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 who use wheelchairs, and they 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 machine. 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 automated to improve ease of use. The original mechanical resistance dial mechanism was replaced with a stepper motor to enable adjustment from either the standard or adaptive sides via the press of a button. Usability testing, including individuals with and without physical disabilities, revealed high ratings for ease of use, safety, comfort, and exercise comparability of both sides of the rowing machine.

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 who require 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 wheelchairs to perform daily tasks [1], [2]. 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 [3], [4]. Common complaints among people that require wheelchairs include a lack of space between equipment for wheelchair access and concerns about needing or requesting assistance [5].

Rowing can help alleviate shoulder pain, which is a common complaint among individuals who use wheelchairs. Studies have demonstrated that consistent upper body exercise and proper increases in workout resistance can help reduce shoulder pain [6], [7], [8]. 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 [9].

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 [10] (**Figure 1**) was adapted to create the Adaptive Rowing Machine, which accommodates users in wheelchairs while still retaining the machine's original functionality. This modified design allows users in wheelchairs to complete a modified rowing exercise on the adaptive side of the machine without external assistance. To confirm the ability of the Adaptive Rowing Machine to provide a comparable and safe upper-body workout, usability testing was conducted. Participants with and without physical disabilities were recruited to participate in usability testing. After completing the tests, all users filled out surveys regarding their perceived safety, comfort, and ease of use regarding various design components.

Figure 1. Standard Matrix Rower. This figure illustrates the standard rower fabricated by Johnson Health Tech [10].

Description of Adaptations

Pulley Plates and Antlers

An additional pulley was integrated into the Adaptive Rowing Machine (**Figure 2**) 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 during rowing exercise from the adaptive side. The pulley plates support the second pulley and are mounted on the rower using the same connection points as the original pulley. At the top of the pulley plates, the antler 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 (**Figure 2**) 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. The lap pad can be lowered onto a user's lap via a pin adjustment mechanism.

Console Rotation Mechanism

A stepper motor and associated circuit (**Figure 2**) 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. This allows the user to view rowing metrics during their workout.

Resistance Adjustment Mechanism

A stepper motor was implemented as part of the Adaptive Rowing Machine's resistance dial mechanism (**Figure 3**), 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 is equipped with a display to show the resistance level.

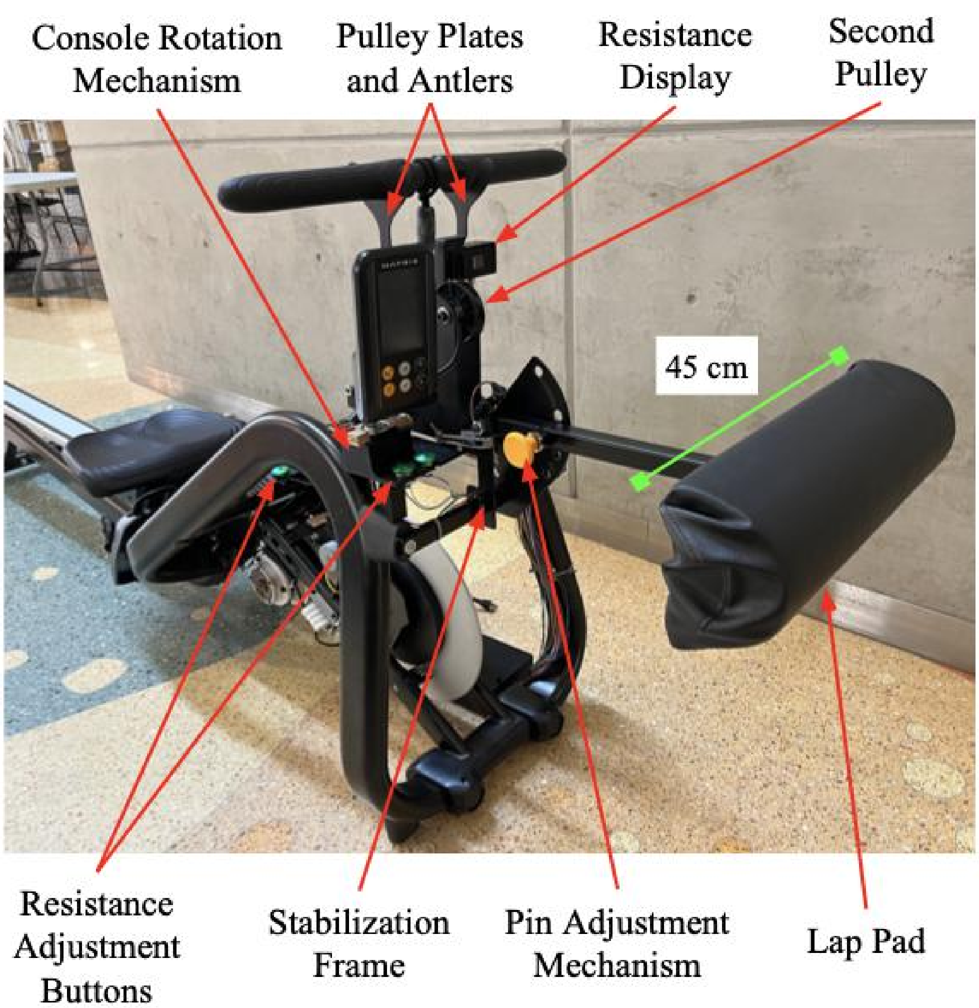

Figure 2. Adaptive Rowing Machine. The assembly shown, in the perspective of the adaptive side of the machine, includes the pulley support plates with antlers, the console rotation mechanism and electronics box, and the metal adjustable stabilization frame. The resistance mechanism, aside from the display, is not visible in the image.

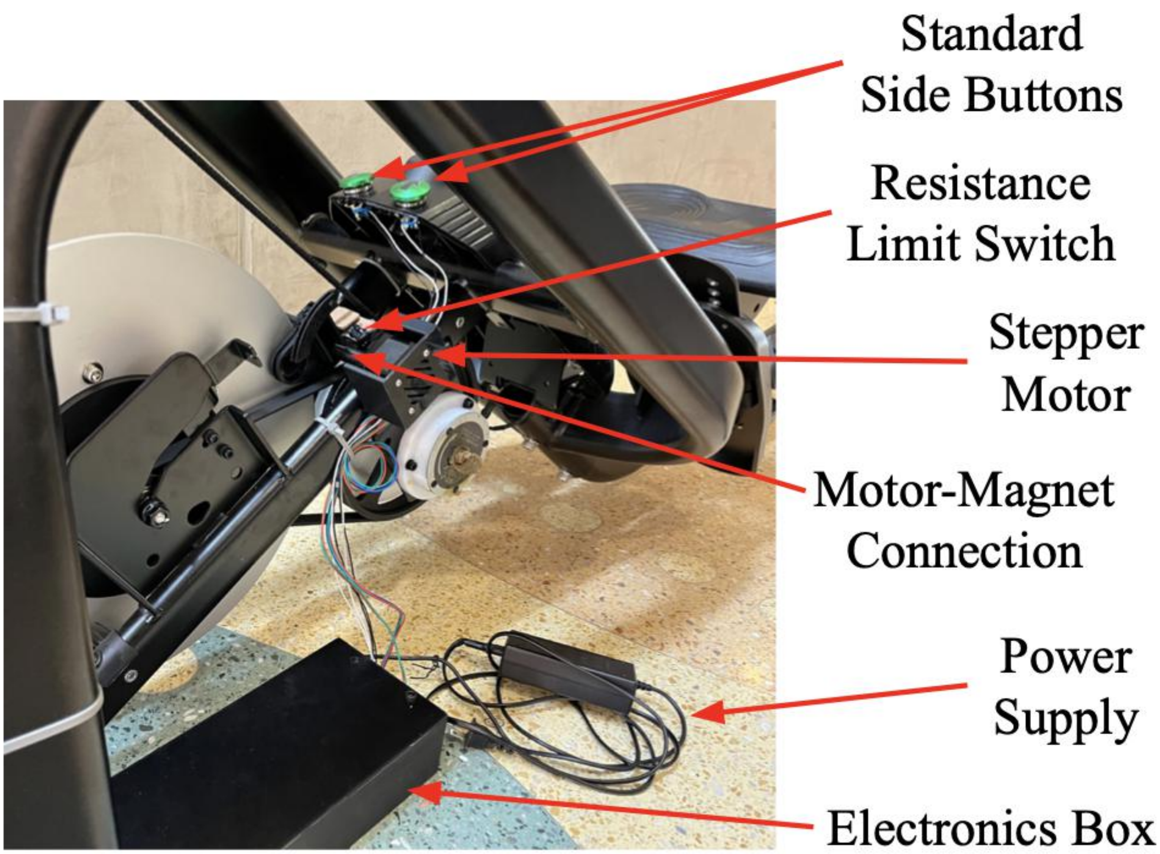

Figure 3. Resistance Adjustment Mechanism. The resistance adjustment mechanism consists of a stepper motor and associated housing, a limit switch, and the pre-existing magnet housing. At the onset of power, the system resets the resistance level to one, and that value can subsequently be changed via push buttons on the standard and adaptive sides of the machine. The electronic components controlling the behavior of this mechanism are housed within the electronics box. The display (attached to the antlers) is not visible in the image. The adaptive side resistance adjustment buttons are not visible above, but are labeled in Figure 2.

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. Prior to completing testing, exemption was provided by the Institutional Review Board (IRB). All participants signed consent forms and were provided with relevant details regarding the testing protocols, process, and purpose of the study. Three participants with physical disabilities were recruited to test the adaptive side. To compare the adaptive side to the standard side, ten participants without physical disabilities were recruited. Two tests were conducted on the

Adaptive Rowing Machine. The Adaptive Side test examined users with physical disabilities who may 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 have physical disabilities 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 who did not require a wheelchair, to analyze the safety and effectiveness of rowing on the wheelchair accessible side of the machine. The two surveys (adaptive side survey and comparison survey) were administered to the appropriate group 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 utilizing the Likert scale, which ranged from 1 to 5 (1 being the most negative feedback option and 5 being the most positive). Example questions on the surveys include the following: “How would you describe your experience grabbing the rowing handle to start your exercise?”, “How would you describe your experience changing the resistance level?”, and “How safe did you feel using the rowing machine?”. 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 approximately 30 seconds at a comfortable rowing pace. This test was completed on low (1), medium (5), and high (9-10) resistance levels. 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 into the machine, as normal in a standard rowing machine. The users were then directed to grab the handlebar from the antlers and place it in its original resting location near the sliding seat. Each participant completed approximately 30 second rowing trials on low (1), medium (5), and high (9-10) resistance levels. Afterward, the participants placed the handlebar back in the antlers, 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 secure themselves on the adaptive side of the rowing machine with the use of the lap pad and stabilization frame, as well as wheelchair brakes. The users followed a protocol similar to that mentioned in the *Adaptive Side* test. After pulling the lap pad down onto their lap, the participants were directed to complete around 30 second rowing trials at a comfortable pace on low (1), medium (5), and high (9-10) resistance levels. However, for the Adaptive and Standard Side Comparison test, users were directed to not use their legs while rowing on the adaptive side. After completing the testing on the adaptive side, the participants placed the handlebar back in the antlers 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 the perceived difference in workouts between the adaptive and standard sides.

Results

Table 1. Adaptive Only Survey Results

Adaptive Side Only Survey Results (3 Testing Participants with Physical Disabilities)		
Adaptive Side	Average Score (Out of 5)	Standard Deviation
Overall Ease of Use	4.80	0.41
Overall Safety	4.83	0.41
Comfort	4.33	1.15
Likelihood of Future Use	4.67	0.58

Table 2. Comparison Survey Results

Standard and Adaptive Side Survey Results (10 Testing Participants without Physical Disabilities)		
Standard Side	Average Score (Out of 5)	Standard Deviation
Overall Ease of Use	4.22	1.02

Overall Safety	4.80	0.42
Comfort	4.60	0.52
Adaptive Side	Average Score (Out of 5)	Standard Deviation
Overall Ease of Use	4.72	1.35
Overall Safety	4.75	0.44
Comfort	4.50	0.52
Standard and Adaptive Comparison	Average Score (Out of 5)	Standard Deviation
Workout Comparability	4.38	0.50
Console Use and Transition	4.89	0.33
Likelihood of Future Use	4.50	0.53
Ease of Resistance Adjustment	4.90	0.32

Adaptive Side

The adaptive side testing participants provided very positive feedback on the Adaptive Rower design. All three participants had previously used a standard rowing machine, so each had experience with rowing and could therefore use that prior experience as a baseline to score their interaction with the adaptive rower in the anonymous survey. Questions were grouped into four broad categories of analysis: Overall Ease of Use, Overall Safety, Comfort, and Likelihood of Future Use. Overall Ease of Use, which encompassed the ease of manipulating the rower handle, console, and resistance dial, scored a 4.80 out of 5, with a standard deviation of 0.41. Similarly, Safety averaged a score of 4.83 with a standard deviation of 0.41, addressing security of the wheelchair during rowing while the lap pad was in use. No testing participant felt as though they would tip over the wheelchair while rowing on the adaptive side. Finally, Comfort and Likelihood of Future Work score 4.33 and 4.67, respectively, with corresponding standard deviations of 1.15 and 0.58. Overall, the adaptive rowing experience scored highly in all areas, with safety being the overall highest score in all the categories.

Adaptive and Standard Side Comparison

Ten participants without physical disabilities tested the standard and adaptive sides of the rower. Almost all participants had used a standard rowing machine prior to testing; only one individual had no previous experience using a rowing machine. The comparison survey had three sections:

Standard Side, Adaptive Side, and Comparison Between Sides. Similar to the adaptive only side survey, each section's results were grouped into categories for analysis. The standard and adaptive side categories included Overall Ease of Use, Overall Safety, and Comfort. Workout Comparability, Console Use and Transition, Ease of Resistance, and Likelihood of Future Use averages were reported for the comparison section. All scores and standard deviations for the standard and adaptive sides were comparable, for Overall Ease of Use, Overall Safety, and Comfort with each category scoring 4.5 or higher out of 5. Comparison section results also scored highly. Workout Comparability received a 4.38 with a standard deviation of 0.50, indicating that testing participants found the workouts from both sides of the rowing machine comparable in terms of muscle activation and intensity. The rower was overall found to be very user-friendly, as Console Use and Transition averaged a score of 4.89 and Ease of Resistance Adjustment received a 4.90, with standard deviations of 0.33 and 0.32, respectively. The majority of participants indicated that they are very likely to use a similar device in the future, as reflected in the Likelihood of Future Use category with a score of 4.50 and standard deviation of 0.53.

Altogether, the users that tested both sides of the rowing machine gave very positive feedback and scored each category highly. Despite these results, several survey responses provided suggestions for improving the adaptive rower design. The two main suggestions provided on the surveys included moving the console and buttons closer to the user on each side of the machine and increasing the adjustability of the lap pad and stabilization frame to accommodate more individuals and their wheelchairs.

Discussion

A standard Matrix rowing machine was successfully adapted to accommodate individuals in wheelchairs since the handlebar now rests in a more central location between the standard and adaptive sides, and it can be reached easily from both sides of the machine. No external assistance is required to transition the rower between the standard and adaptive sides. Additionally, the lap pad and stabilization frame were added to the adaptive side of the machine to provide comfort and security to individuals rowing in wheelchairs. This safety mechanism is adjustable to secure users and wheelchairs of varying sizes while minimizing the movement of the wheelchair during exercise to prevent tipping and decrease risk of injury. The console which provides the metrics of the rowing workout automatically rotates between the standard and adaptive sides based on which side is in use, further increasing the ease of use. This permits users to view their rowing metrics while working out. Lastly, the resistance mechanism was modified from the original mechanical system to an electronic system such that the resistance level of the rowing workout can be changed via the press of a button from either the standard and adaptive sides of the rower. Two display screens show the current resistance level to users.

As can be seen in **Table 1** and **Table 2**, positive feedback on usability was received from testing participants. This data confirmed the safety, comfort, ease of use, and exercise comparability of both the standard and adaptive sides of the Adaptive Rowing Machine. Since there were testing participants with little to no rowing experience and varying fitness levels, this may have served as a source of error. Users with no previous rowing experience may have had difficulty rating survey questions since they did not have a baseline to compare their adaptive workout experience. Additionally, use of legs on the adaptive side by users not requiring wheelchairs and an inconsistent rowing pace during trials may have skewed the survey results. Furthermore, multiple individuals oversaw usability testing independent of each other, creating the possibility of variations in test administration.

Although substantial progress has been made on this project, a couple areas of improvement were noted during the design process. Further research and exploration is needed to improve the accuracy and reliability of the resistance adjustment mechanism, as slight errors in the mechanism function occurred during testing. Furthermore, the adjustability of the stabilization frame must be increased to accommodate more individuals and wheelchairs on the adaptive side of the rower. Overall, the Adaptive Rowing Machine fills the gap in the market for exercise equipment which accommodates both individuals who do and do not require the use of a wheelchair. Accordingly, this device increases gym inclusivity and benefits the general population by providing exercise options to those who may or may not have lower extremity disabilities or injuries.

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Declaration of Interest

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Table of Contents for Appendices References:

Appendix A: PDS

Johnson Health Tech: Adaptive Indoor Rower for Wheelchair Users

Product Design Specifications
Feb 28th, 2023

Client: Mrs. Staci Quam (staci.quam@johnsonfit.com)
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Lab: 307

Function:

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 themself 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.

References for PDS

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[8] "Rowing Solutions – Adapted Rowing Machine (AROW)." 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.

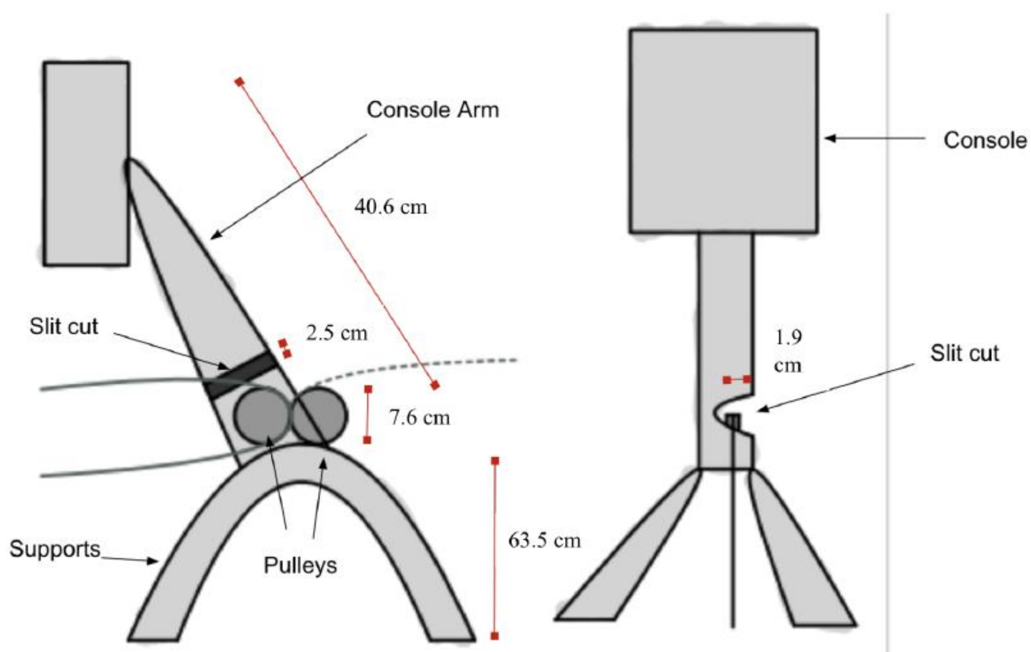


Figure 1. Visual Representation of 2 Pulleys with Slit Design. The 2 Pulleys with Slit design consists of two pulleys that are at the same height. The rope can be transferred from one pulley to the other to switch from standard to adaptive rowing. A slit cut will be made in the console arm to allow for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

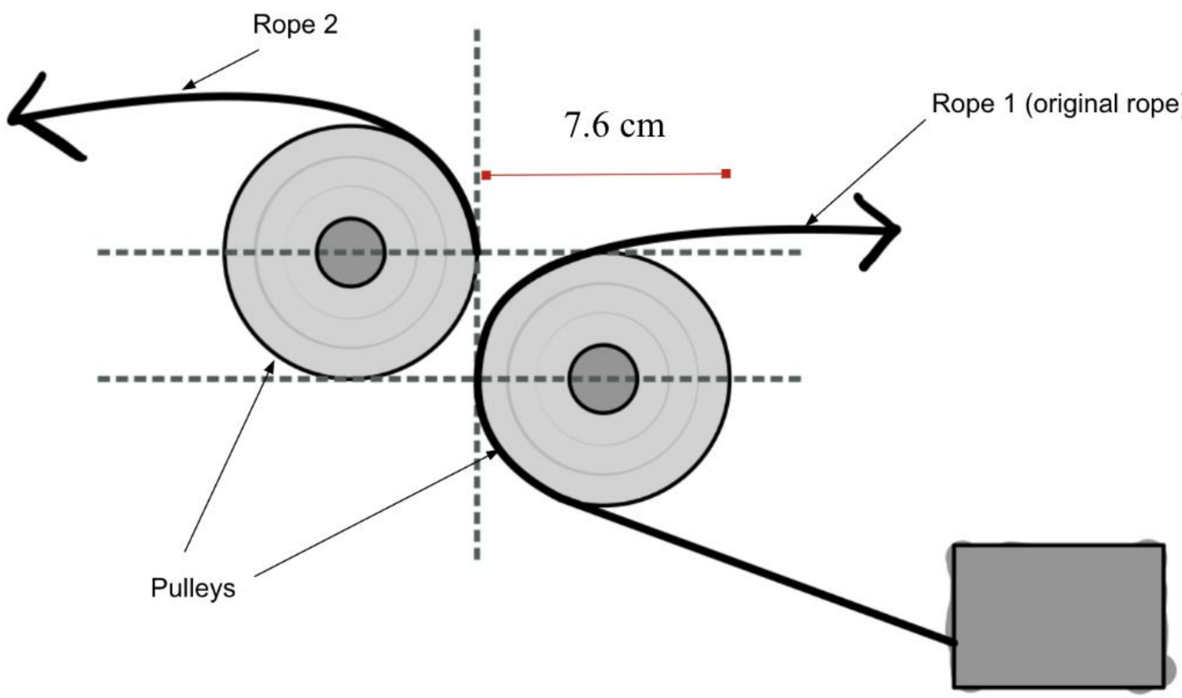


Figure 2. Visual Representation of 2 Pulleys with 2 Ropes. The 2 Pulleys with 2 Ropes design involves adding an additional pulley, handle, and rope to the existing rowing machine. The transitioning of the handle and rope from the standard side to the adaptive side would not be required since there would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

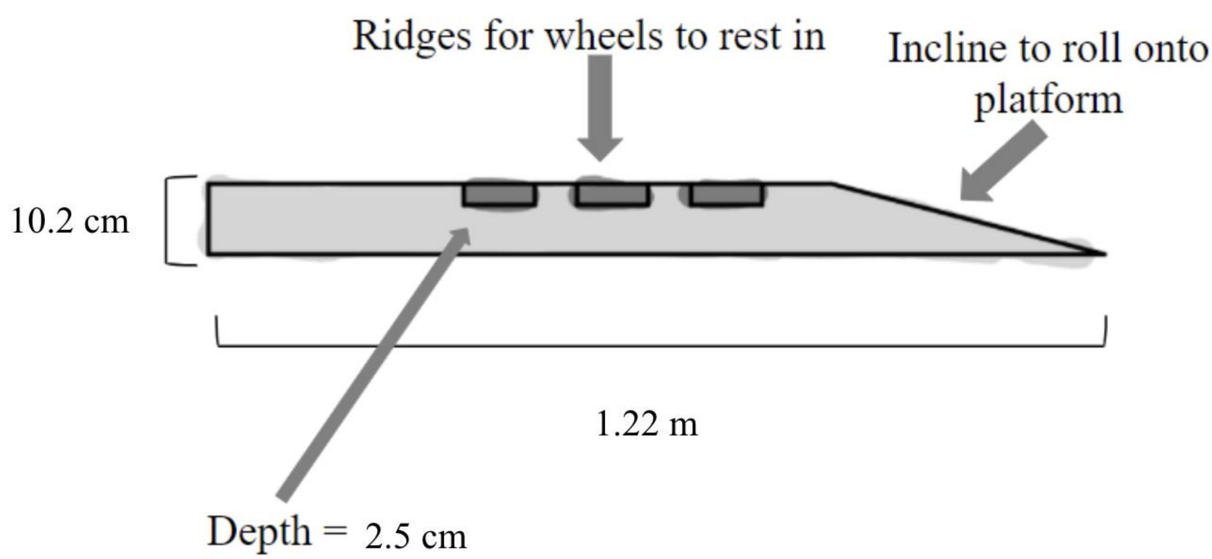


Figure 3. Visual Representation of the Highway Ridges Design. The platform has an incline down to the floor so that the user can roll up and into place on top of the platform. The base will have ridges cut into it for the wheels to rest in during the action of rowing to stabilize the wheelchair.

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.

