this study.

Participant's signature \_\_\_\_\_ Date \_\_\_\_\_

### **2. Device Documentation**

#### **NAME OF DEVICE**

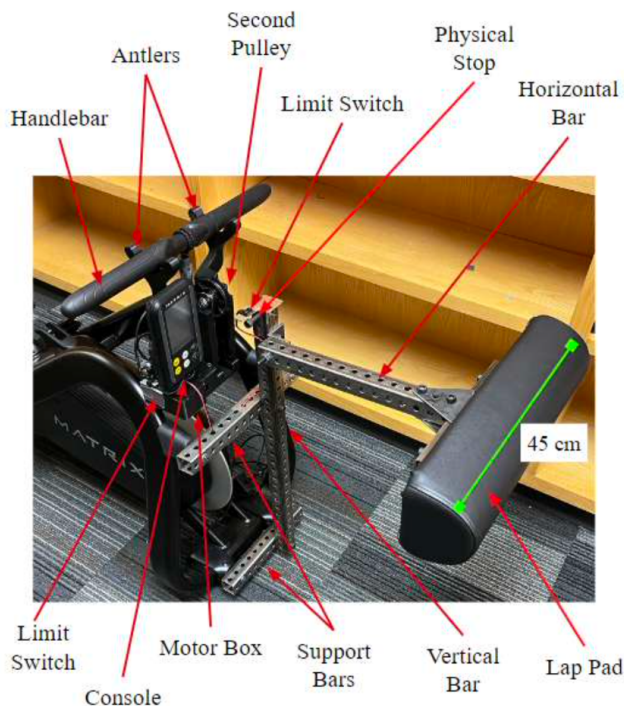
Matrix Adaptive Rowing Machine

\*Note: The Matrix Adaptive Rowing Machine is intended as exercise equipment. The Matrix Adaptive Rowing Machine is not considered to be a medical device.

#### **DESCRIPTION OF DEVICE**

The Matrix rowing machine is an approved device; please see the attached user manual. Adaptions made to the original approved device include removing the rower neck, adding antler-like structures that hold the rowing handle in place, repositioning the console adjacent to the antler-like structures, attaching a stabilization frame for securing a wheelchair in place, and altering the resistance dial mechanism such that users from both the standard and adaptive sides can easily manipulate the workout resistance level. Figure 1 shows the current Matrix Adaptive

Rowing Machine which will be modified slightly in the final version currently under fabrication. The stabilization frame will be welded together with a slightly smaller lap pad that fits between the armrests of a typical wheelchair. The antler-like structures that hold the rowing handle will be constructed from metal (most likely steel) instead of tough PLA. Please see the attached design report for an in-depth explanation of the prototype's fabrication, as well as additional images of the adaptations. The resistance dial mechanism is currently in an initial prototyping phase and does not have a fabrication plan at this time.



**Figure 38. Prototype Assembly.** The prototype assembly includes the pulley support plates with antlers, the console rotation mechanism and electronics box, and the metal adjustable stabilization frame. Please note that in the final product (will be fabricated in the coming weeks), the stabilization frame will be welded instead of secured using bolts, the antler-like structures will be constructed from metal, and the resistance dial mechanism will be modified such that users from both sides of the machine may interact with it (no prototype yet, not shown in image).

## INTENDED USE

The Matrix Adaptive Rowing Machine has been modified from the standard Matrix Rowing Machine to accommodate individuals in wheelchairs through the aforementioned adaptations. The Matrix Adaptive Rowing Machine is a more inclusive device which can be easily converted between the standard and adaptive sides. This device is adjustable for user height and arm reach, and therefore can accommodate users and wheelchairs of various sizes while still maintaining the safety standards of the original device. The Matrix Adaptive Rowing Machine is intended for gym or home use to maintain and/or build an individual's strength and general fitness. The standard side provides the traditional full-body rowing workout while the adaptive side offers an upper body strength workout for individuals requiring the use of a wheelchair.

**PRIOR USE**

Previously, the Matrix Adaptive Rowing Machine was used for individual use in homes and fitness centers and has also been used in clinical settings. The adaptations which allow wheelchair access have not previously been utilized.

**SAFETY RISK FEATURES**

Many efforts were made to ensure the safety of the Matrix Adaptive Rowing Machine. These include: a stability frame with a lap pad restraint that limits the movement of the user and their wheelchair, 3D printed housing for electronics to minimize the risk of shock, and removal and smoothing out of sharp edges and surfaces to diminish risks for abrasions and lacerations. Preliminary testing demonstrated the effectiveness of the stabilization frame at resisting wheelchair tipping and undesirable user movements below the waist during the course of the exercise. Please see the attached design report for the testing analysis.