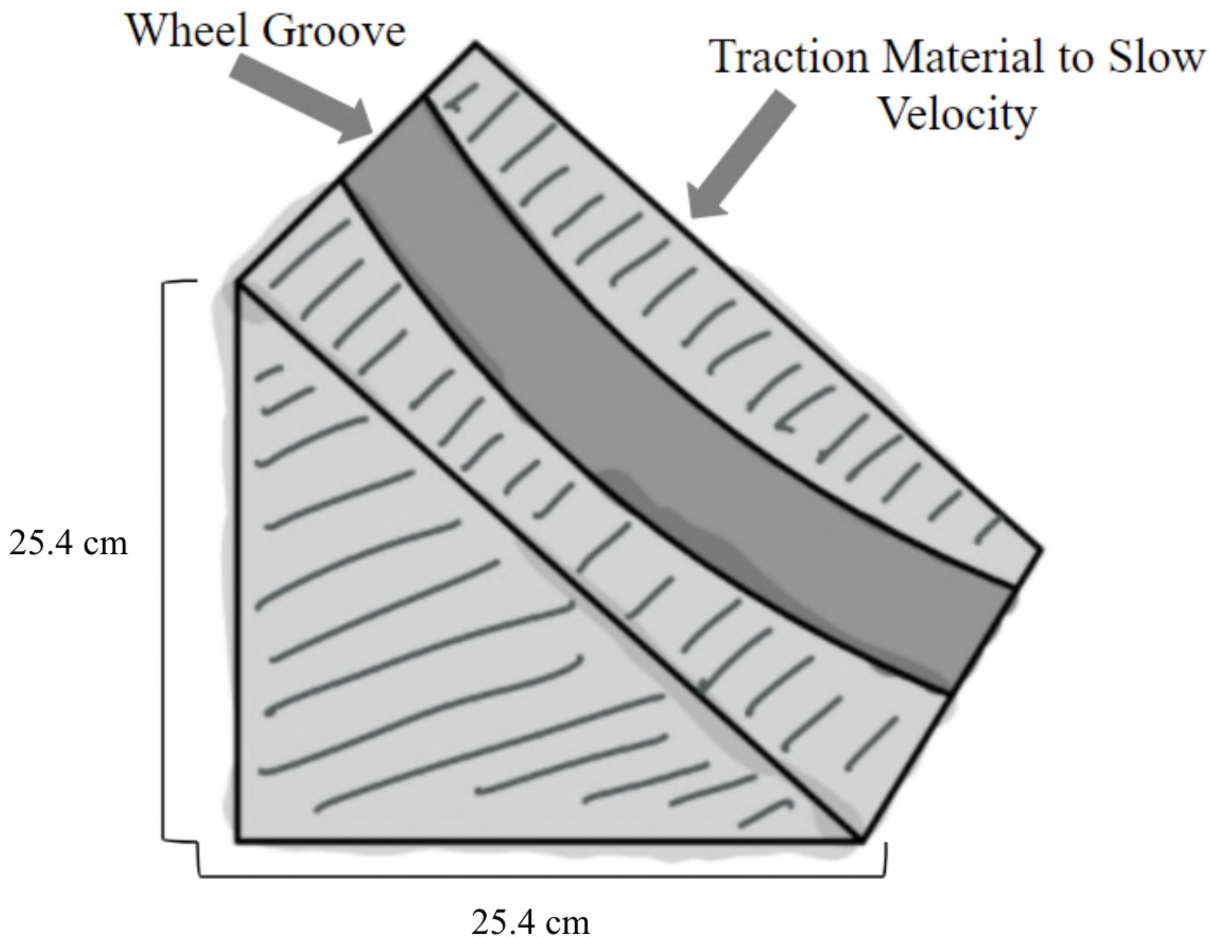


Figure 4. Visual Representation of the Traction Blocks Design. The block has a semicircle groove down the middle which allows for the user to experience slight recoil during the action of rowing. The user will roll up and into the block, which is covered in a traction-like material to reduce velocity,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

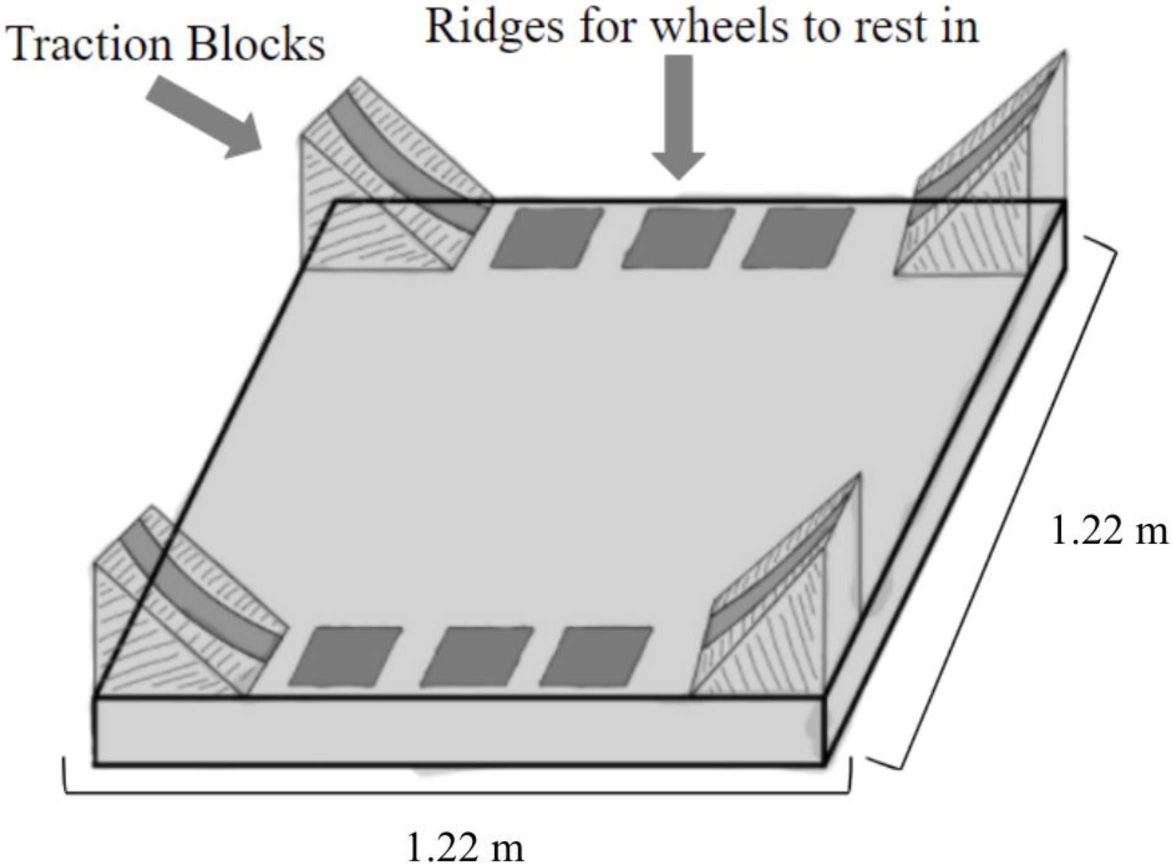


Figure 5. Visual Representation of the Combined Design. The inclined platform with ridges is combined with 4 traction blocks to prevent translation / rotation of the wheelchair during the action of rowing.

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.

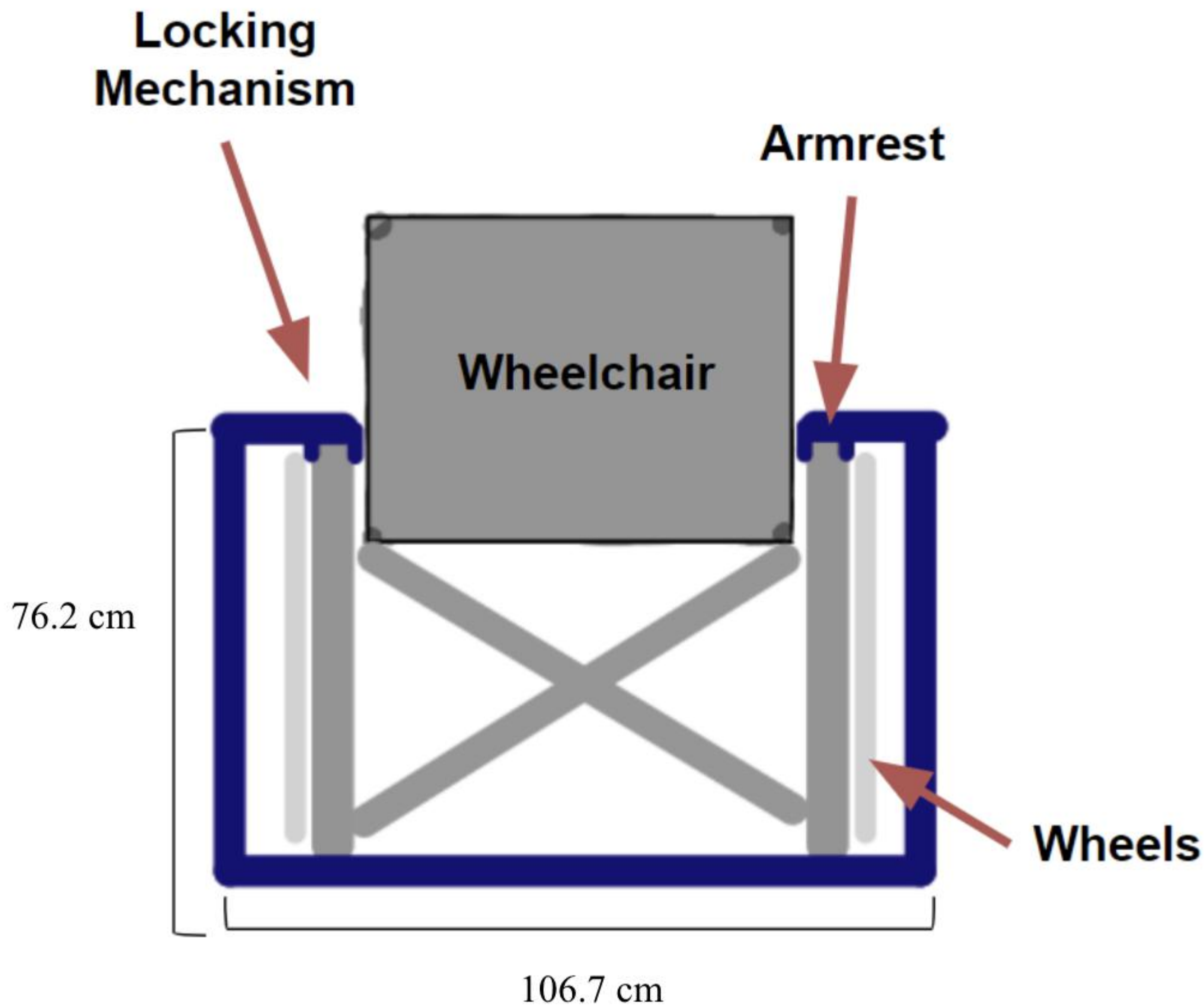


Figure 6. Visual Representation of the Armrest Hooks Design. The base platform will have two sideboards connected via a hinge that can swing up to be parallel with the wheels. Extendable hooks will reach out and grasp the armrests of the wheelchair to prevent side-to-side rotation during the action of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

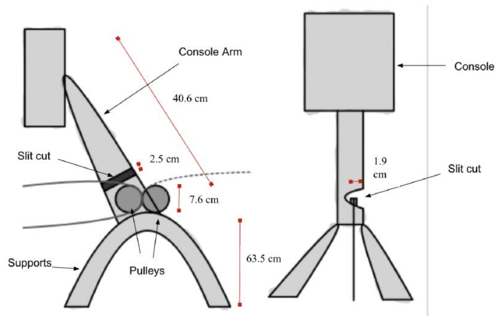
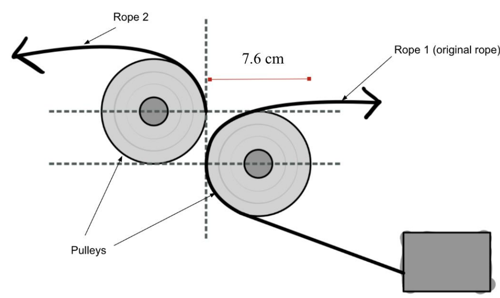
II. Preliminary Design Evaluation

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.

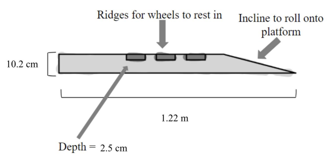
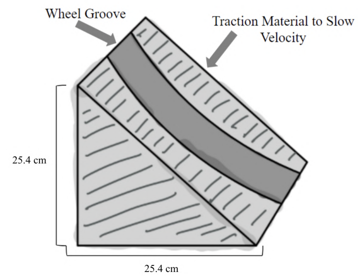
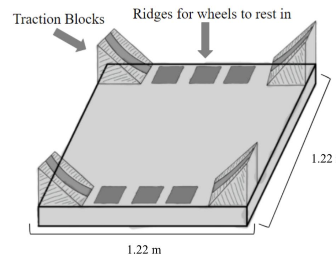
B. Pulley Design Matrix

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.

<table>
<tr><th>Design</th><th colspan="2">2 Pulleys with Slit

</th><th colspan="2">2 Pulleys with 2 Ropes

</th></tr>
<tr><td>User Stability / Safety (25%)</td><td>4/5</td><td>20</td><td>5/5</td><td>25</td></tr>
<tr><td>Ease of Fabrication (25%)</td><td>4/5</td><td>20</td><td>2/5</td><td>10</td></tr>
<tr><td>Ease of Use / Ergonomics (20%)</td><td>4/5</td><td>16</td><td>5/5</td><td>20</td></tr>
<tr><td>Versatility (10%)</td><td>5/5</td><td>10</td><td>5/5</td><td>10</td></tr>
<tr><td>Durability (10%)</td><td>5/5</td><td>10</td><td>5/5</td><td>10</td></tr>
<tr><td>Cost (10%)</td><td>5/5</td><td>10</td><td>3/5</td><td>6</td></tr>
<tr><td>Total for each design:</td><td colspan="2">86</td><td colspan="2">81</td></tr>
</table>

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** 	
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
Total for each design:	**95**		**76**		**73**	

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.

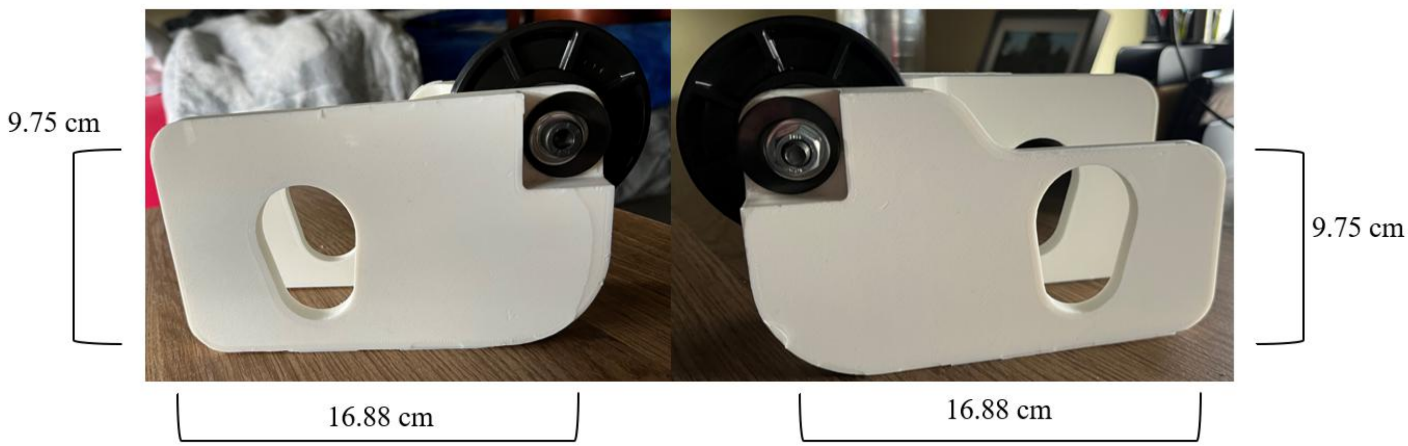


Figure 2. Left and Right Pulley Support Plates. The left (left) and right (right) pulley support plates fit tightly around the pulley bearing and have a cavity that fits around the metal support arms for the rower neck. The right pulley support plate has material taken off of the top surface to allow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

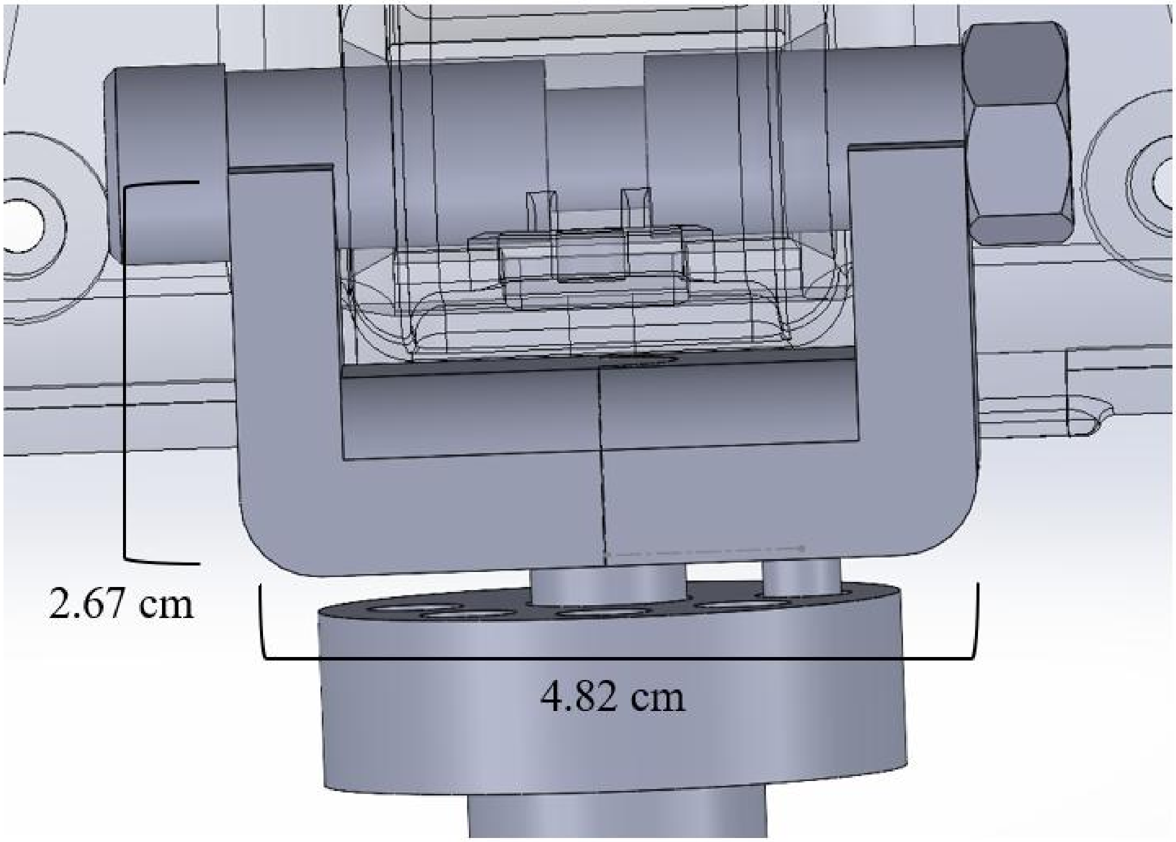


Figure 3. Field Goal Posts Allow Original Console Rotation. The field goal posts have cylindrical components that insert into the back of the display console to allow it to rotate about its original axis. This allows the user to adjust the angle at which the console is bent.

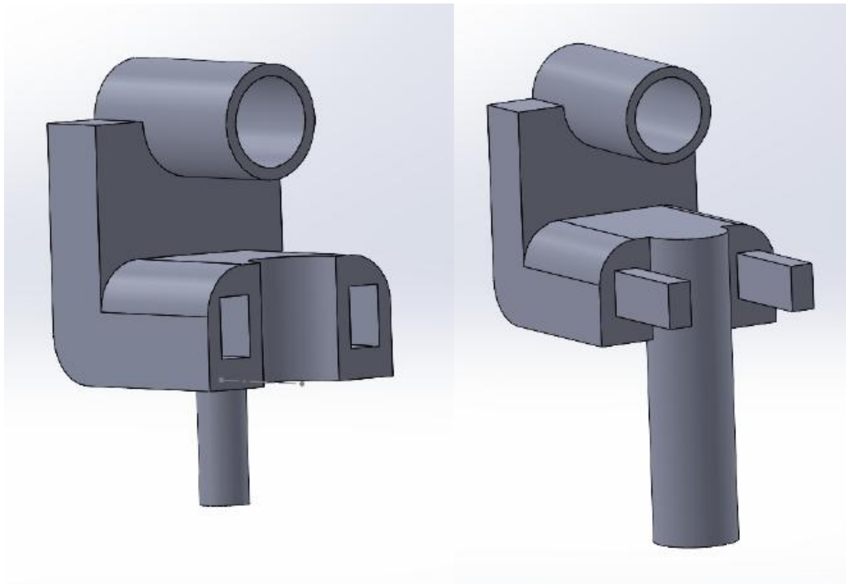


Figure 4. Female and Male Field Goal Posts. The female (left) and male (right) field goal posts fit together via extending inserts on the male piece and a circular peg on the male piece that fit into corresponding cavities on the female piece. The male piece has a large and longer peg to rotate around 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.

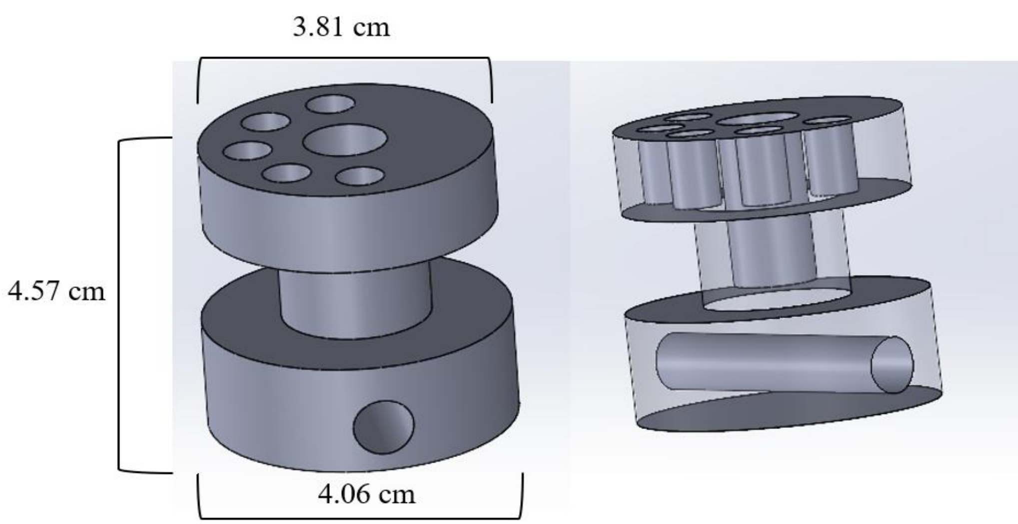


Figure 5. Swivel Receiving Bracket. The swivel receiving bracket has a center cavity to allow the large peg on the male field goal post to rotate. It also has five smaller cavities for the guiding peg to insert into to adjust the degree of rotation of the console. A through hole in the bottom allows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

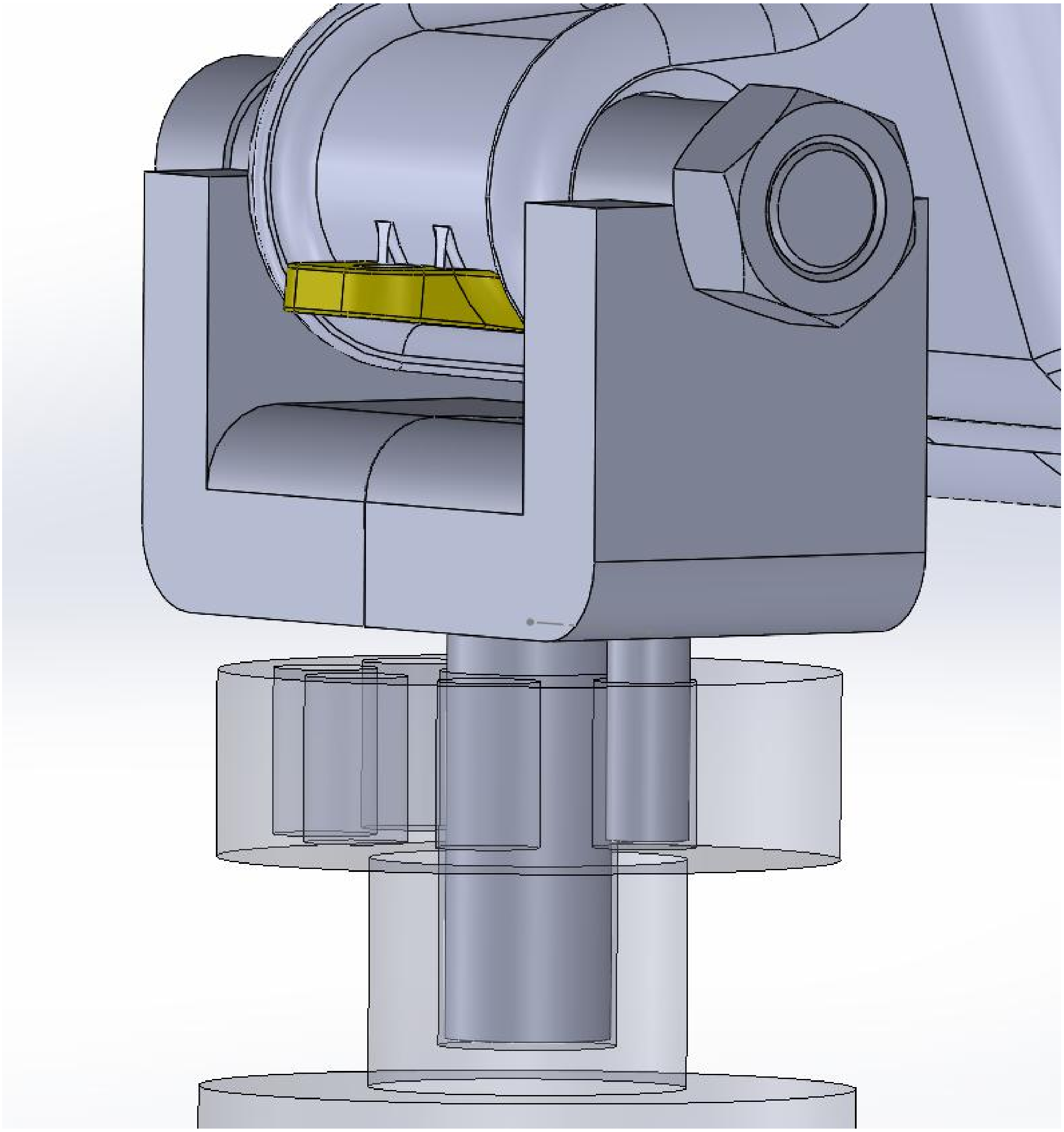


Figure 6. Rotation of Display Console. The large peg fits into the center rotating cavity of the receiving bracket, while the guiding peg fits into one of five smaller cavities to adjust the degree of rotation of the console.

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**.

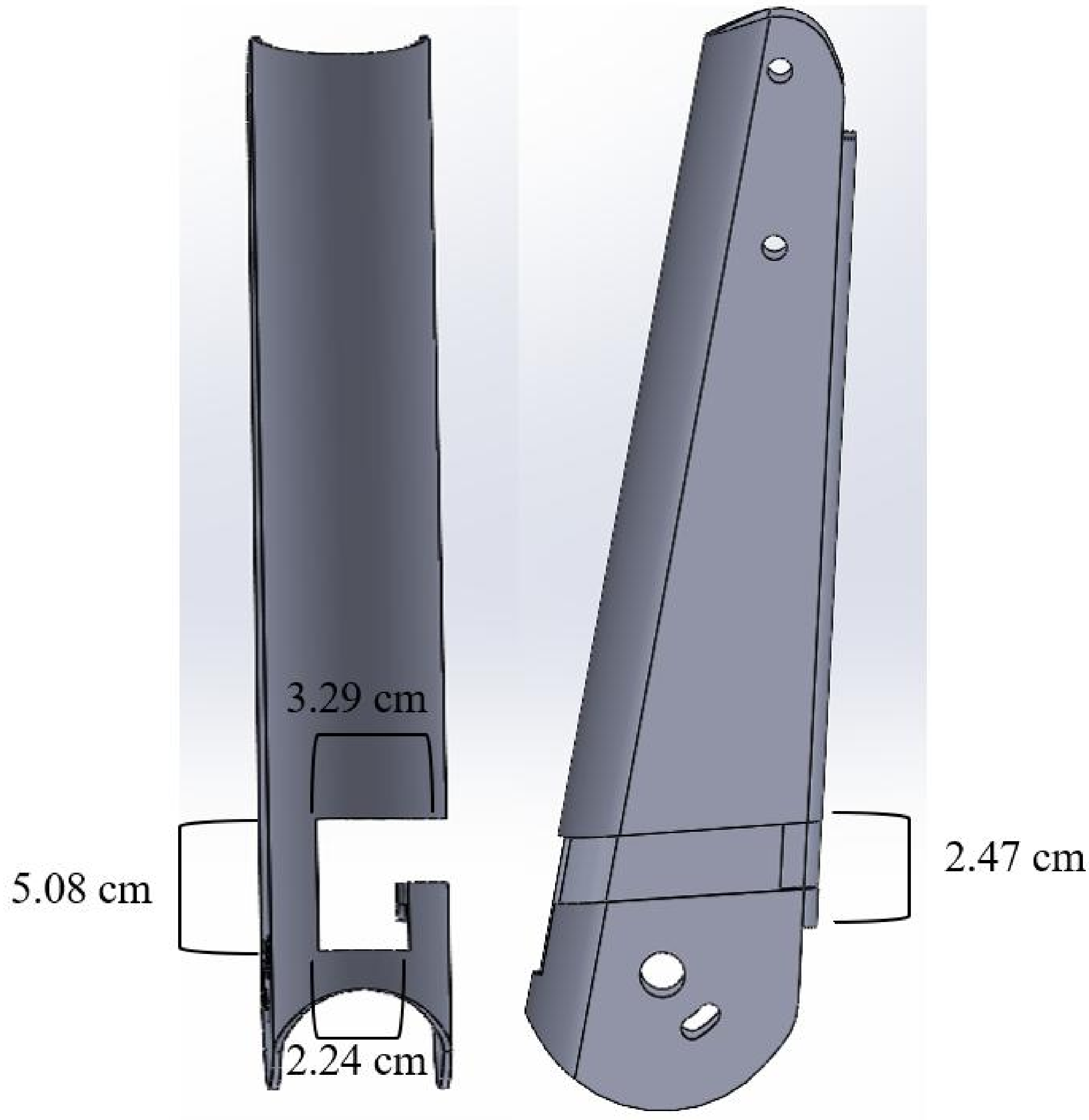


Figure 7. Rower Neck with Slit. The rower neck has a slit in the right side that allows for the rope to be transitioned from the standard to the adaptive side.

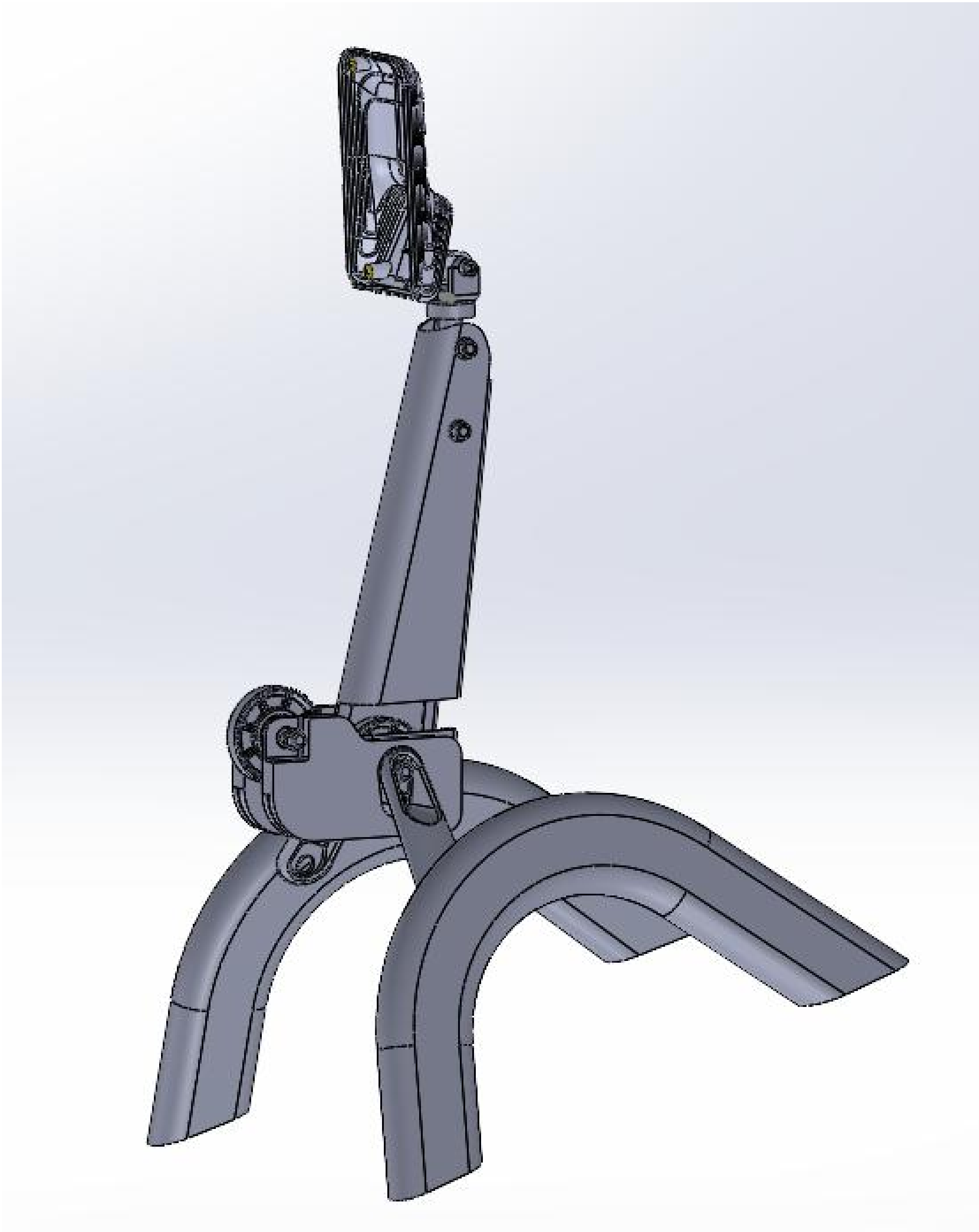


Figure 8. Full SolidWorks Assembly. The adaptations made to the original rower include adding an additional pulley stabilized by mirroring support plates, cutting a slit into the rower neck to transition the rope and handlebar from one side to the other, and a swivel bracket that allows the user to rotate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

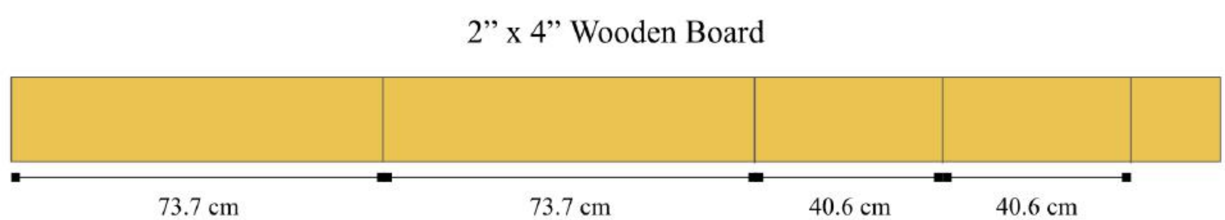


Figure 9. Measurements on 2” x 4” Board. Two 73.7 cm markings were made on the 2” x 4” board along with two 40.6 cm markings.

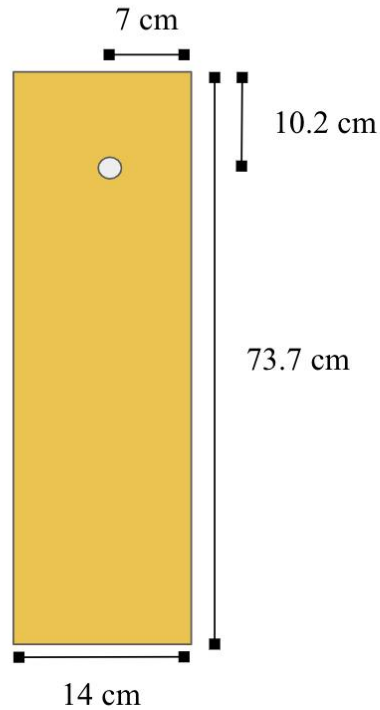


Figure 10. Hole Marking for Vertical Support Board. Markings were made 7 cm across the width and 10.2 cm down the length of the 73.7 cm vertical support boards. The holes that were drilled at these markings held the support straps that attach to the wheelchair.

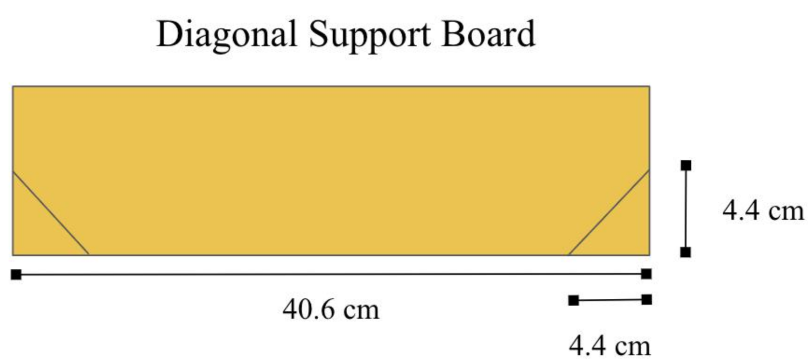


Figure 11. Diagonal Support Board Measurements. On the 40.6 cm diagonal support boards, 4.4 cm markings were made along the width and the length of the board. These markings were then connected with a diagonal line.

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**).

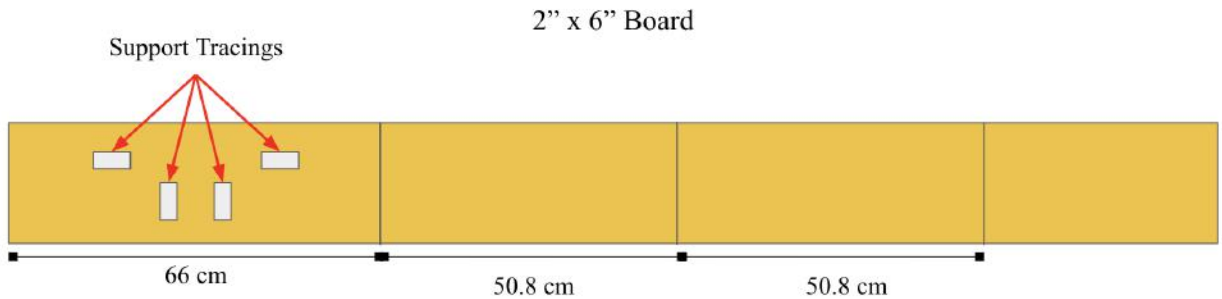


Figure 12. Markings on 2” x 6” Wooden Board. The 66 cm baseboard marking and two 50.8 cm horizontal support markings were made on the 2” x 6” wooden board. The tracings of the rowing machine’s front supports were also made on the baseboard portion of the 2” x 6” board.

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.

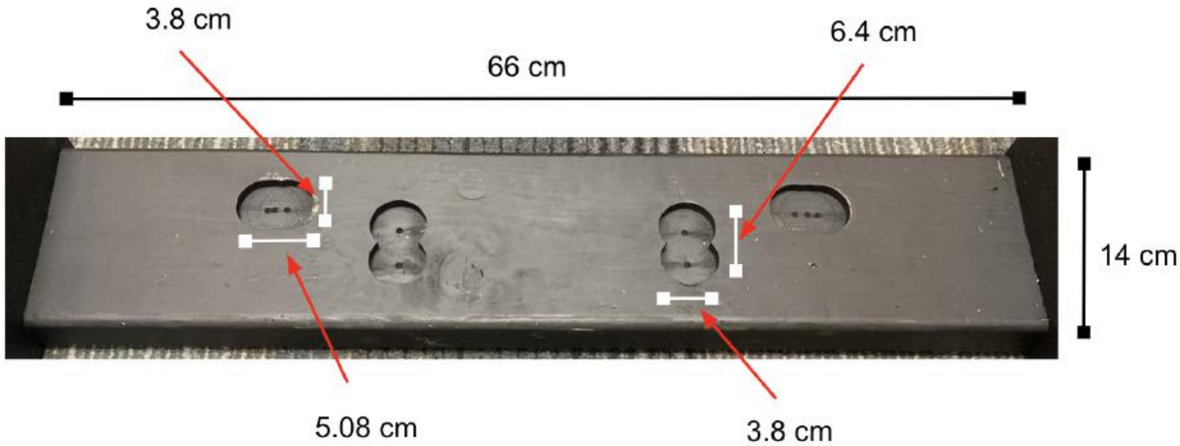


Figure 13. Base Board for Wooden Support. The base board for the wooden support base rests underneath the rowing machine. The divots in the board allow for the rubber supports and wheels of the rowing machine to remain in place without movement during rowing.

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**.

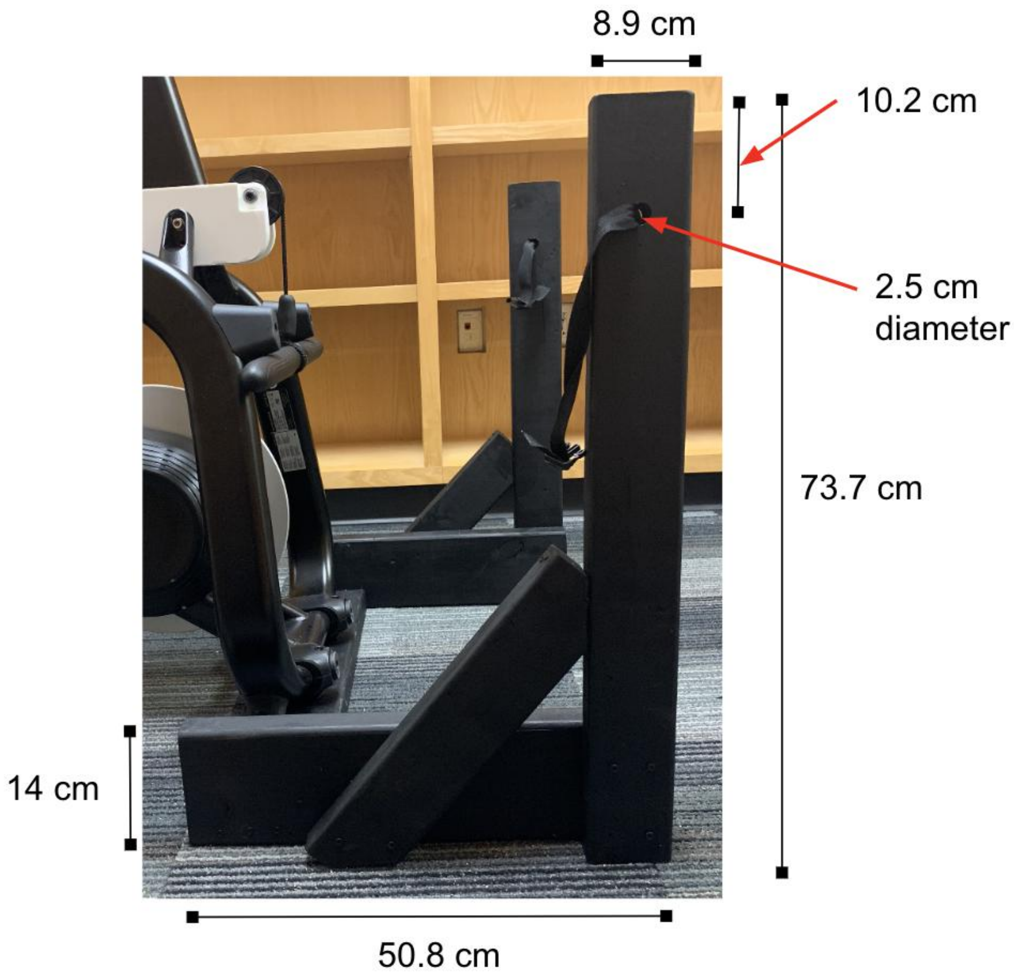


Figure 14. Side View of Wooden Support. The 50.8 cm boards that are attached to the baseboard create separation from the rowing machine to allow for the user to complete the rowing motion comfortably. Additional diagonal supports were added to the base to further enhance the strength and stability of 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.

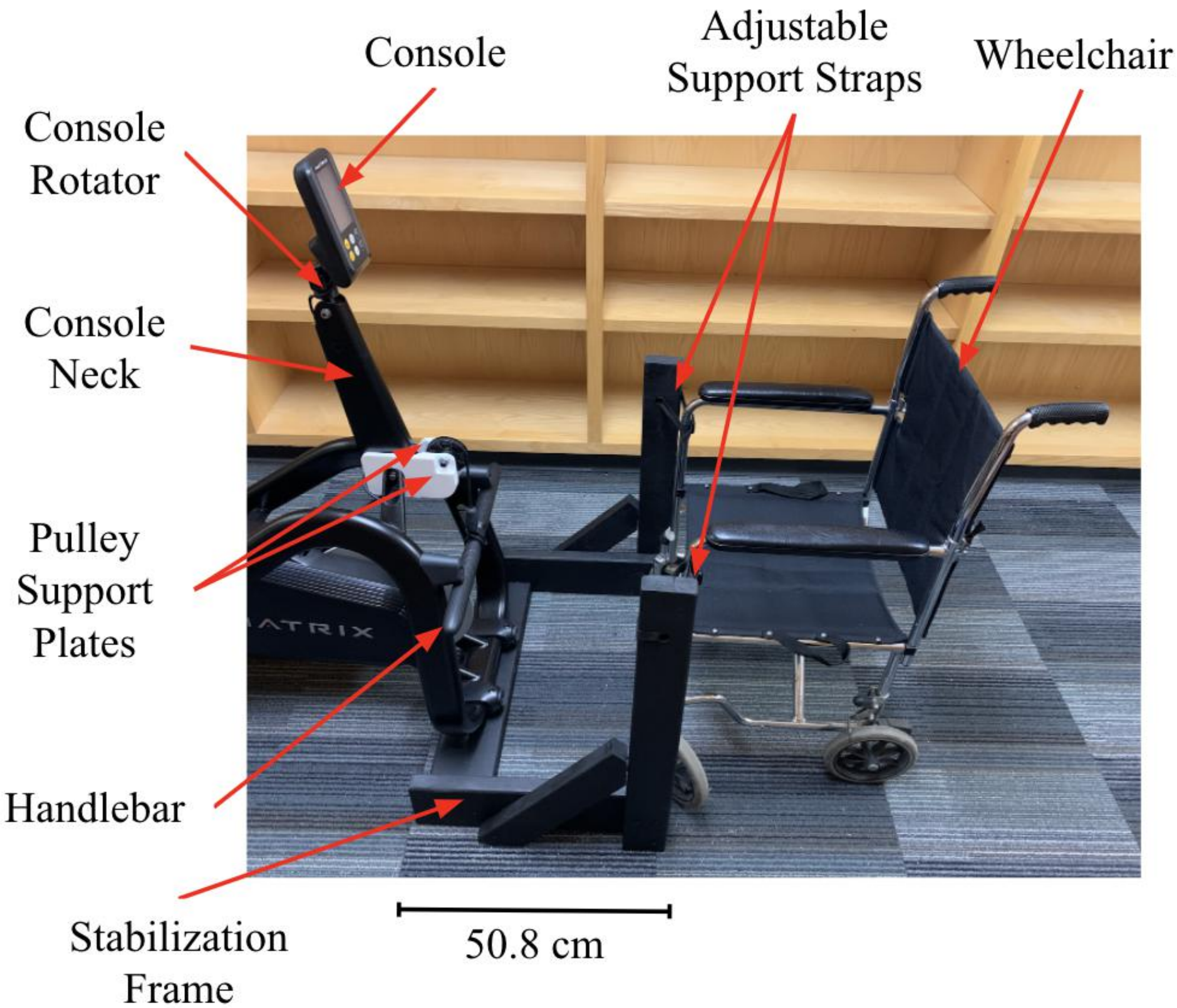


Figure 15. Full Assembly. The full assembly includes the pulley support plates, the console rotator, and the wooden support base. The wheelchair is locked into the support base using adjustable straps.

References for Appendix C:

[1] "Rower | Matrix Fitness - United States." https://matrixfitness.com/us/eng/group-training/cardio/rower (accessed Feb. 07, 2022).

[2] "Ultimaker Tough PLA TDS," *Ultimaker Support*. https://support.ultimaker.com/hc/en-us/articles/360012759599-Ultimaker-Tough-PLA-TDS (accessed May 01, 2022).

[3] "5 Pack 1" Side Release Buckle Dual Adjustable 5 Yards 1" PP Strap Webbing Outdoor Camping Backpack Sleeping Bag Tent Belt Tied Band Accessories #CS023-25 (Size 1" (5 Buckle + 5 Yards Webbing)) : Arts, Crafts & Sewing." 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.

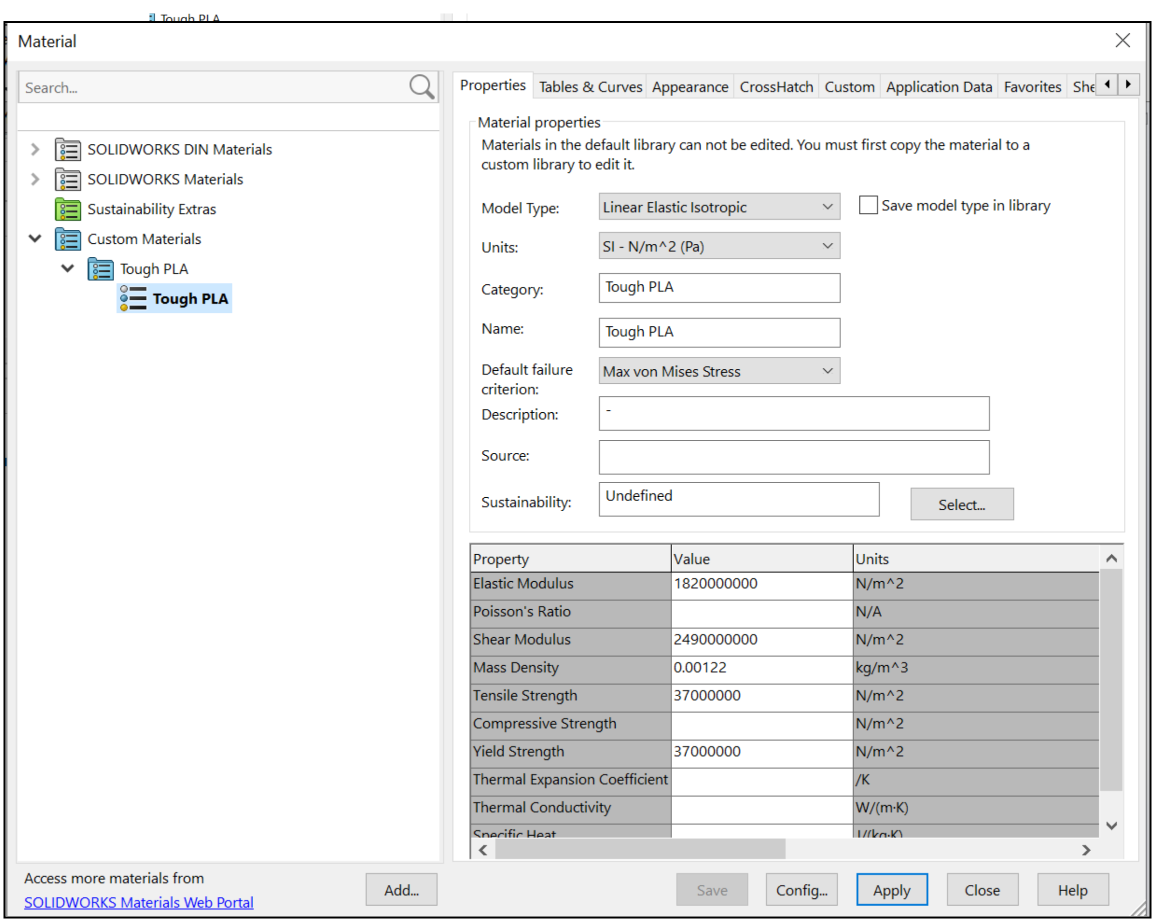


Figure 1. Tough PLA Material Specifications. The pulley support plates were modeled as Tough PLA, to accurately predict the stresses and displacements that will develop in the plates under a maximum load.

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 [1] 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.

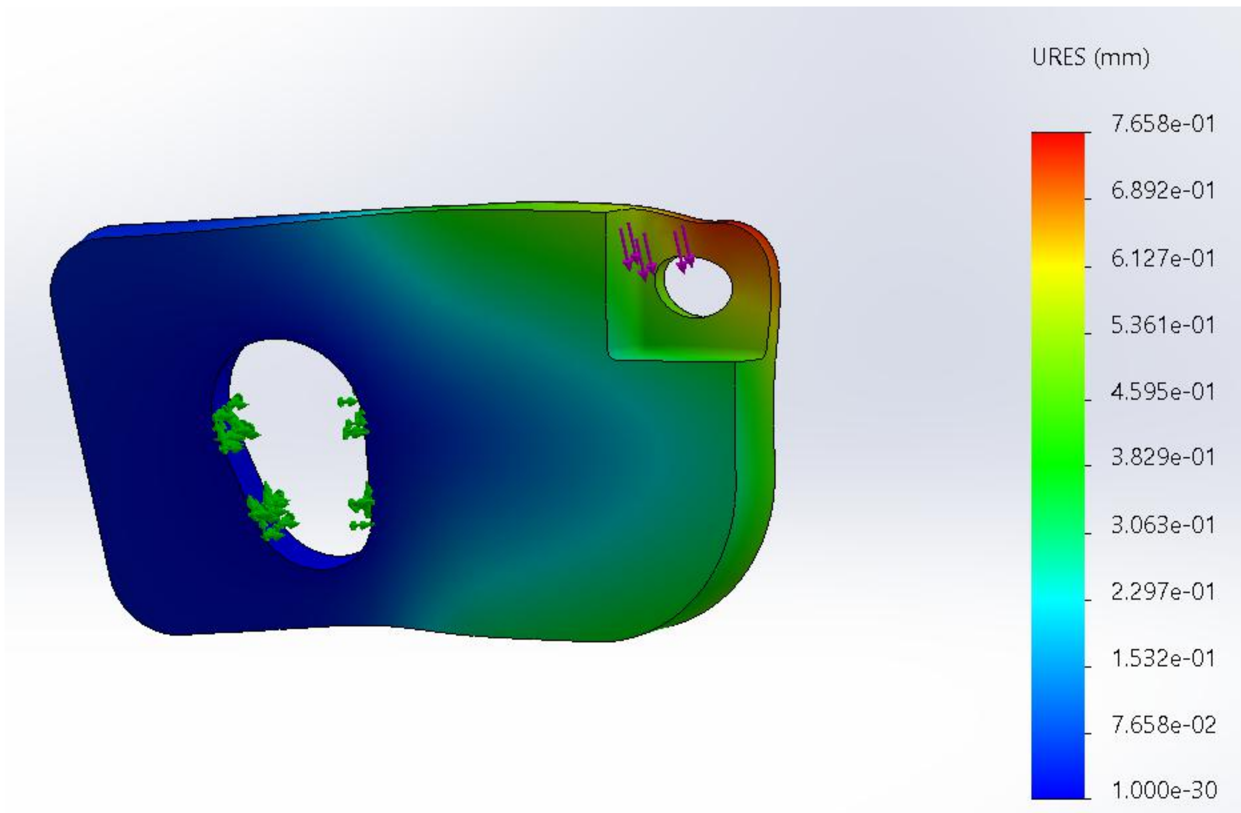


Figure 2. Displacements for Left Pulley Support Plate. The left pulley support plate only experiences a maximum displacement of 0.7658 mm under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

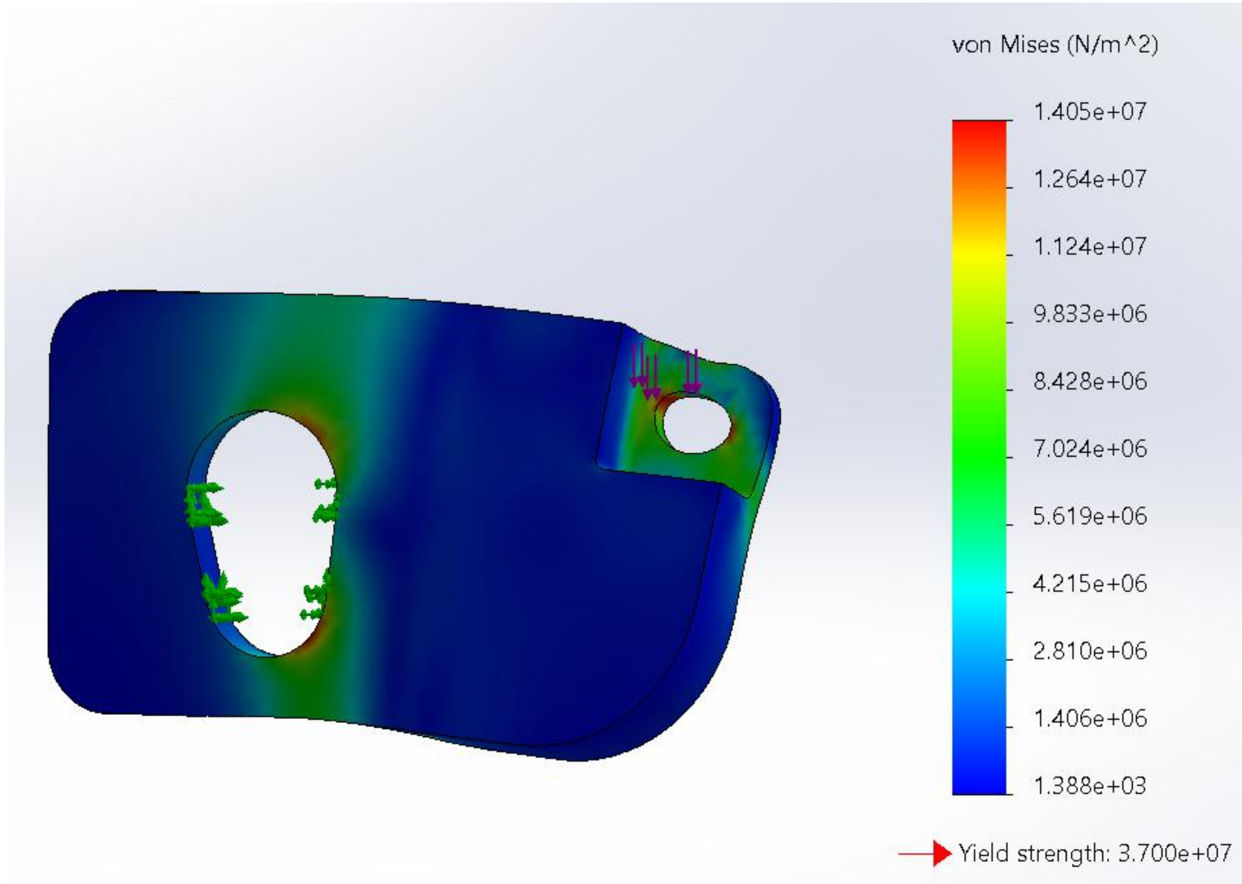


Figure 3. Stresses for Left Pulley Support Plate. The left pulley support plate only experiences a maximum stress of 14.05 MPa under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

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.

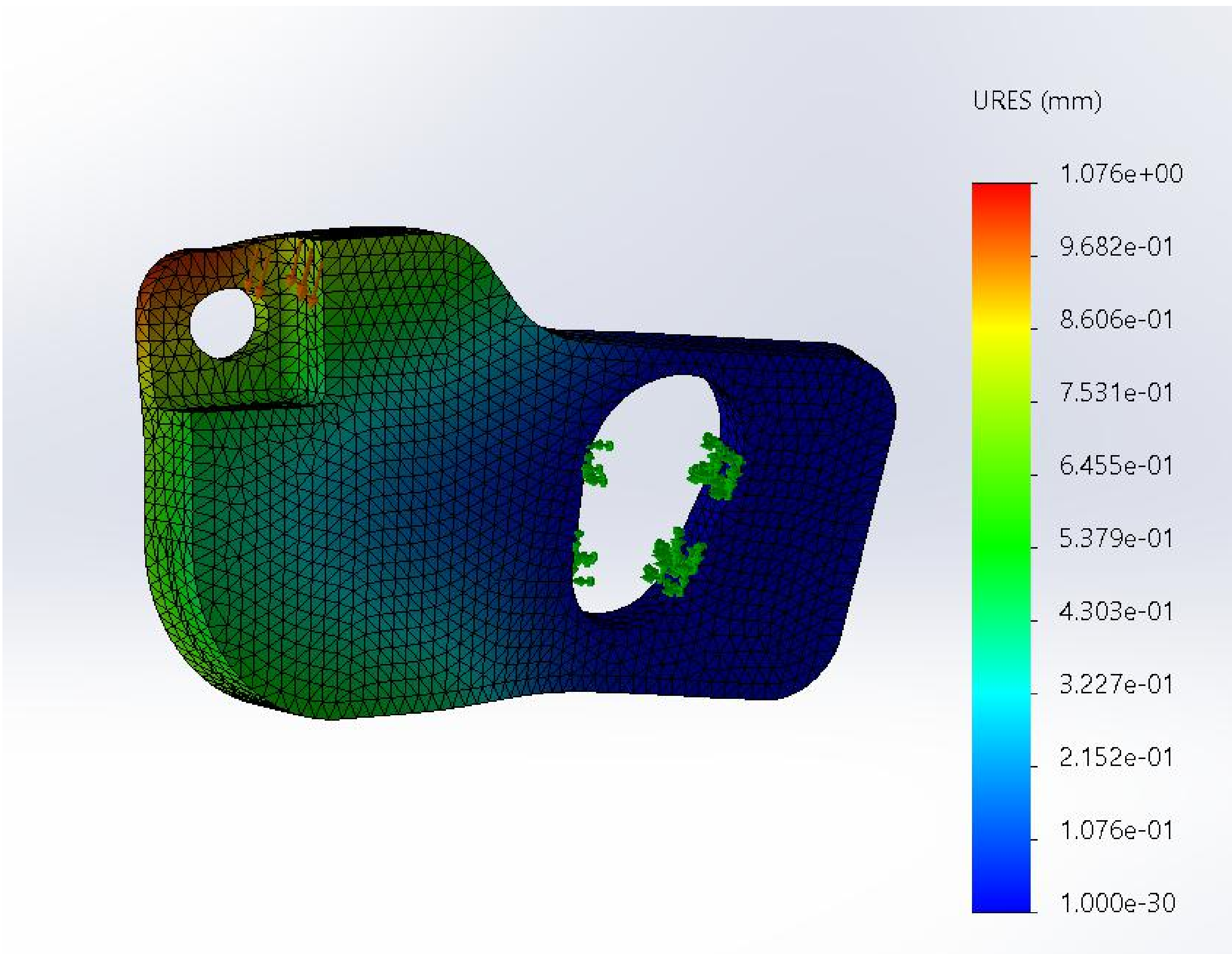


Figure 4. Displacements for Right Pulley Support Plate. The right pulley support plate only experiences a maximum displacement of 1.076 mm under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

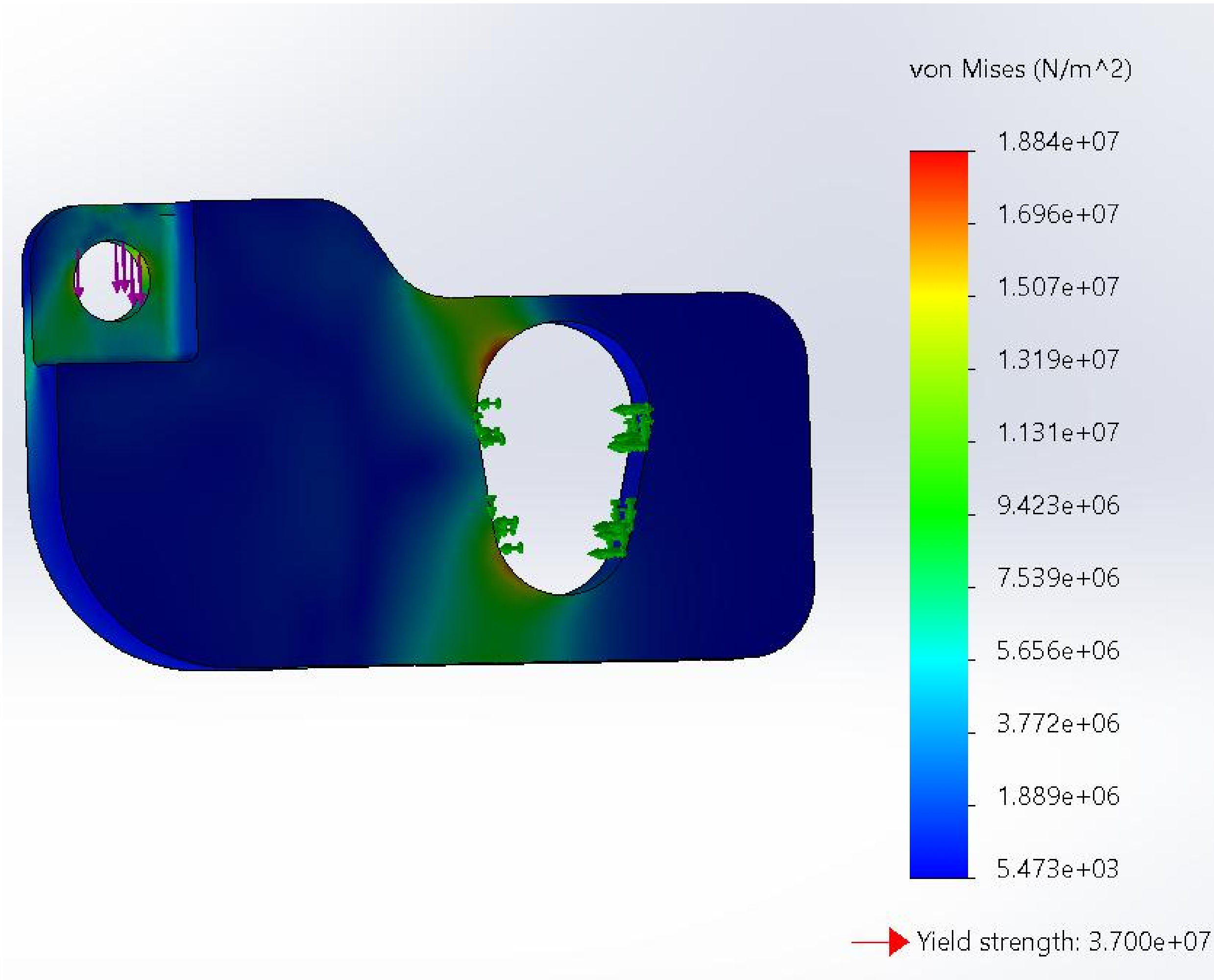


Figure 5. Stresses for Right Pulley Support Plate. The right pulley support plate only experiences a maximum stress of 18.84 MPa under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

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 themself 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.

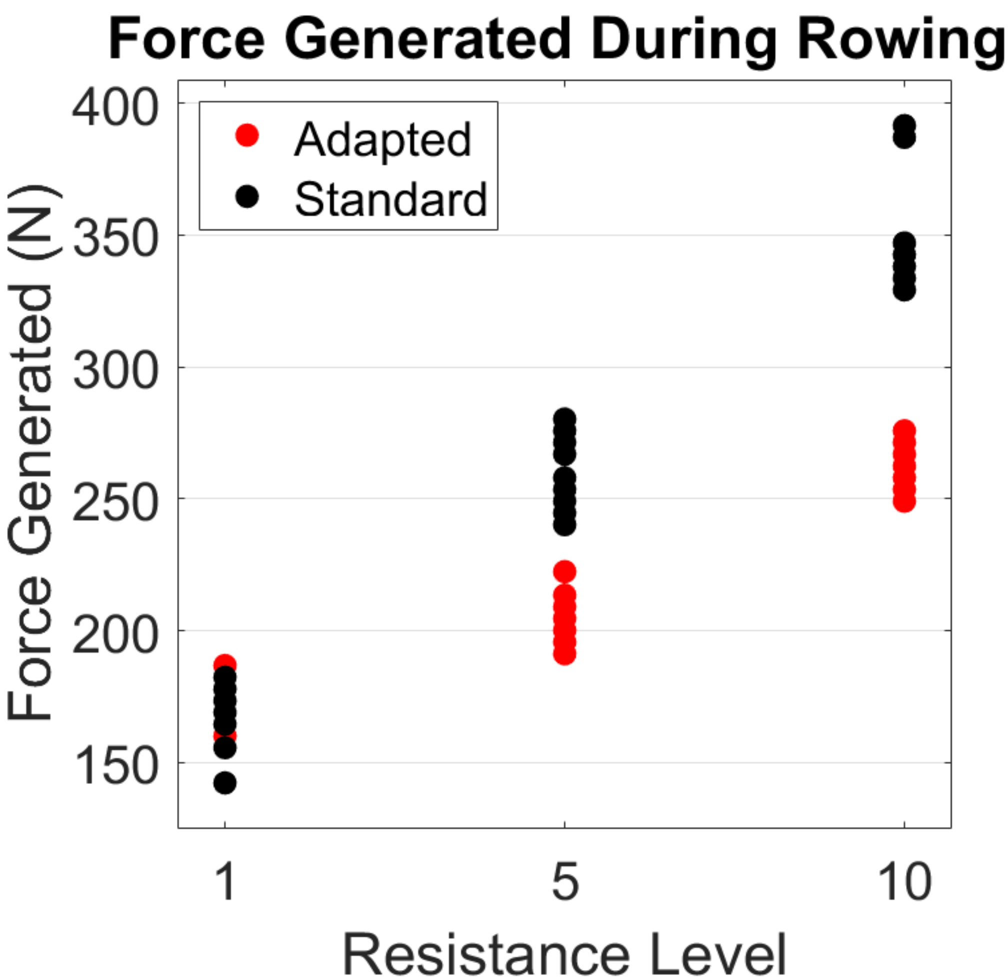


Figure 6. Force Generated During Rowing. The force generated during rowing on each side plotted against the resistance level was taken ten times for resistance levels of 1, 5, 10. More force was generated on the standard side, but the overall force generated increased at each resistance level for both 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 [3]. 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.

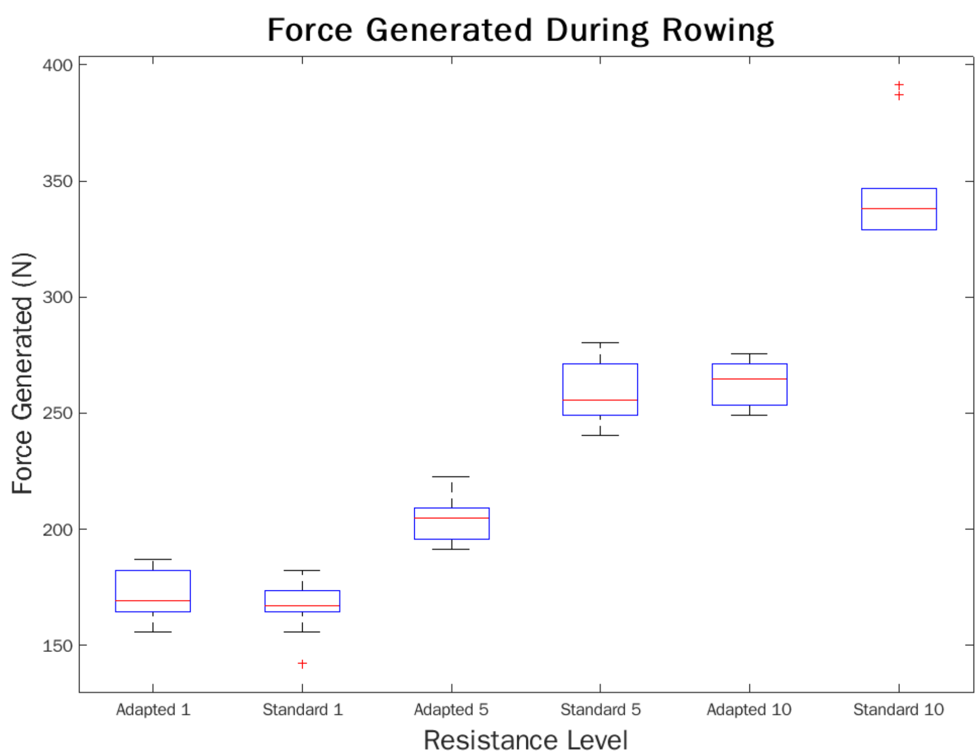


Figure 7. Box Plot of Force Generated During Rowing. The box plot for the rowing conducted at resistance levels of 1, 5, 10 demonstrates the general increase in force generated for each resistance level. The red asterisks indicate outliers in the ten data points for each side at each resistance level.

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.

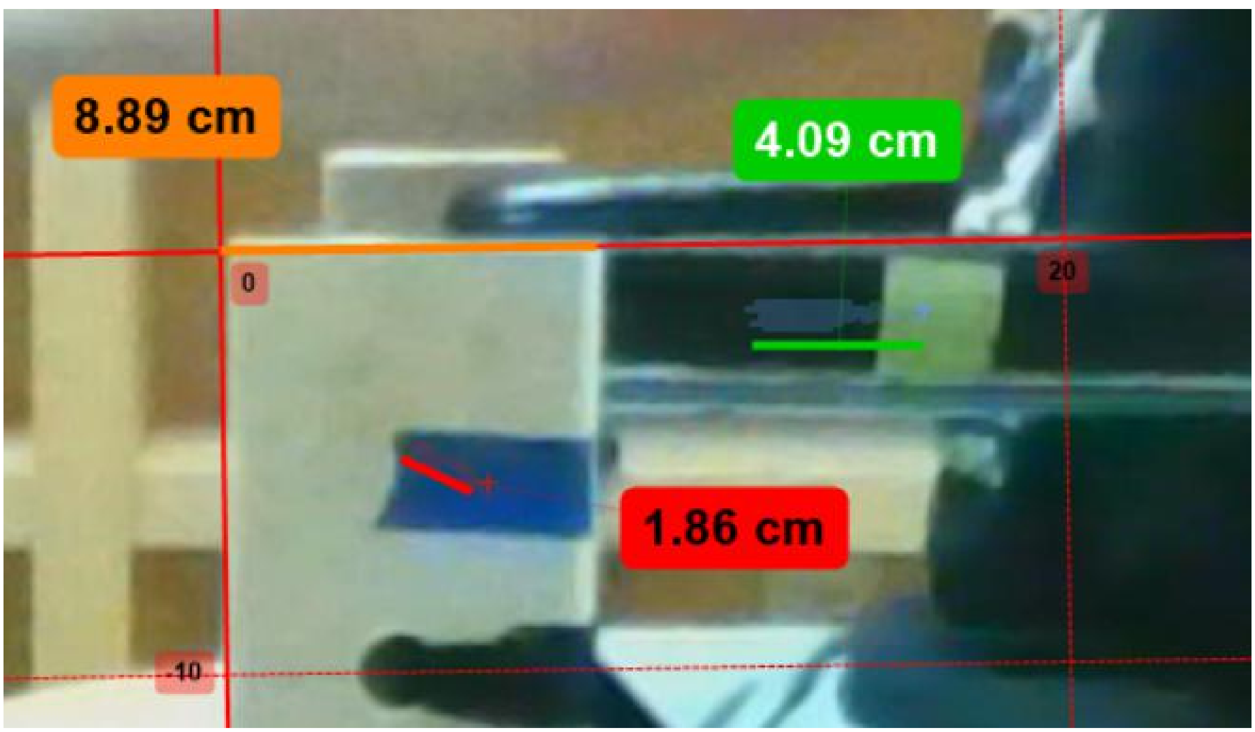


Figure 8. Maximum Displacement in Vertical Support of the Wooden Base and Wheelchair. The orange label and line contain the known distance for the calibration curve. The green label and line highlight the displacement of the wheelchair. The red label and line indicate the displacement of the vertical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

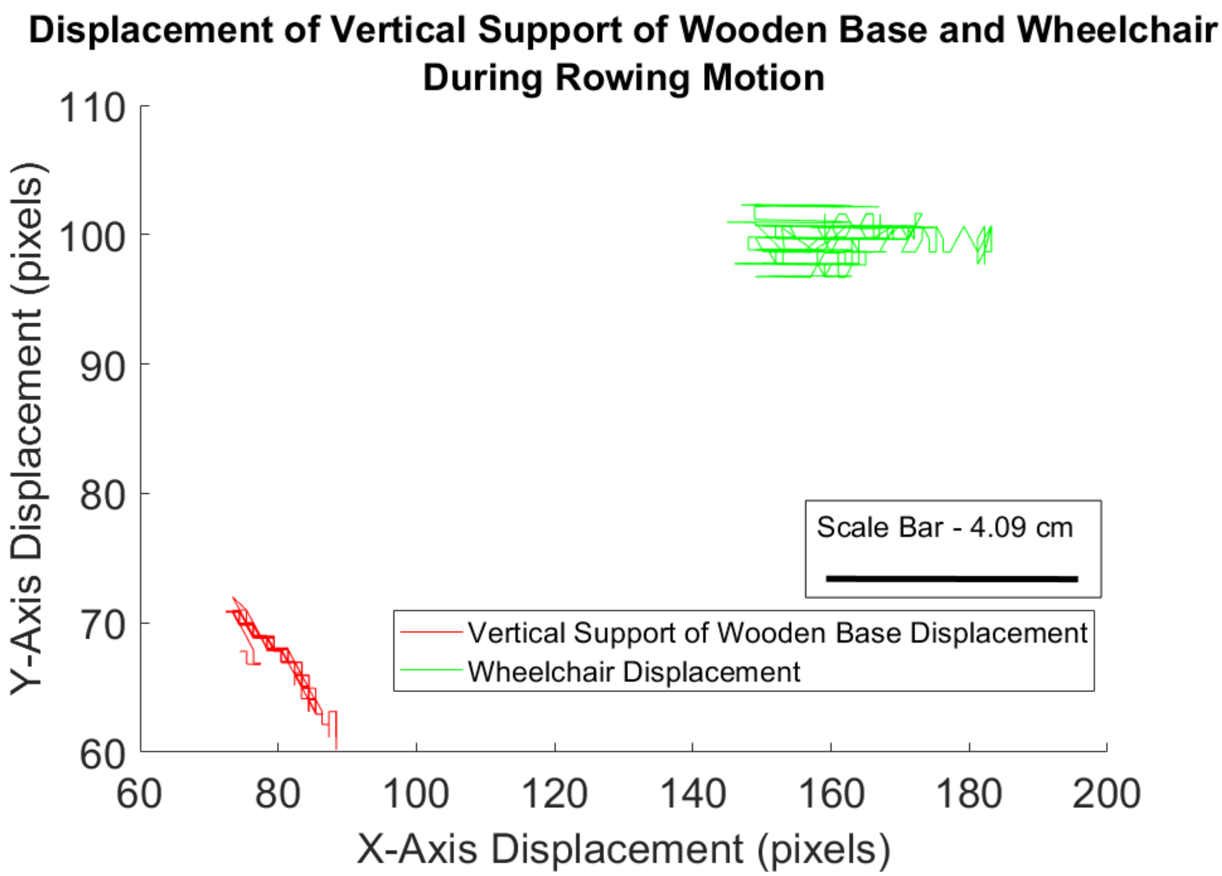


Figure 9. Movement Data Plot for Vertical Support of Wooden Base and Wheelchair. The red line represents the movement exhibited by the vertical support of the wooden base. The green line represents the movement exhibited by the wheelchair.

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.**

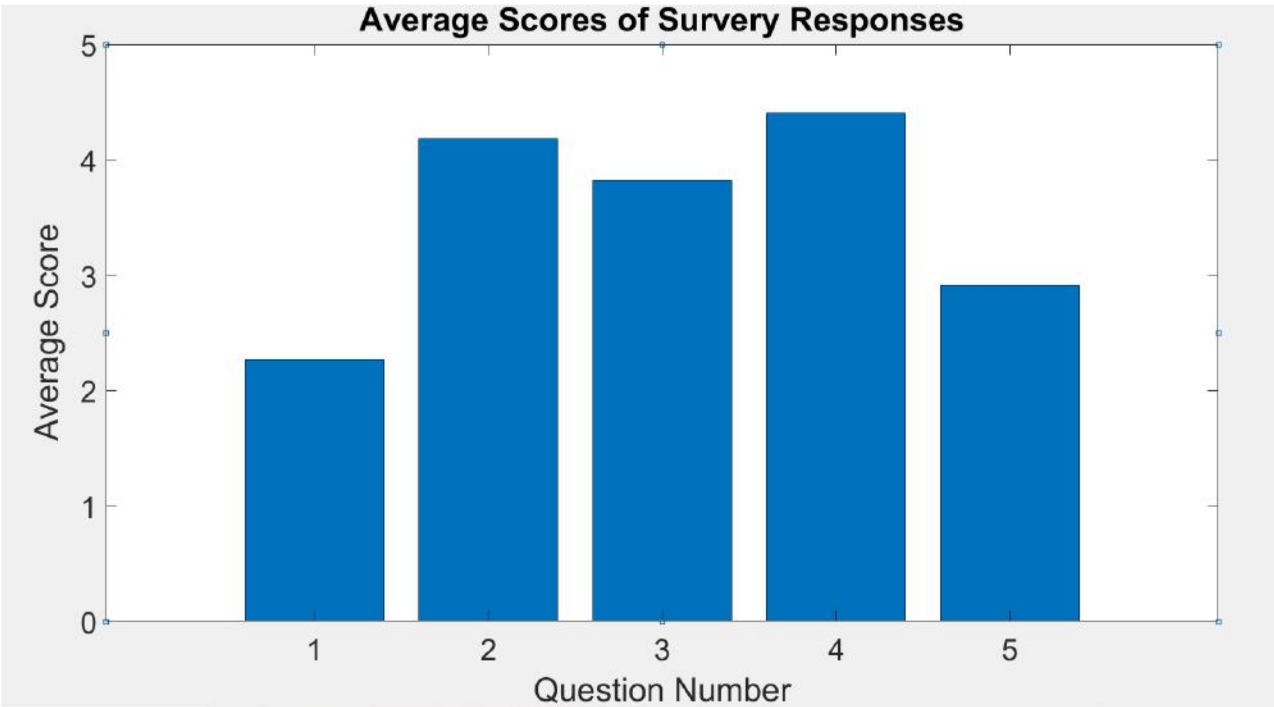


Figure 10. Average Score of Survey Responses. The average responses to each of the five numerically rated questions are displayed to summarize user feedback from using the Adaptive Rower.

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.

References for Appendix D:

[1] N. Découfour, F. Barbier, P. Pudlo, and P. Gorce, "Forces Applied on Rowing Ergometer Concept2®: a Kinetic Approach for Development (P94)," p. 8.

[2] "Ultimaker Tough PLA TDS," *Ultimaker Support*. https://support.ultimaker.com/hc/en-us/articles/360012759599-Ultimaker-Tough-PLA-TDS (accessed May 01, 2022).

[3] "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 [1]. 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 [2]. 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 [3]. 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 [2]. 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 [2].

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** [1]. 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.

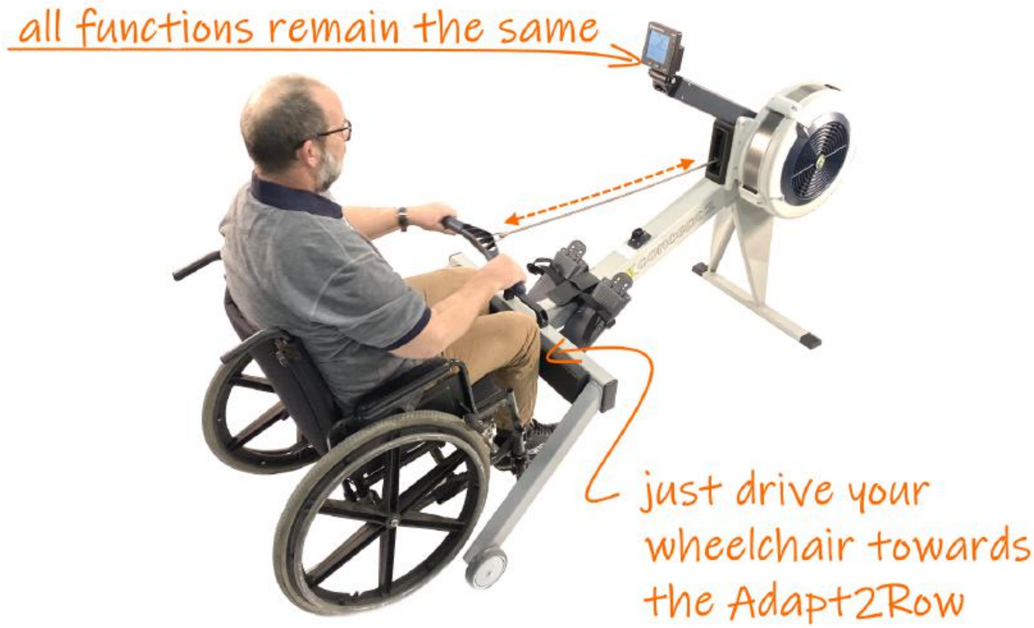


Figure 2. Adapt2Row on a Concept2 Rowing Machine. Adapt2Row allows for both standard and adaptive rowing on the Concept2 rowing machine but still requires outside assistance to transition between both states [4].

References for Appendix E:

[1] "Adapting the Indoor Rower | Concept2." https://www.concept2.com/adaptive-rowing/adapting-indoor-rower (accessed Dec. 12, 2022).
[2] "Rowing Solutions – Adapted Rowing Machine (AROW)," Feb. 08, 2022. https://adaptederg.commons.bcit.ca/rowing-solutions/ (accessed Feb. 07, 2022).
[3] "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).
[4] "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

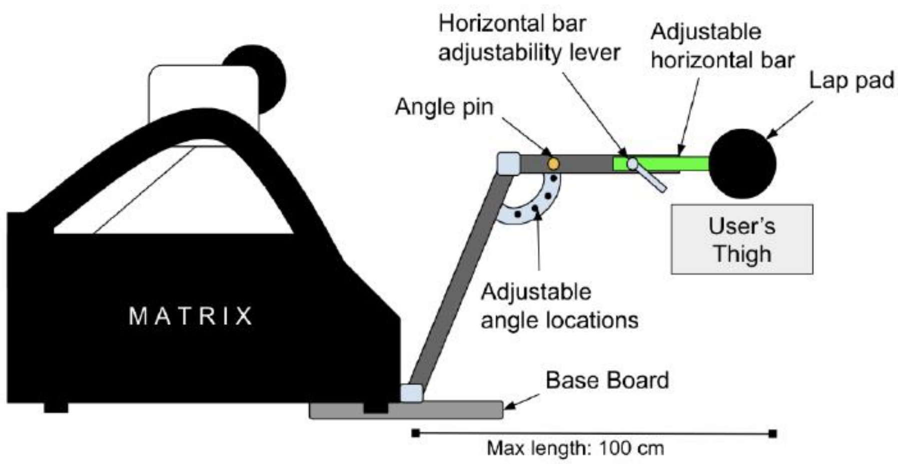
A. Stabilization Frame

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.

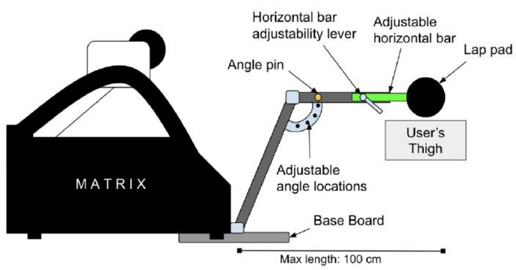
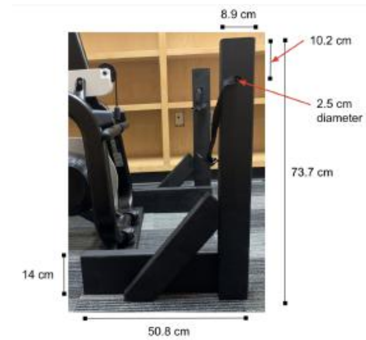
c. Stabilization Frame Design Criteria

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	**Pad Support**		**Base Stabilization Frame**	
	 *Note: Drawings not to scale			
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
Total for each design:	**84**		**61**	

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.

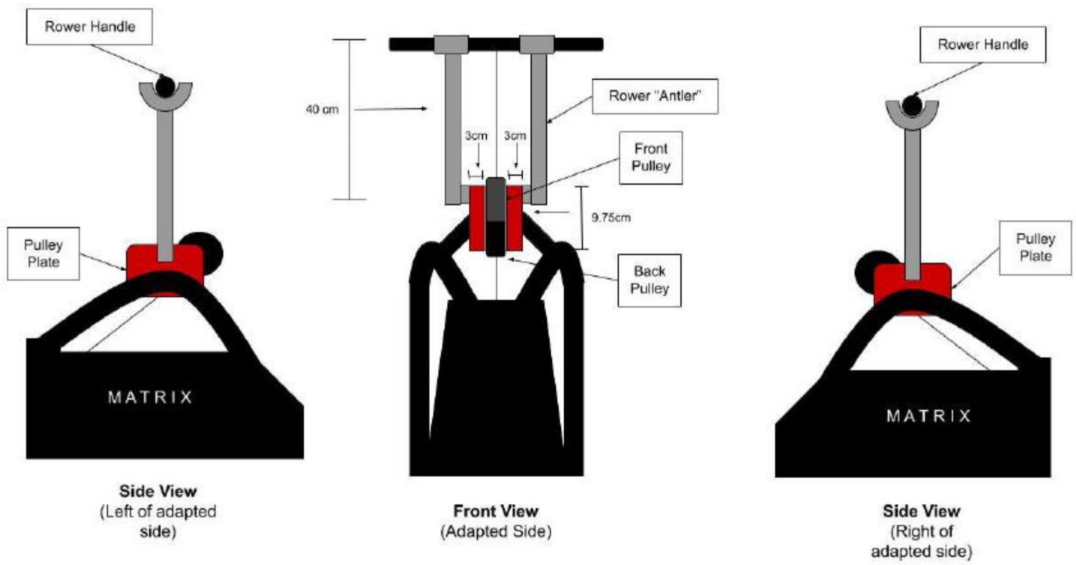


Figure 2. Antler Design. This design relocates the handle bar of the rower to a more central location and allows the user to row from the adaptive or standard side of the rower without needing to remove rope tension before transitioning the bar.

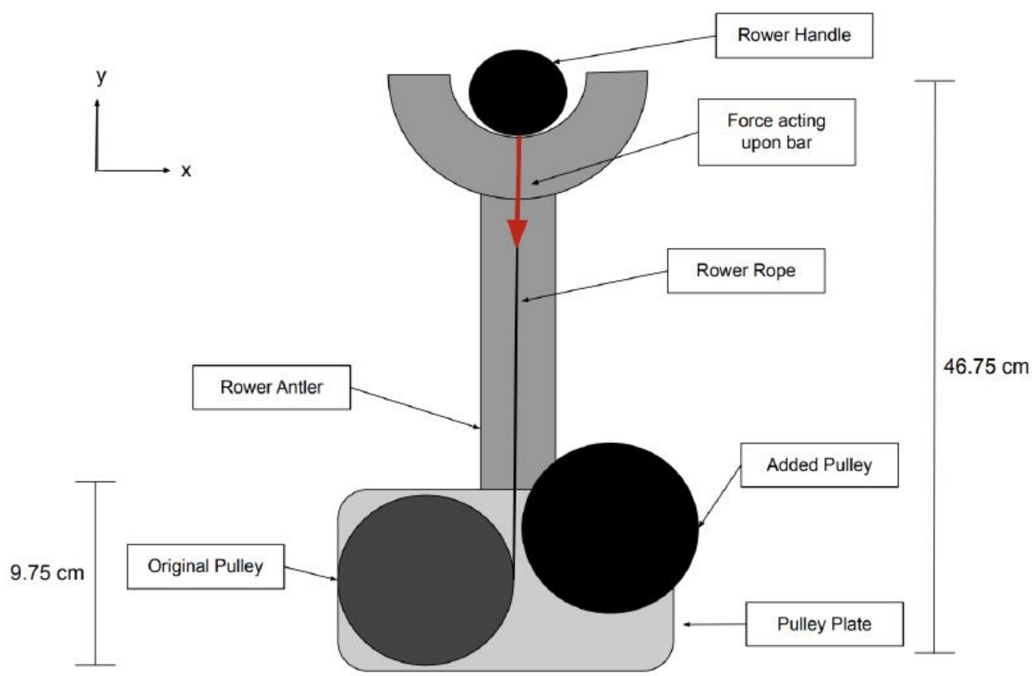


Figure 3. Tension on Handlebar of Antler Design. As part of the antler design, the handlebar is relocated such that it lies directly in between the two pulleys on the rower. Therefore, the net tension acting upon the bar is directly downward.

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° 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° and pushes the peg into the cross-shaped keyhole on the structure.

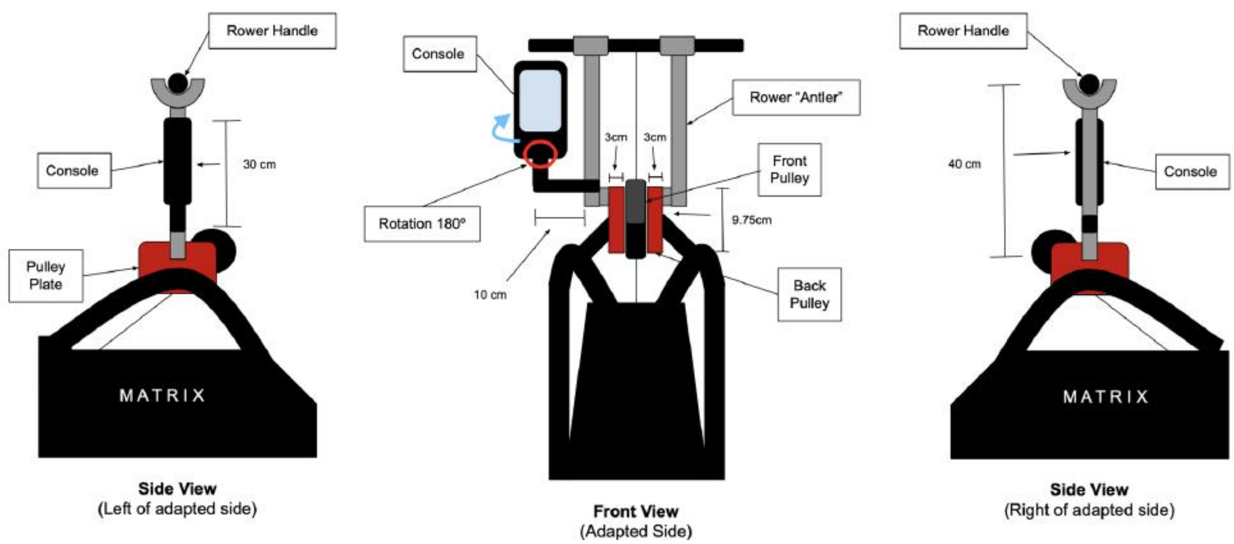


Figure 4. Console Design 1: 1 Pivot Point. This design secures the console to one of the antler structures. A pivot point directly below the console allows 180° manual rotation between the standard and adaptive sides of the machine.

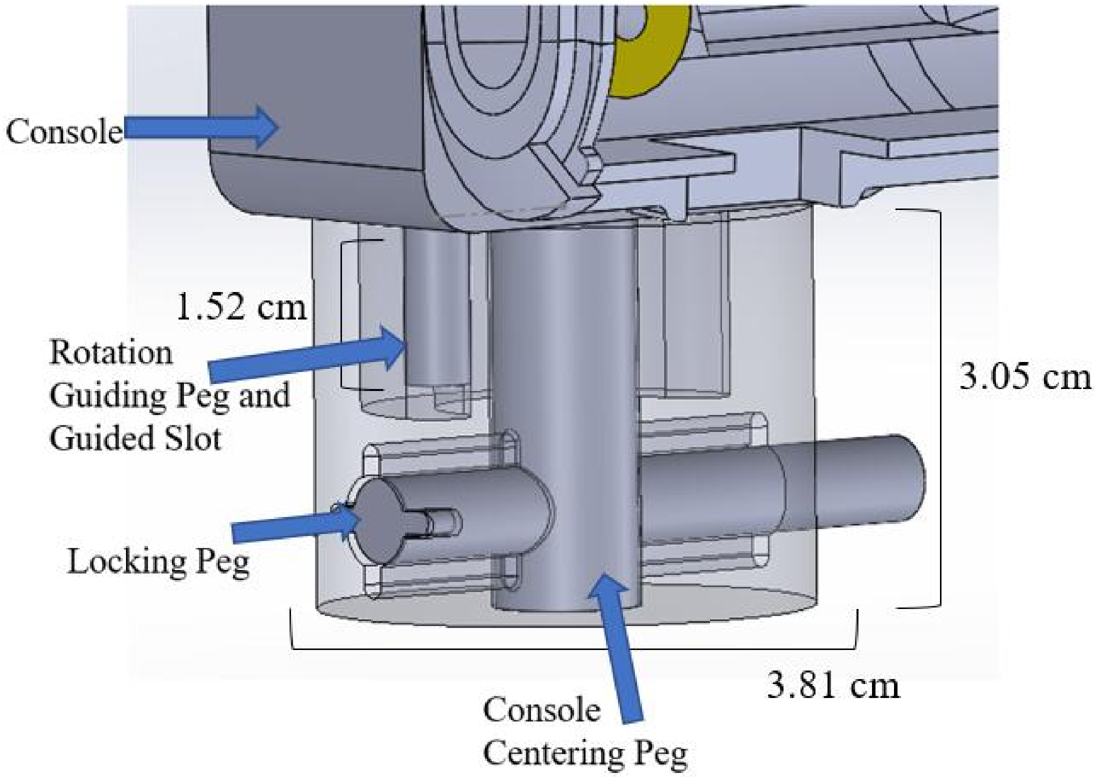


Figure 5. Updated Console Swivel Bracket with Locking Peg. The updated console swivel bracket contains a locking peg to prevent unwanted rotation of the display. When unlocked, the display can rotate 180º to face either the standard or adaptive sides of the machine. Locking only occurs in these two positions, 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**).

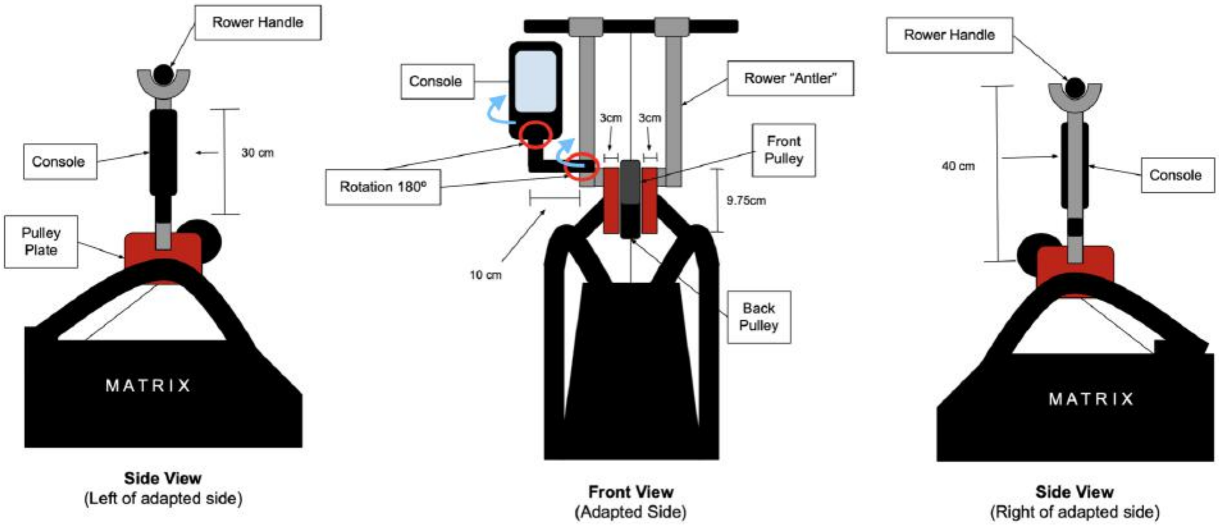


Figure 6. Console Design 2: 2 Pivot Points. This design secures the console to one of the antler structures. Two pivot points increase the viewability and reachability of the display. One pivot point allows the console to swing towards the user and the midline of the machine. The other pivot point allows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

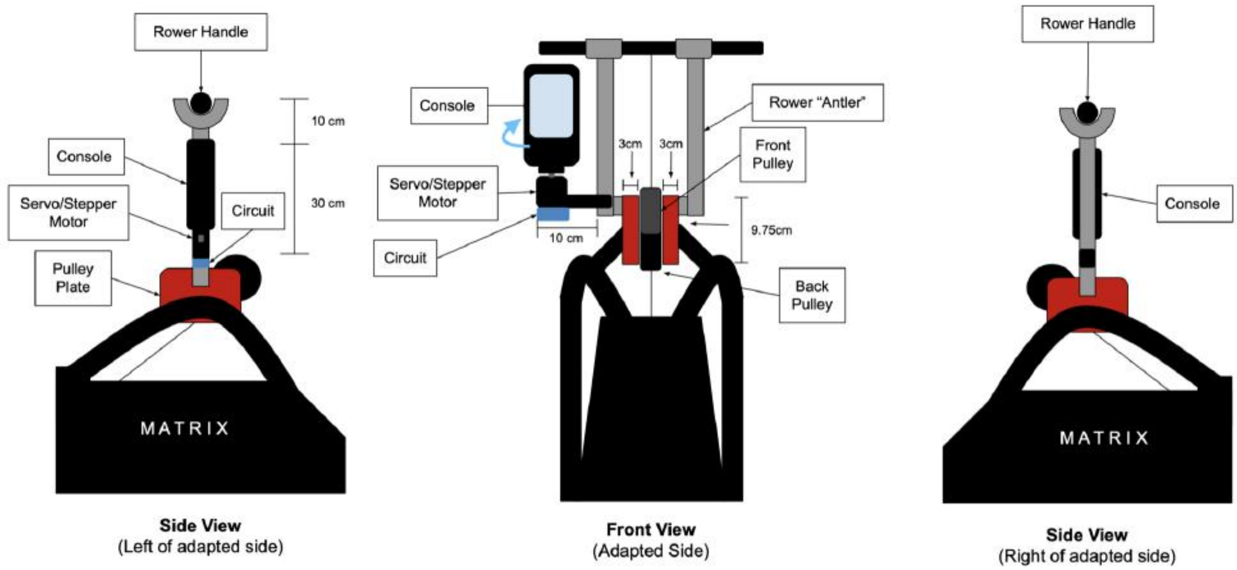


Figure 7. Console Design 3: Motor. This design utilizes a servo/stepper motor to electronically turn the console 180°. All circuit components, except the limit switch (not depicted), motor, and their associated wires will be stowed in a compartment (shown in blue) below the console support for safety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

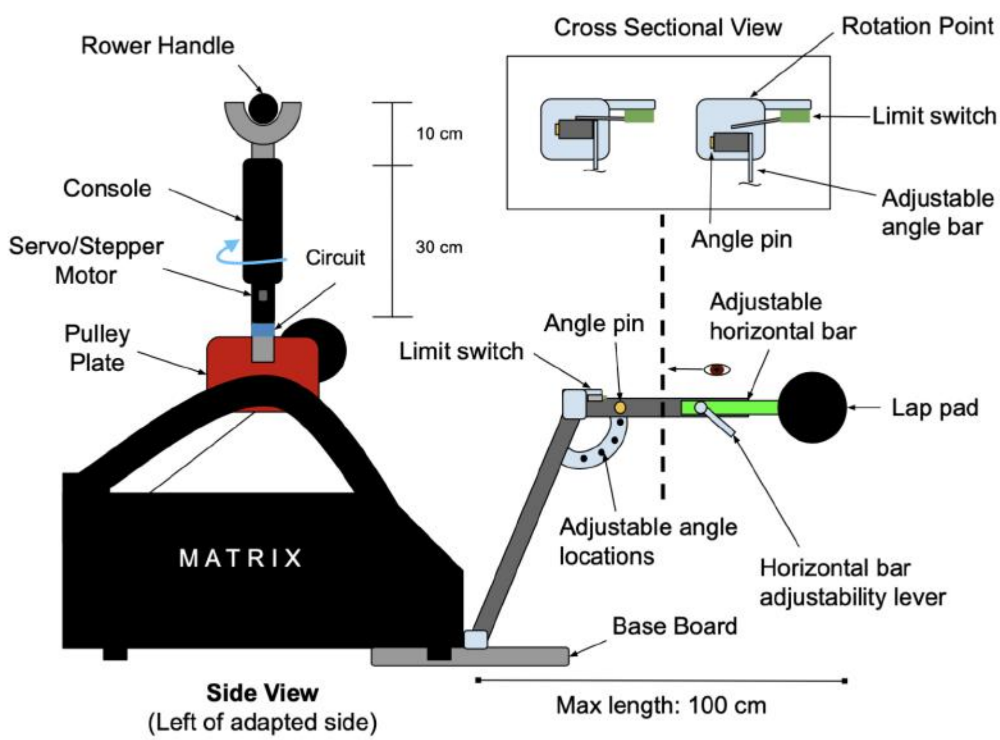


Figure 8. Limit Switch Placement. A limit switch placed above the lap bar near its pivot point provides feedback to the Arduino program about whether the adaptive side is in use or not. Wires (not depicted) run along the stabilization frame and Matrix rower to the electronics box near the console (shown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

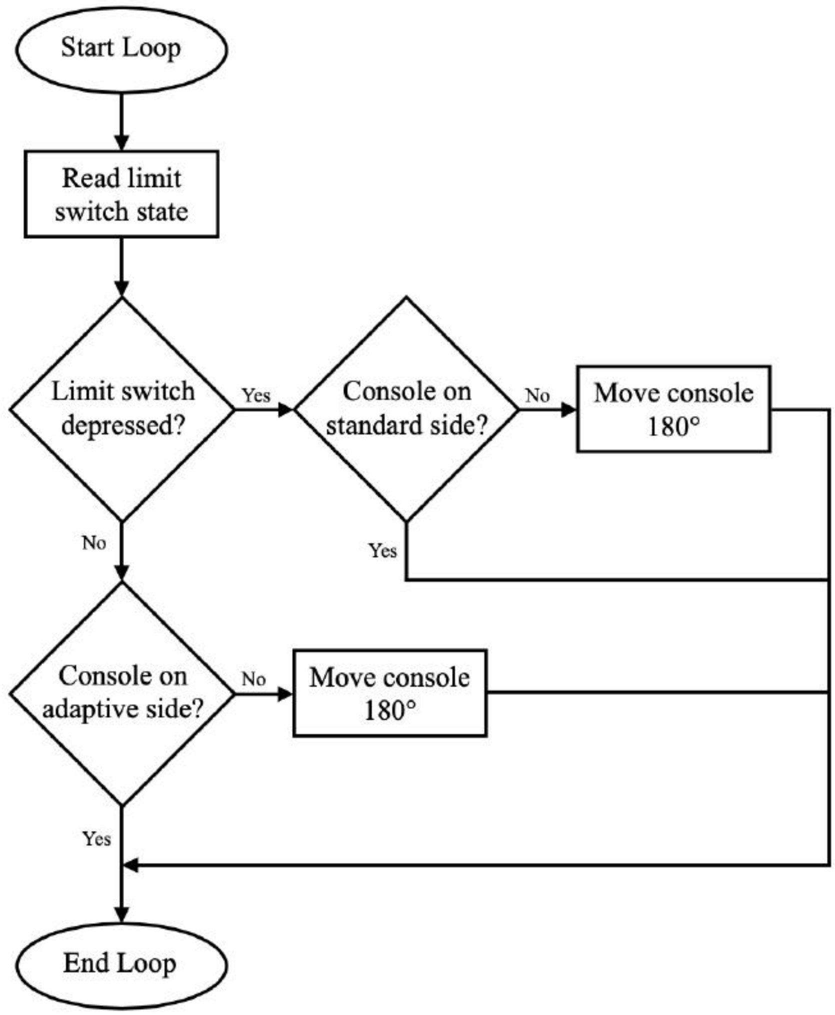


Figure 9. Coding Flowchart. The position of the console is determined by feedback from the limit switch. The console will face the standard side of the machine by default and automatically rotate to the adaptive side when a wheelchair user is secured by the stabilization frame.

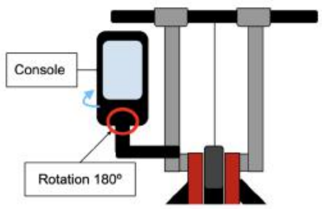
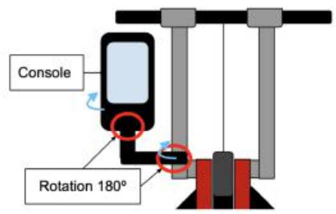
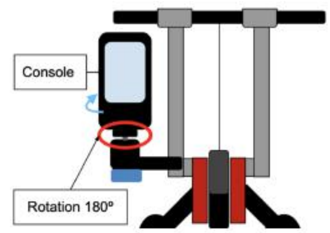
d. Console Rotation Design Criteria

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
Total for each design:	**83**		**76**		**85**	

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.

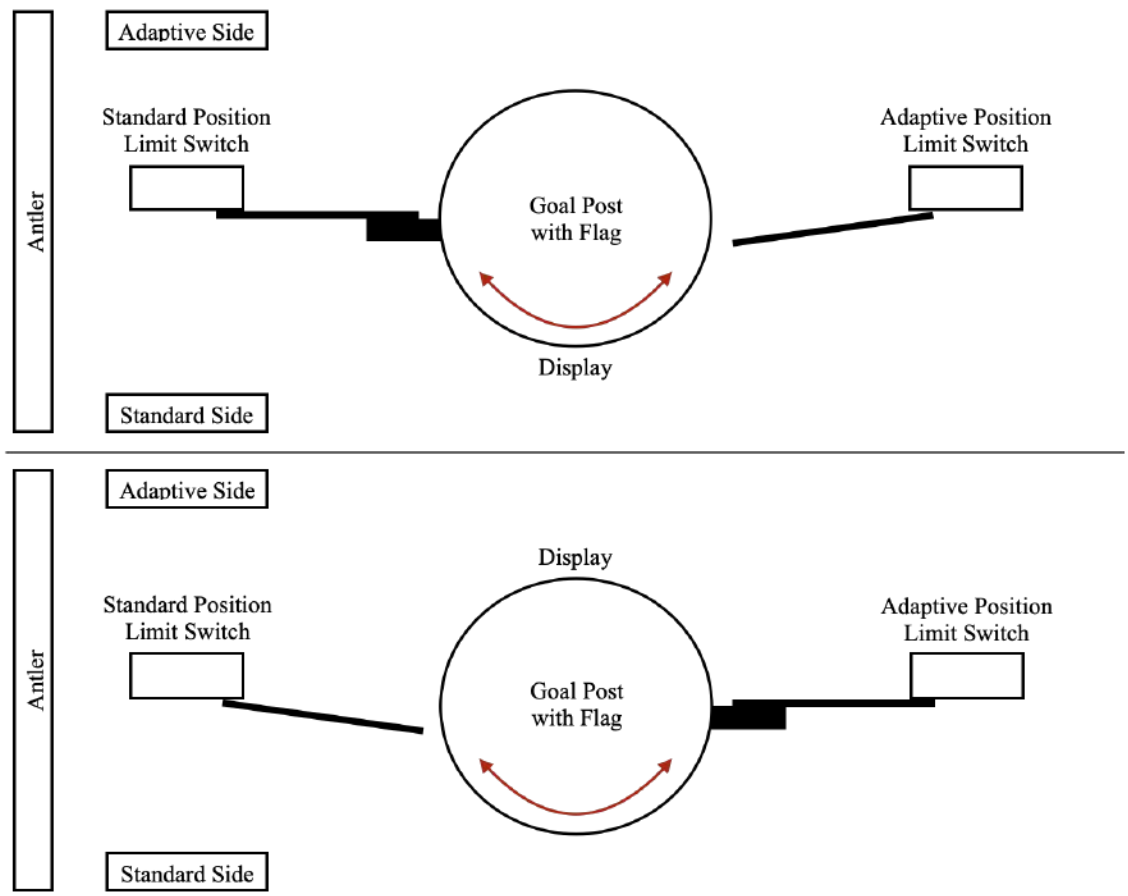


Figure 1. Standard and Adaptive Position Limit Switch Placement. Two limit switches are placed at 180 degrees from each other such that they create stop blocks for rotation between the standard and adaptive sides of the machine. In the top image, the flag on the goal post depresses the standard position 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.

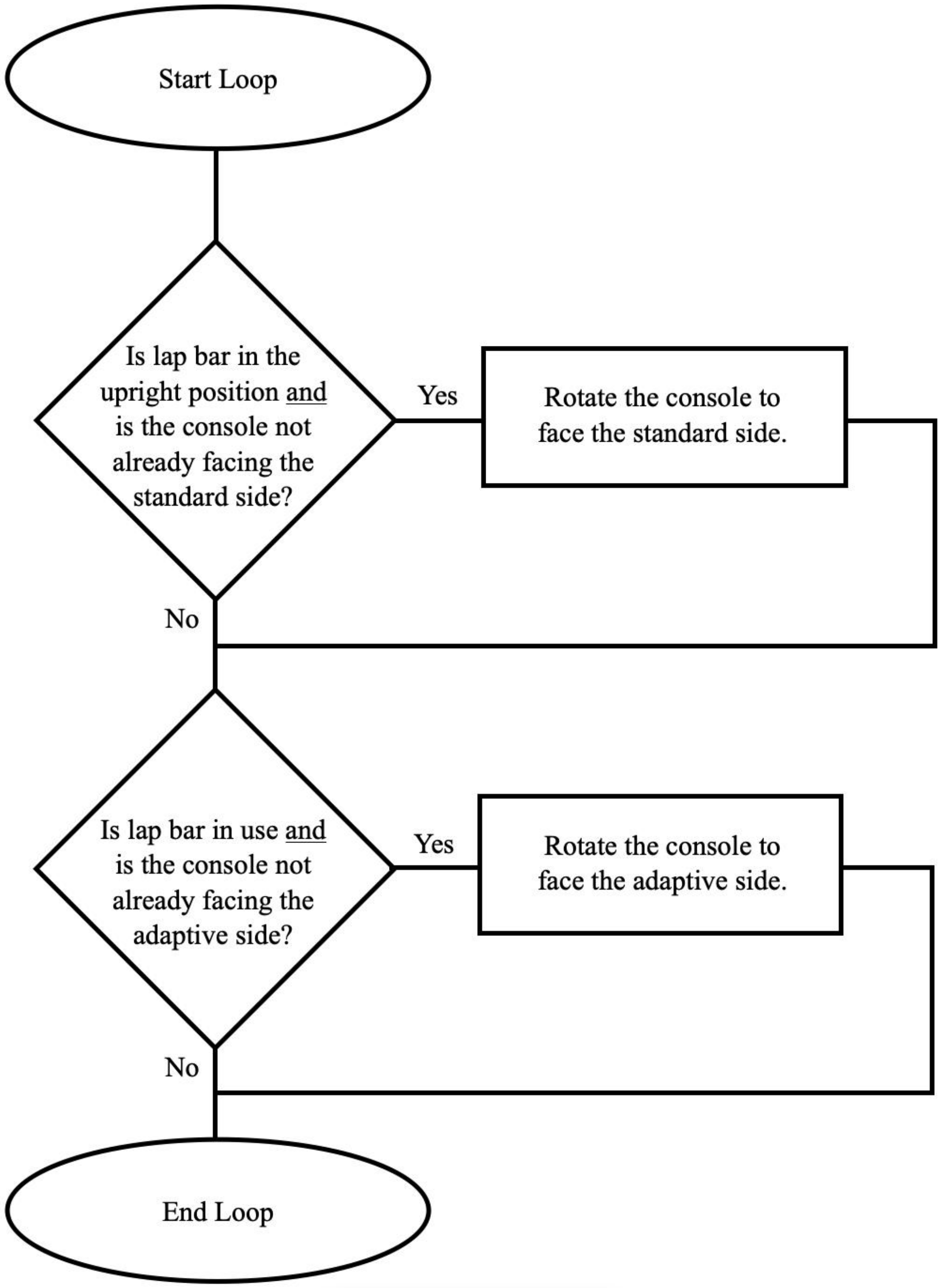


Figure 2. Final Coding Flowchart. Each loop iteration, the code checks the position of the console and compares it to its expected location according to the state of the transition limit switch placed near the pivot point of the lap bar. If the lap bar is upright and the console is not already facing 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 μFarad 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 μFarad 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].

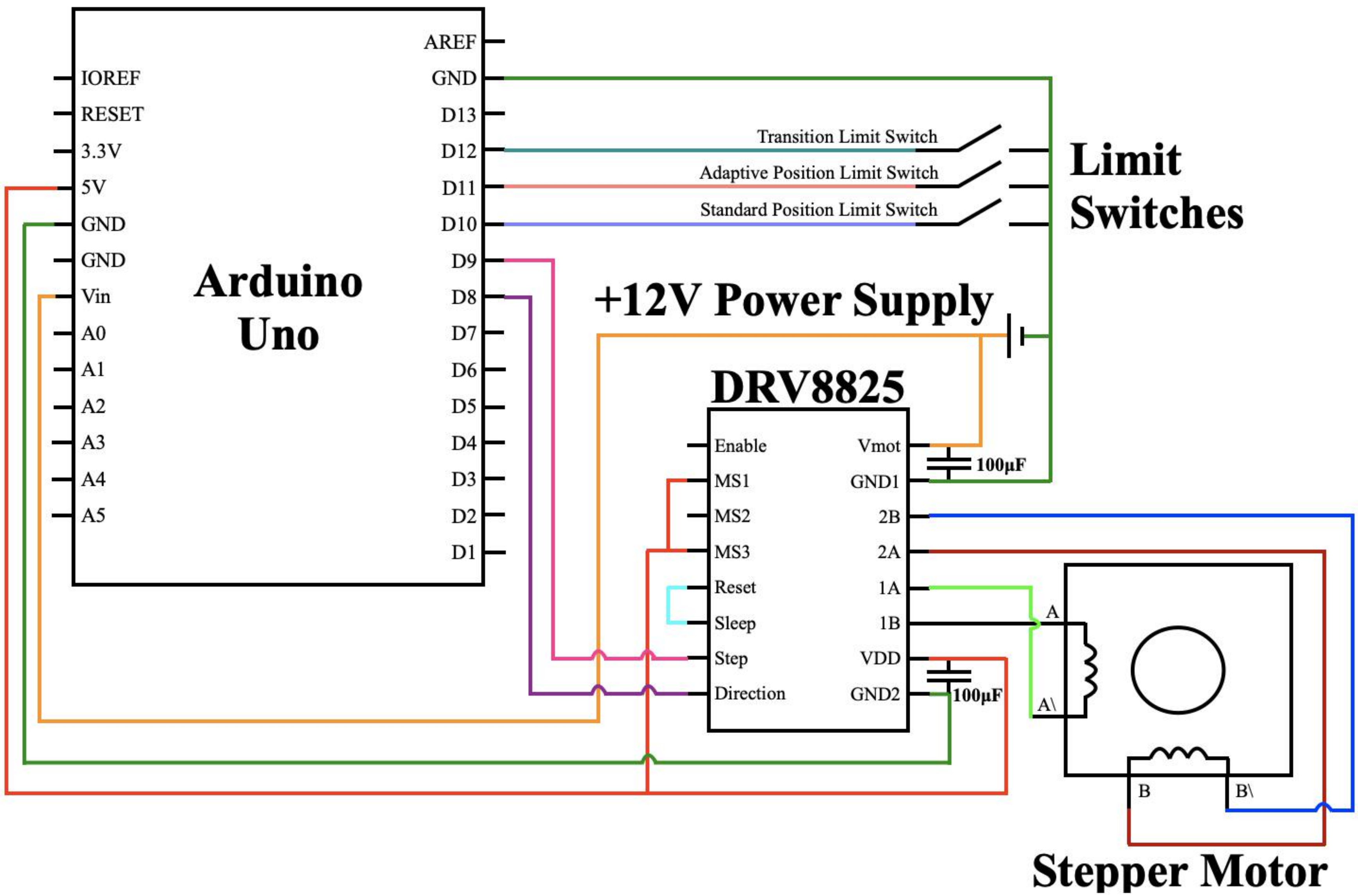


Figure 3. Final Circuit Schematic. The final circuit consists of an Arduino Uno, DRV8825, NEMA17 stepper motor, +12V power supply, two 100 µF capacitors, and three NO limit switches. The colored lines represent the wire connections present between each physical component.

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.

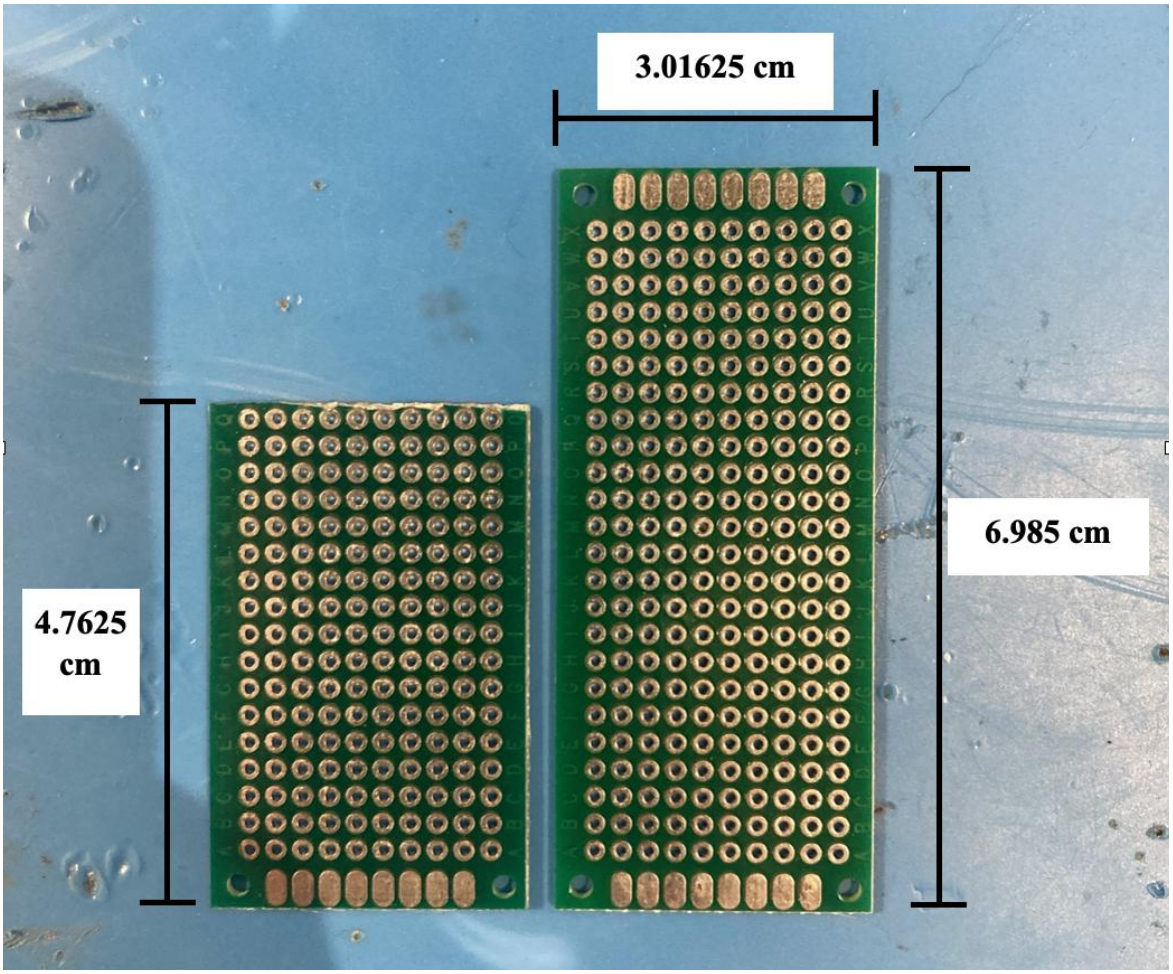


Figure 4. Solder Board. The solder board was sourced from the BME 400 storage closet. To fit within the electronics box, its length was cut down to 4.7625 cm from 6.985 cm.

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.

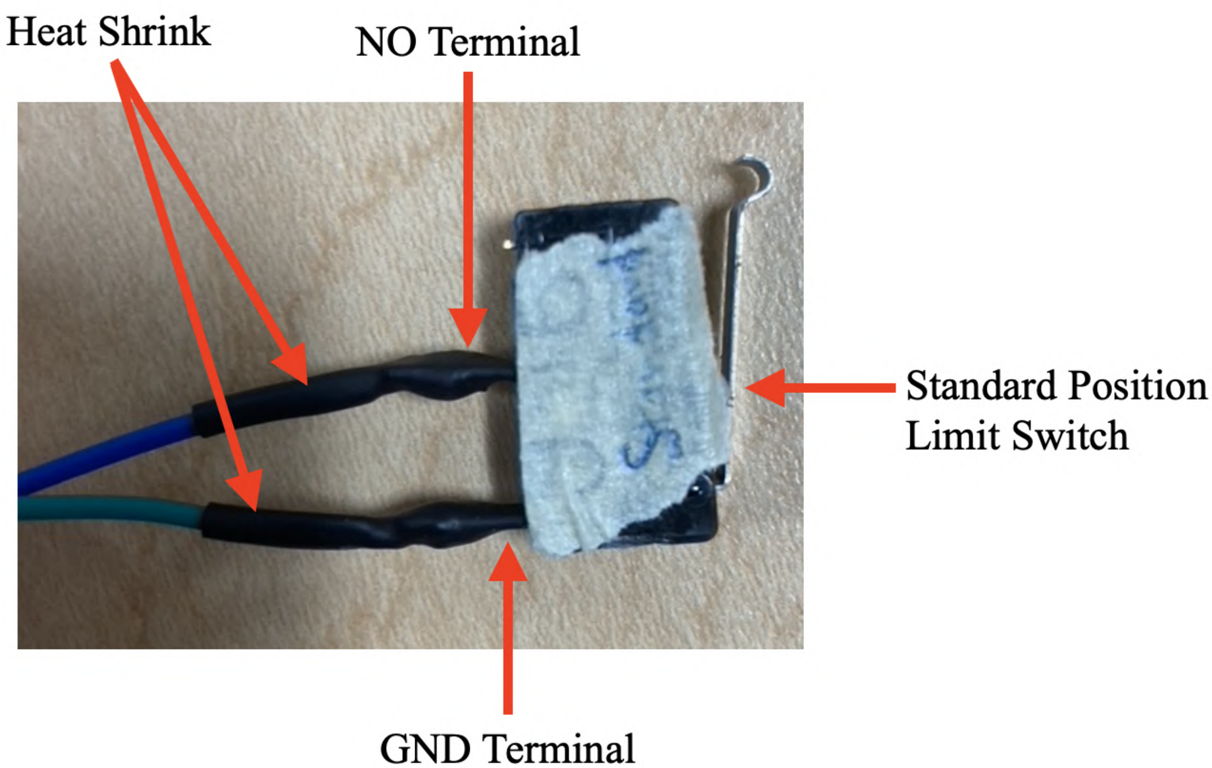


Figure 5. Standard Position Limit Switch Connections. Two wires of approximately 20.32 cm in length are soldered to the standard position limit switch. The green wire (GND) is connected to the terminal labeled with "C" while the blue wire (D10) is connected to the terminal labeled with "NO". These connections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

The solder board was populated with the DRV8225 and two 100 µFarad 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.

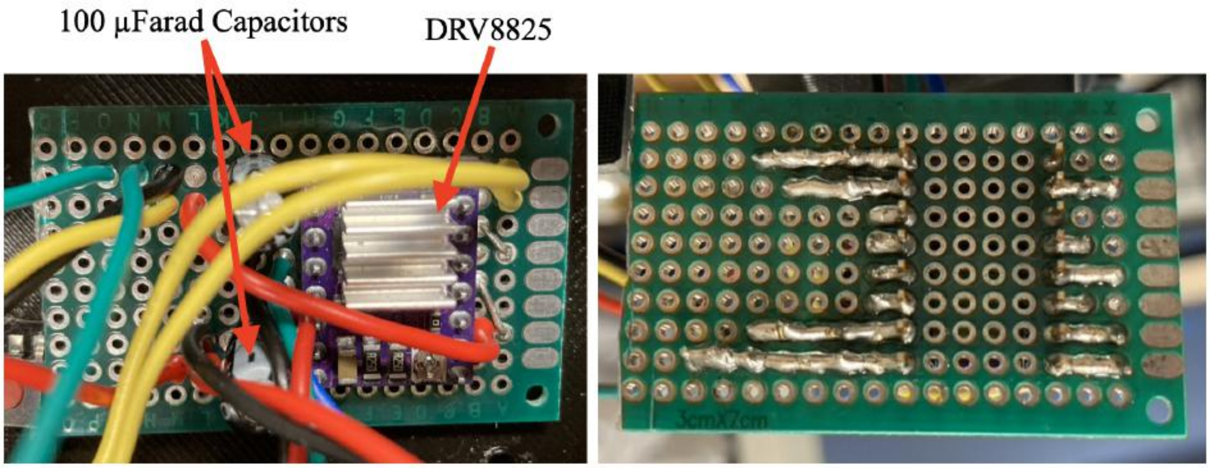


Figure 6. Solder board. The image on the left shows the top face of the solder board populated with the DRV8825, two 100 µFarad capacitors, and wire connections. The image on the right shows the bottom face of the solder board with the ties for each row of connections.

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**).

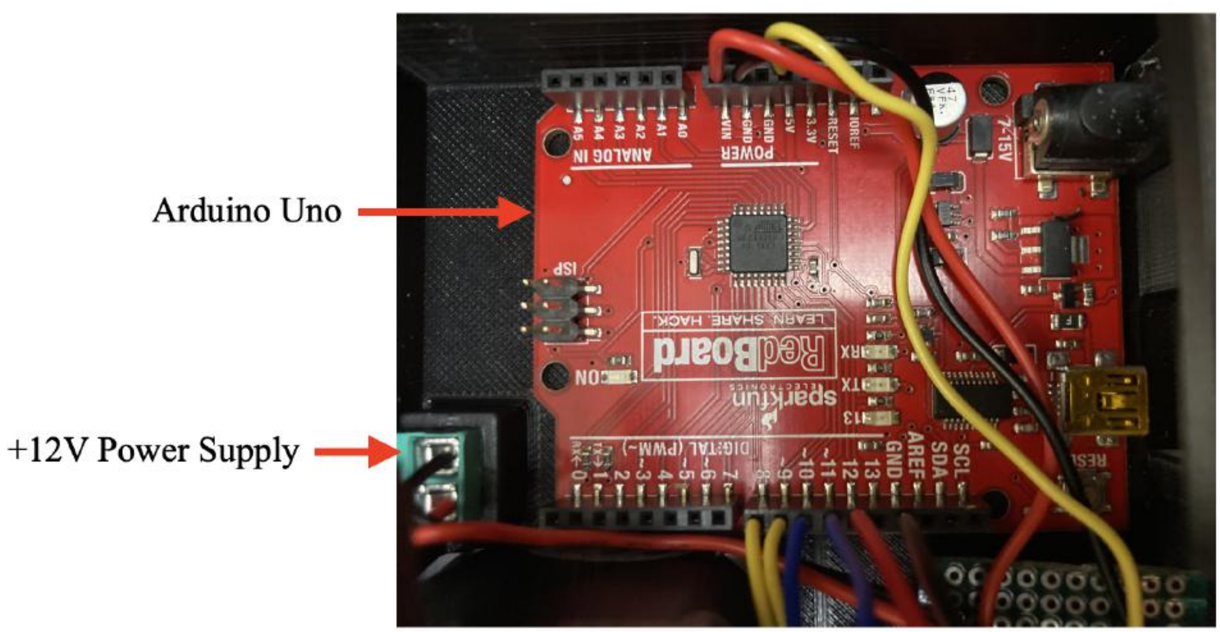


Figure 7. Arduino Uno and +12V Power Supply Connections. This image shows the wires connecting to the Arduino Uno and +12V power supply.

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.

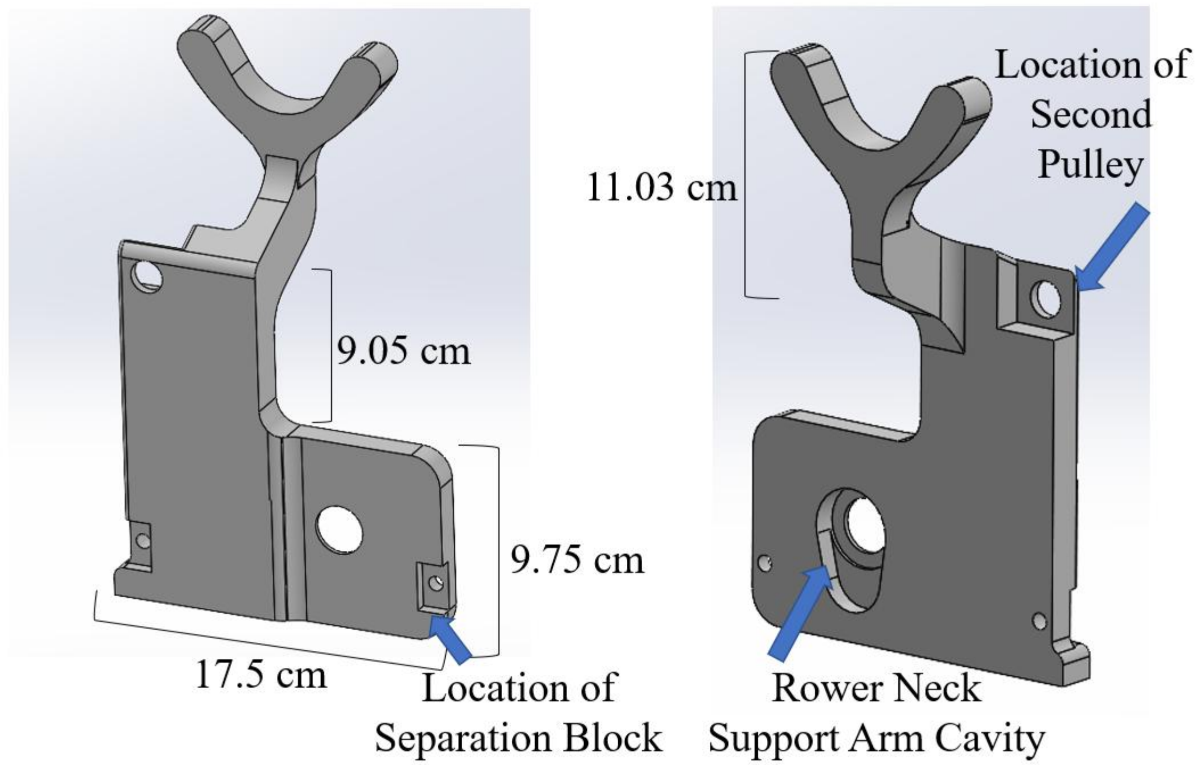


Figure 8. Pulley Support Plates with Antlers. The left and right pulley support plates are mirror images and fit tightly around the pulley bearing with a cavity that fits around the metal support arms for the rower neck. The antler extending upward on each plate holds the handlebar in a neutral location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

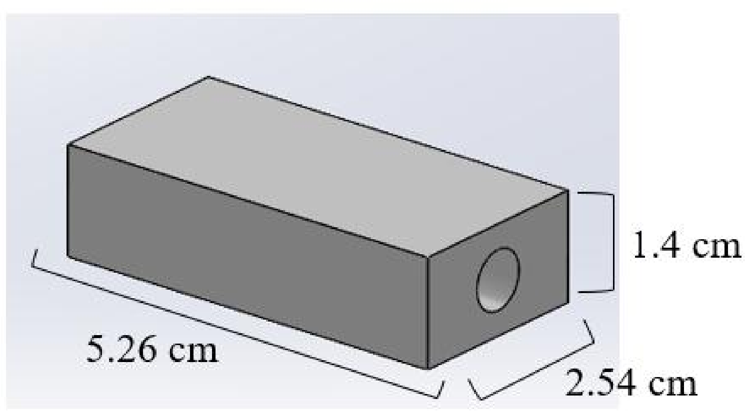


Figure 9. Pulley Support Plates Back Separation Block. The back separation block is inserted between the two pulley plates on the standard side of the rower to offer an outward reaction force that prevents the plates from slipping off the rower neck support arms inward.

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.

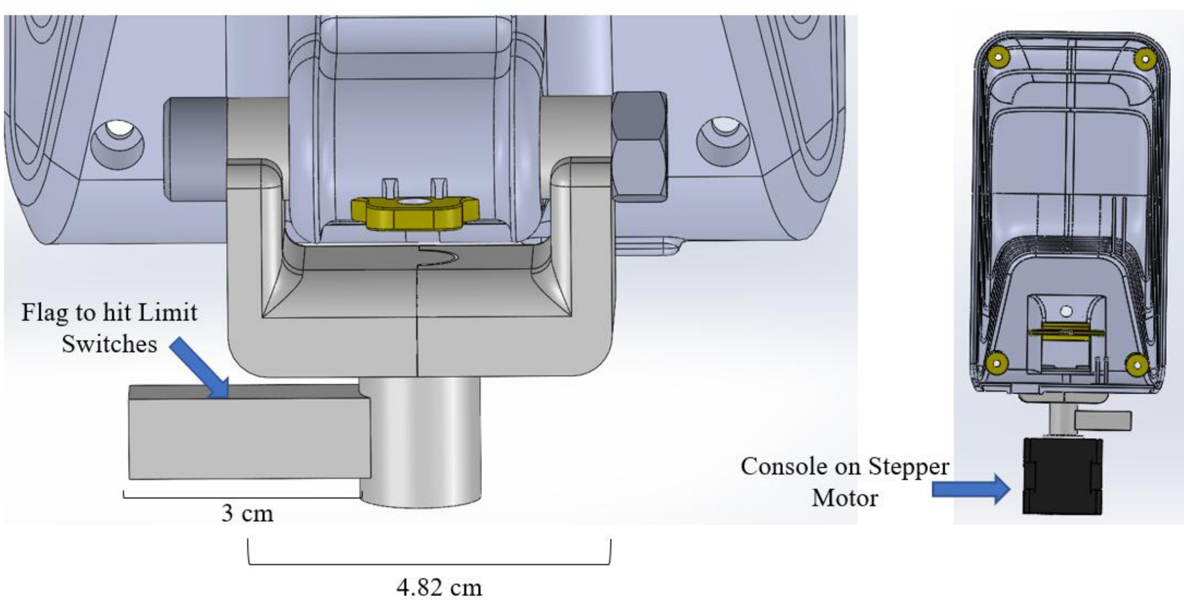


Figure 10. Field Goal Posts Allow Console Angle Adjustment. The field goal posts have cylindrical components that insert into the back of the display console to permit rotation about its original axis (left). This allows the user to adjust the angle at which the console is bent. The full console-field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

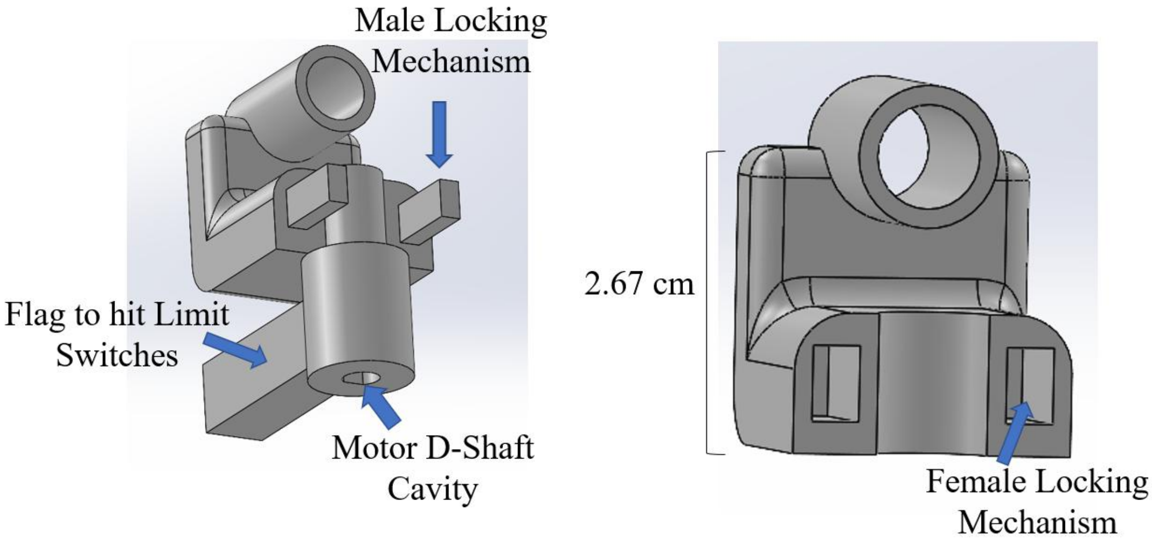
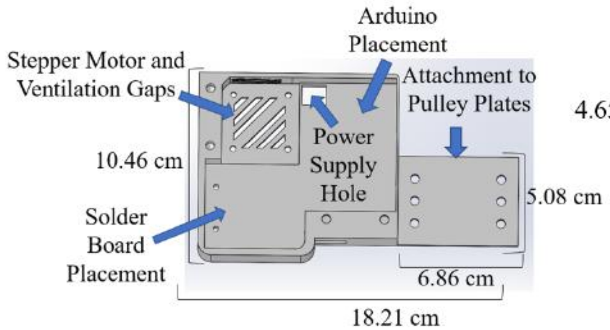


Figure 11. Female and Male Field Goal Posts. The male (left) and female (right) field goal posts fit together via extending inserts on the male piece that fit into corresponding cavities on the female piece. The male piece has a large central peg which press-fits onto the stepper motor's D-shaft and 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 ¼-20 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 ¼-20 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.



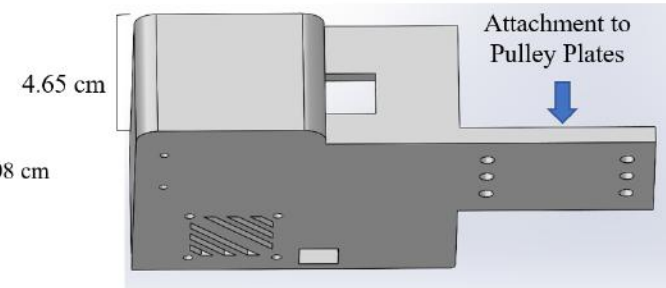


Figure 12. Electronics Box. The top view (left) and bottom view (right) of the electronics box shows sections for each electrical component, including the stepper motor, Arduino, and solder board.

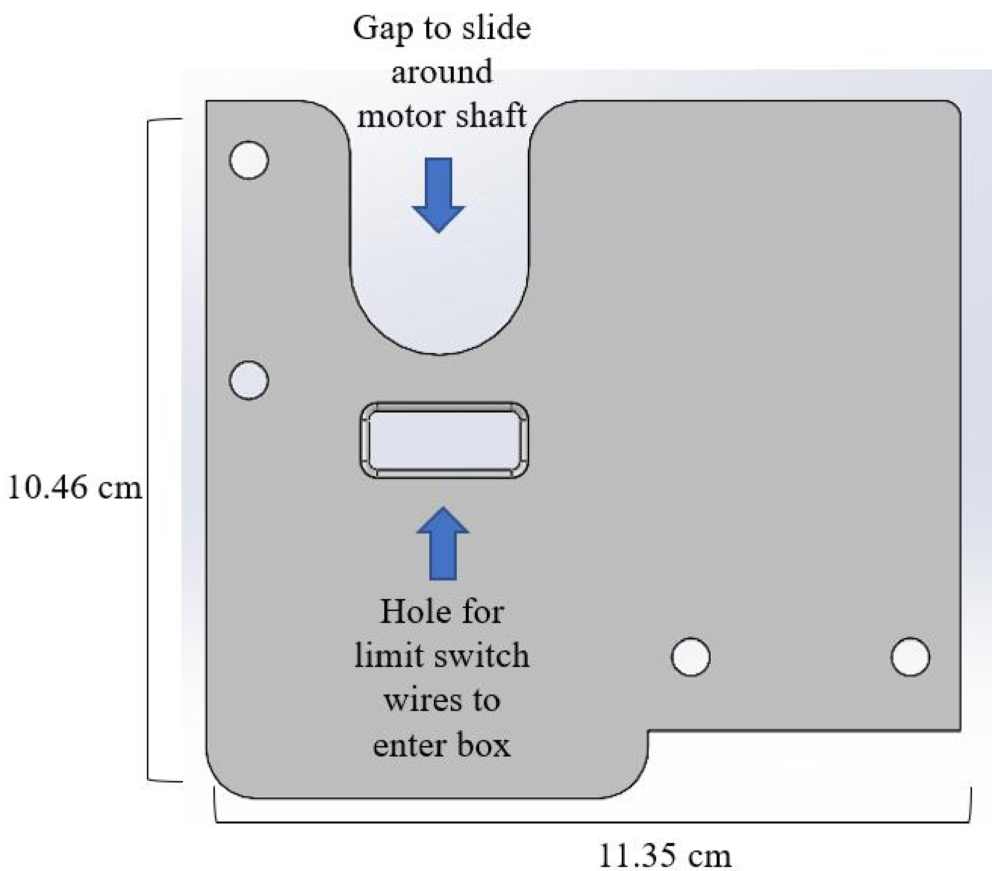


Figure 13. Electronics Box Lid. The electronics box lid fits over the electronics box to cover all electrical components. It includes a gap to allow the lid to be slid around the stepper motor shaft, and a hole to guide all limit switch wires into the box.

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 ¼-20 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**.

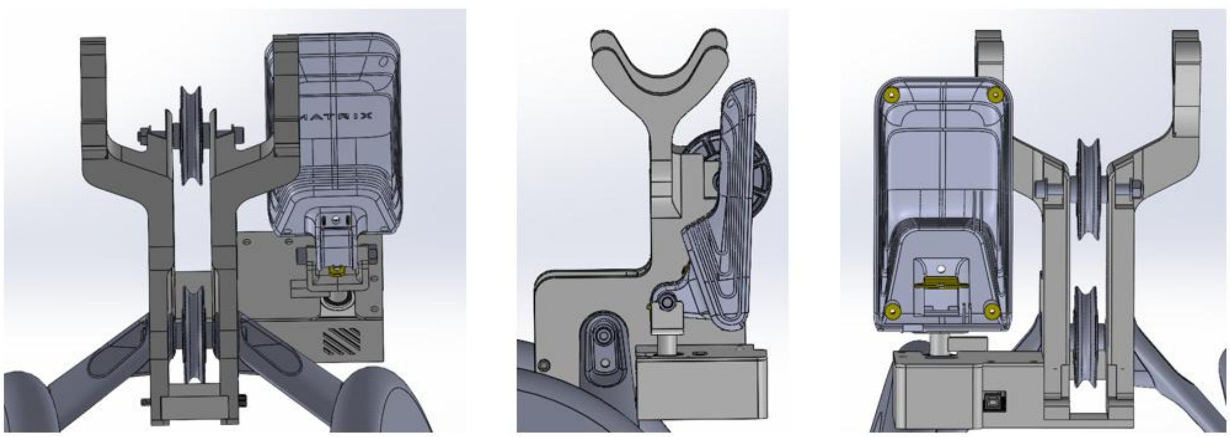


Figure 14. SolidWorks Assembly Back, Side, & Front View. The back (left), side (middle), and front (right) views of the rower assembly are shown. The adaptations made to the original rower include adding a second pulley stabilized by mirroring support plates, antlers to hold the handlebar in a central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

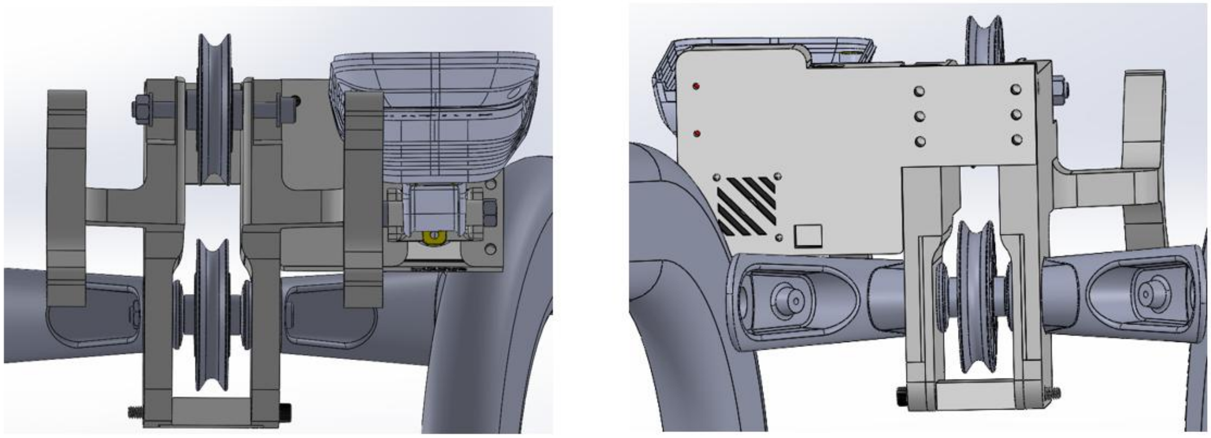


Figure 15. SolidWorks Assembly Top & Bottom View. The top (left) and bottom (right) views of the rower assembly are shown. The adaptations made to the original rower include adding another pulley stabilized by mirroring support plates, antlers to hold the handlebar in a central location, and an electronics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

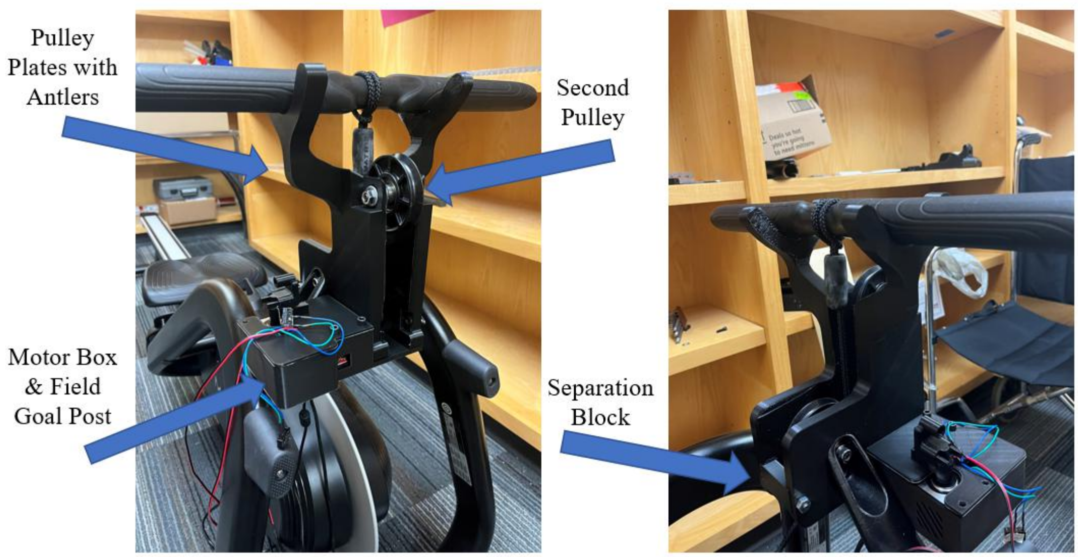


Figure 16. 3D Printed Components on Physical Assembly. The pulley plates with antlers, console rotation field goal posts, and electronics box of the full rower assembly are shown in a front (left) and back (right) view.

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.

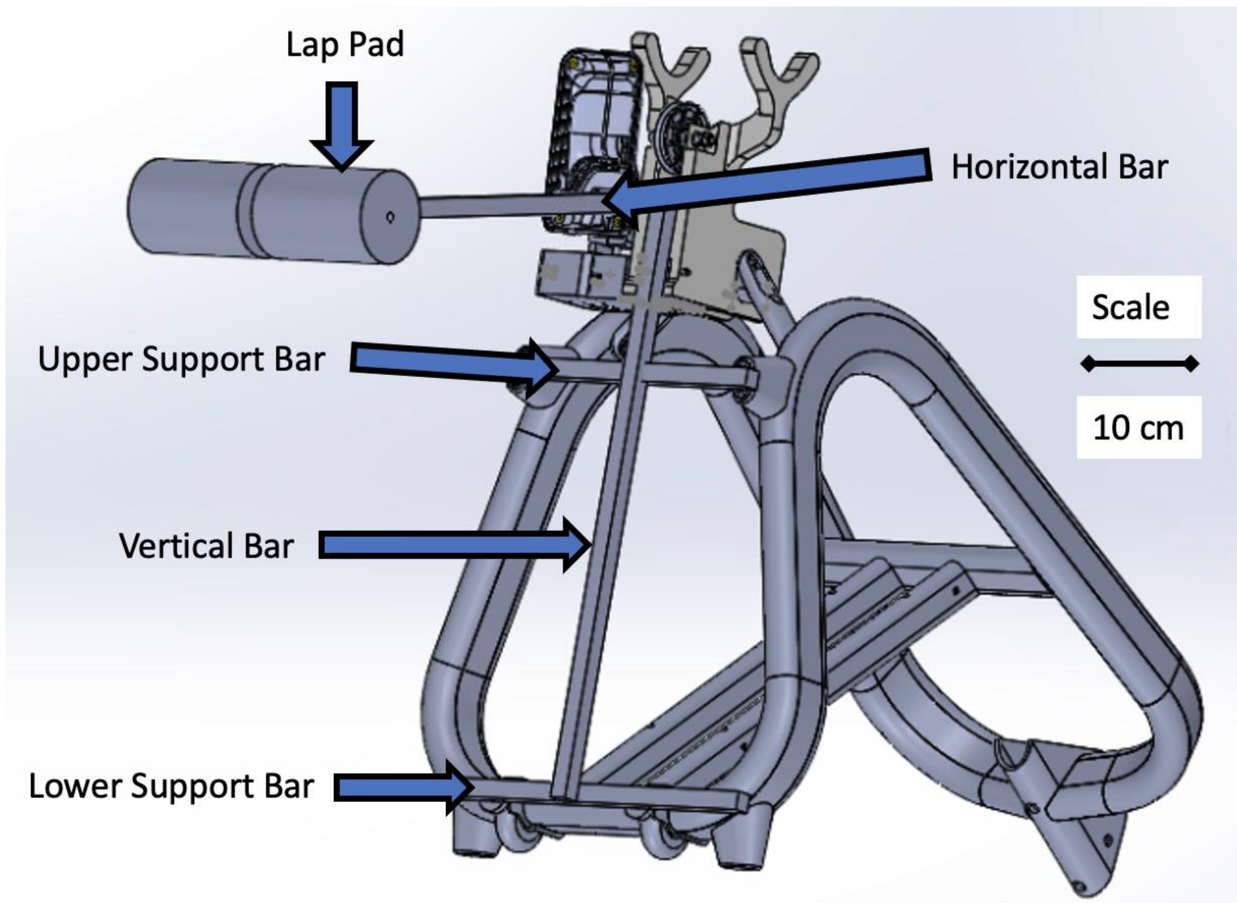


Figure 17. SolidWorks Model of Stabilization Frame. Before sourcing the steel bars from Johnson Health Tech, the stabilization frame was modeled in SolidWorks to determine each bar's dimensions.

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.

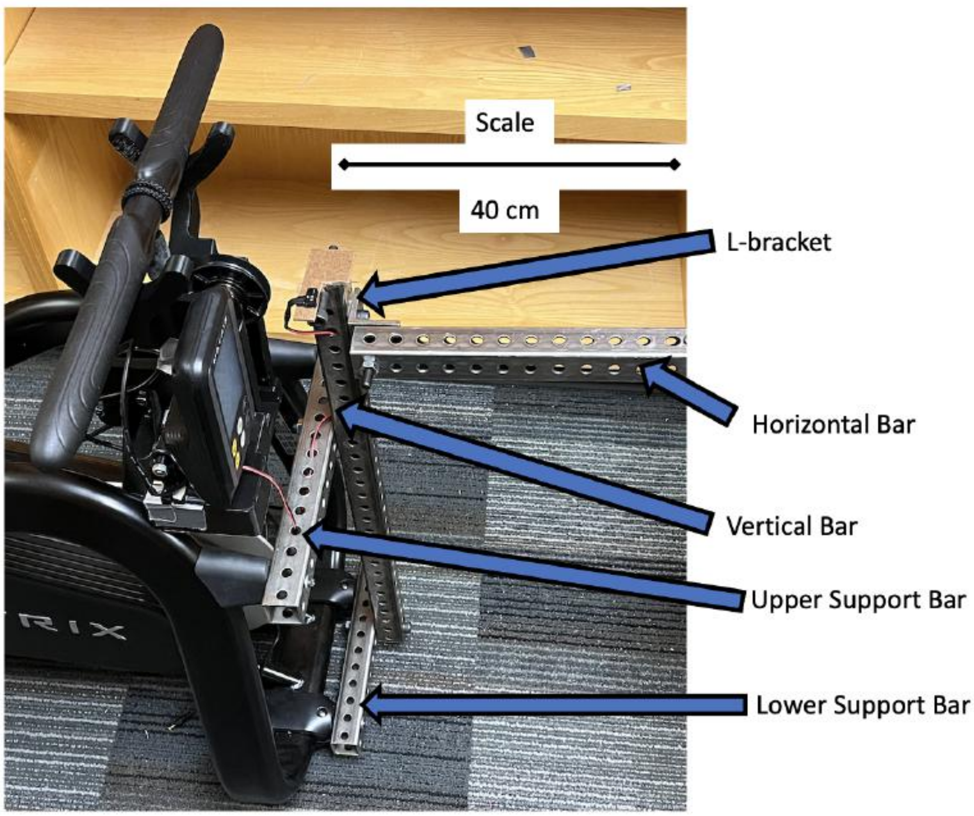


Figure 18. Stabilization Frame Components. The stabilization frame is attached to the backside of the rowing machine. It is made up of two support bars, a vertical bar, and a horizontal bar. The horizontal bar pivots at the top of the vertical bar via an L-bracket and bolt.

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).

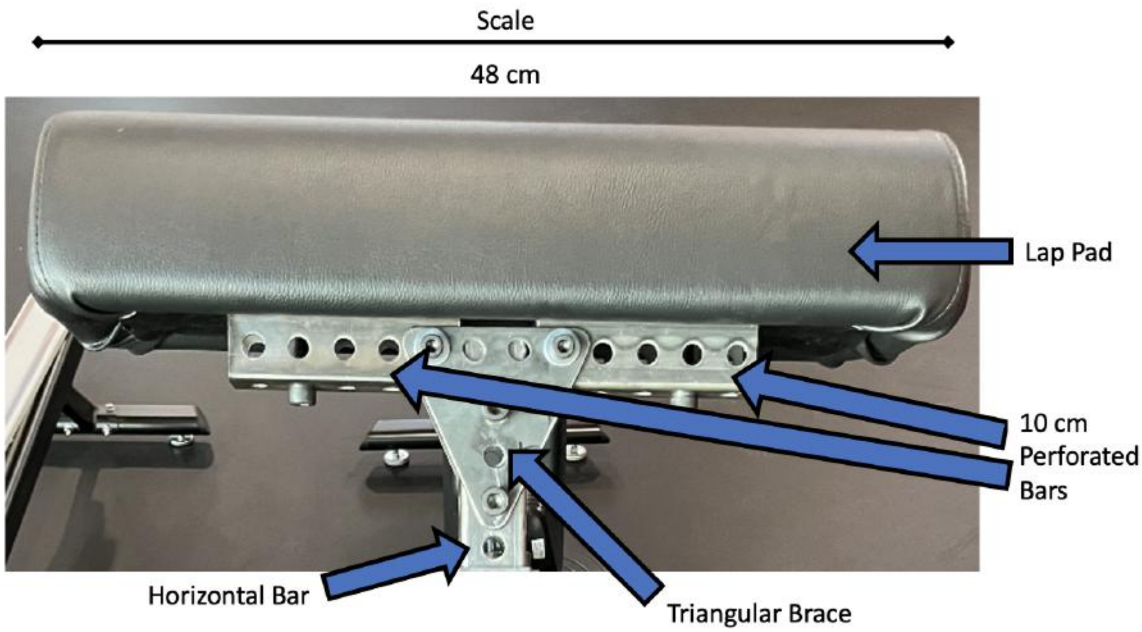


Figure 19. Pad Attachment to Horizontal Bar. The pad was attached to the horizontal bar using two smaller perforated bars, two triangular braces, and M-10 nuts and bolts.

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.

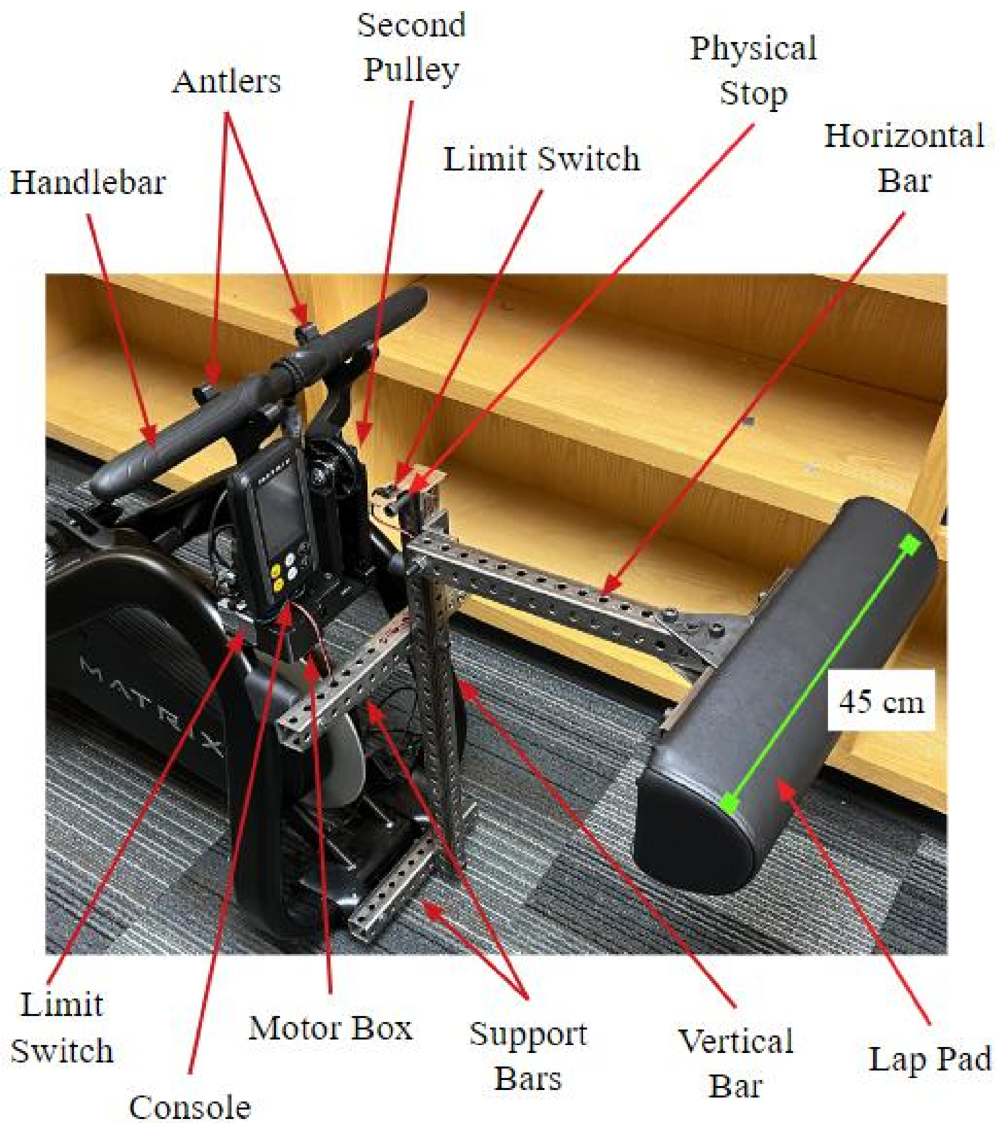


Figure 20. Full Assembly. The full assembly includes the pulley support plates with antlers, the console rotation mechanism and electronics box, and the metal adjustable stabilization frame.

References for Appendix G:

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[21] "How to Control Stepper Motor with DRV8825 Driver & Arduino." https://how2electronics.com/control-stepper-motor-with-drv8825-driver-arduino/ (accessed Dec. 11, 2022).
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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	• 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. • Apply power.	The console rotates to the adaptive side.
2	• 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. • Apply power.	The console rotates to the standard side.
3	• 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. • Apply power.	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	• 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	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.

	switch is pressed. ● Apply power.	
5	● 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. ● Apply power.	The console rotates to the standard side.
6	● 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. ● Apply power.	The console rotates to the adaptive side.
7	● Apply power. ● 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.	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	● Apply power. ● 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	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.

		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.	

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 [1]. 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 [2].

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.

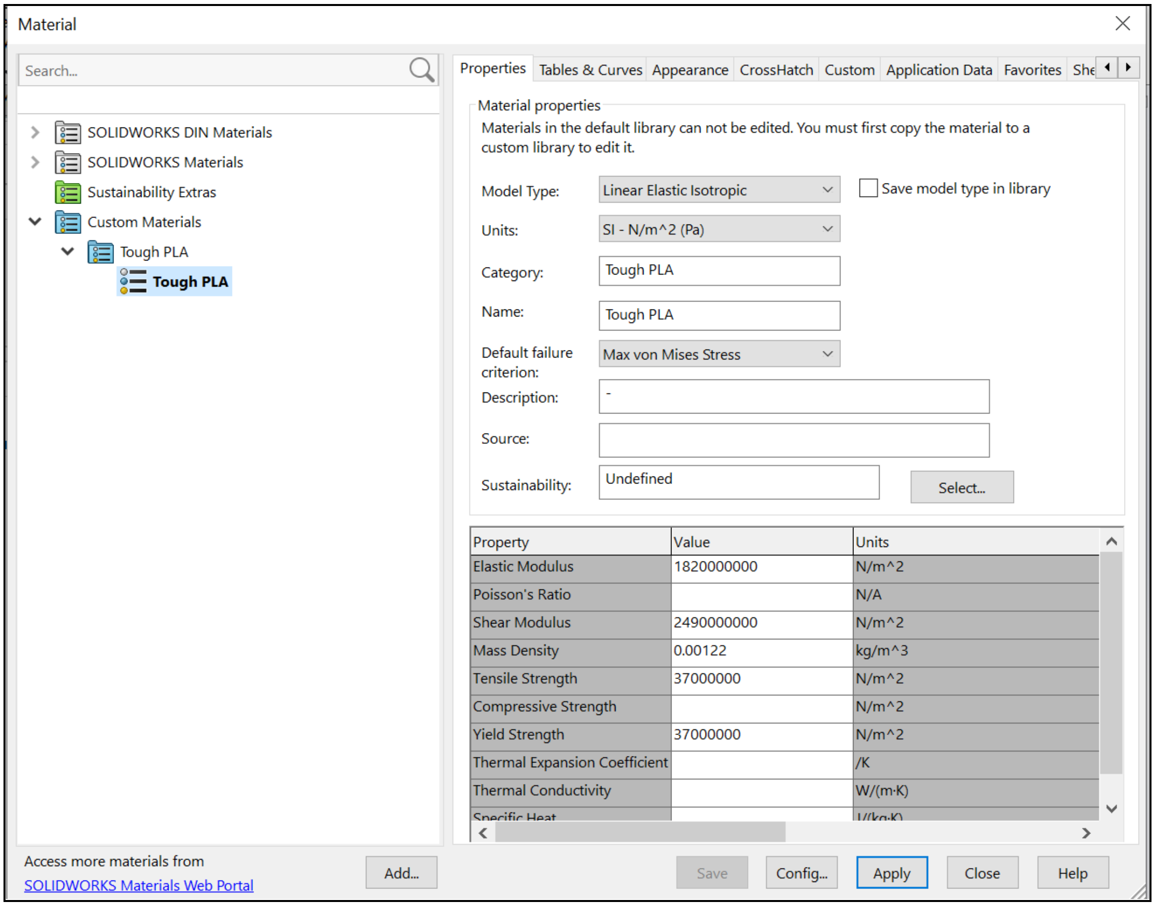

Figure 1. Tough PLA Material Specifications. All 3D printed components were modeled as Tough PLA, to accurately predict the stresses and displacements that will develop in the plates under a maximum load [24].

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.

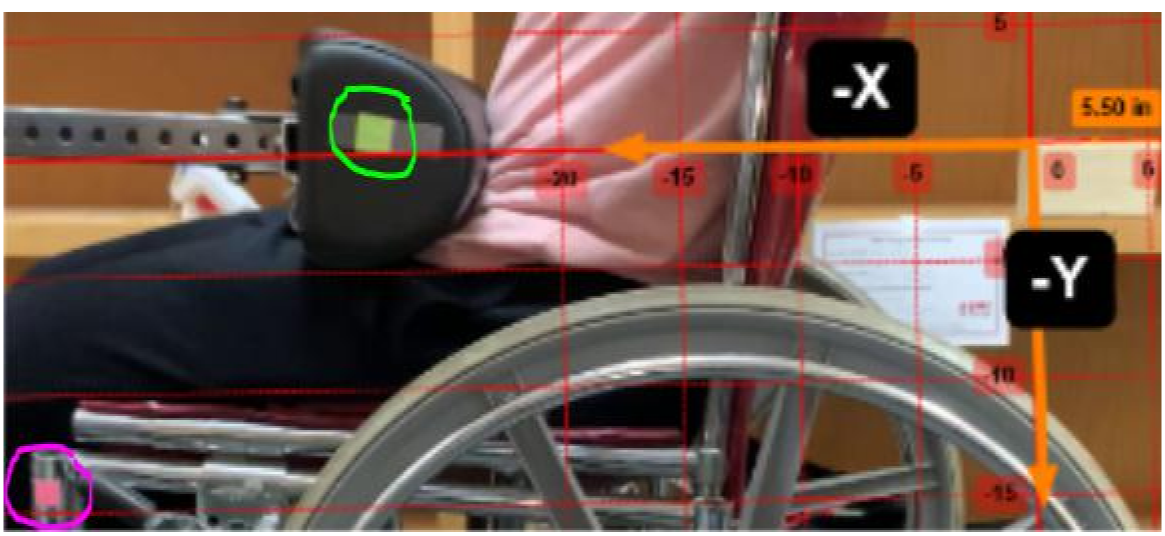

Figure 2. Motion Testing Experimental Setup. Markers (green and pink) placed on lap pad and wheelchair, respectively. Kinovea defaults the coordinate system to originate from the calibration line.

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	• 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. • Apply power.	The console rotates to the adaptive side.	The console rotates to the adaptive side.	3	Pass
2	• 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. • Apply power.	The console rotates to the standard side.	The console rotates to the standard side.	3	Pass
3	• Before power application: Position	The console remains	The console remains	3	Pass

	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. ● Apply power.	stationary until the lap bar is raised such that the transition limit switch is suppressed. Then the console rotates to the standard side.	stationary until the lap bar is raised such that the transition limit switch is suppressed. Then the console rotates to the standard side.		
4	● 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. ● Apply power.	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.	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.	3	Pass

5	• 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. • Apply power.	The console rotates to the standard side.	The console rotates to the standard side.	3	Pass
6	• 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. • Apply power.	The console rotates to the adaptive side.	The console rotates to the adaptive side.	3	Pass

7	• Apply power. • 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.	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	• Apply power. • 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	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.	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.	3	Pass*

	rotating, either raise or lower the lap bar and keep it there.				

*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 [1]. 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.

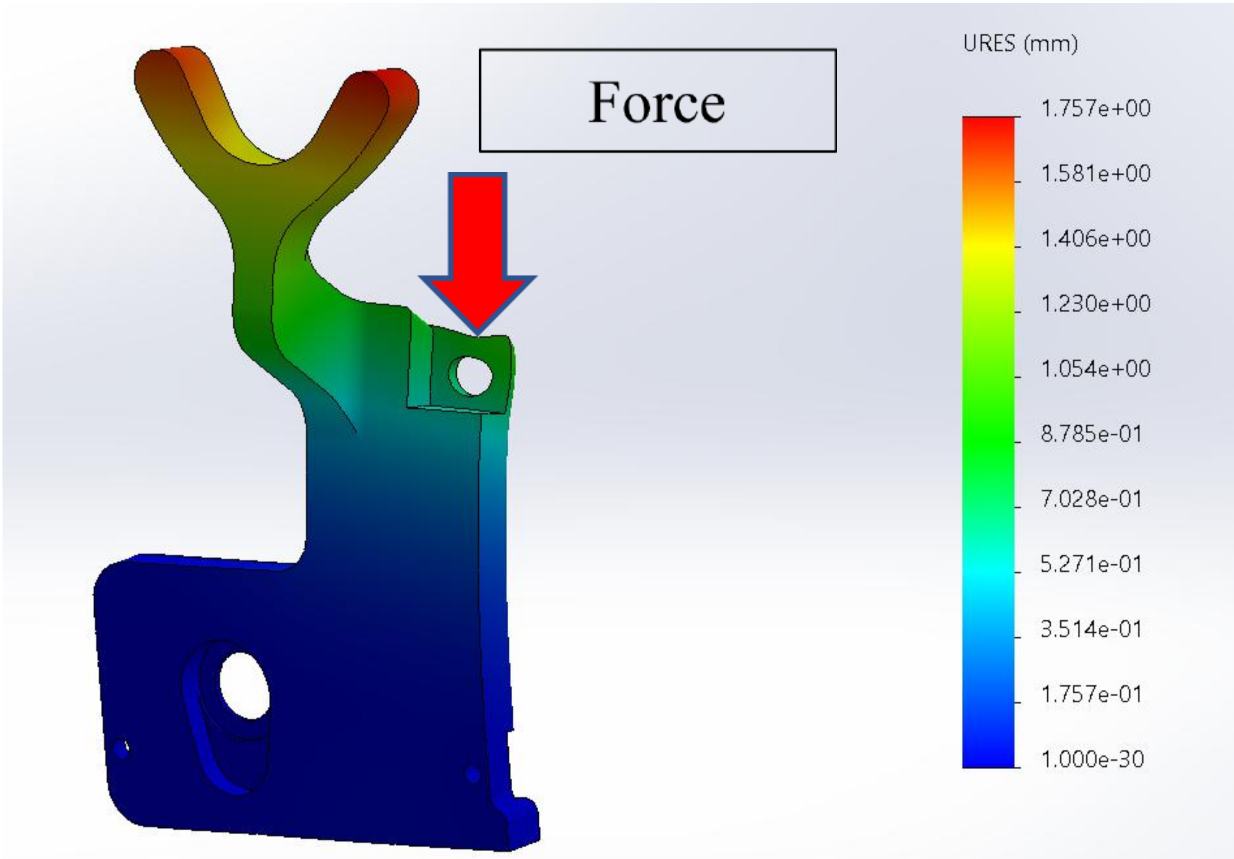

Figure 3. Pulley Plate Deformation. The pulley plate deformed the most at the tips of the antler handlebar cavity due to having the least amount of structural integrity.

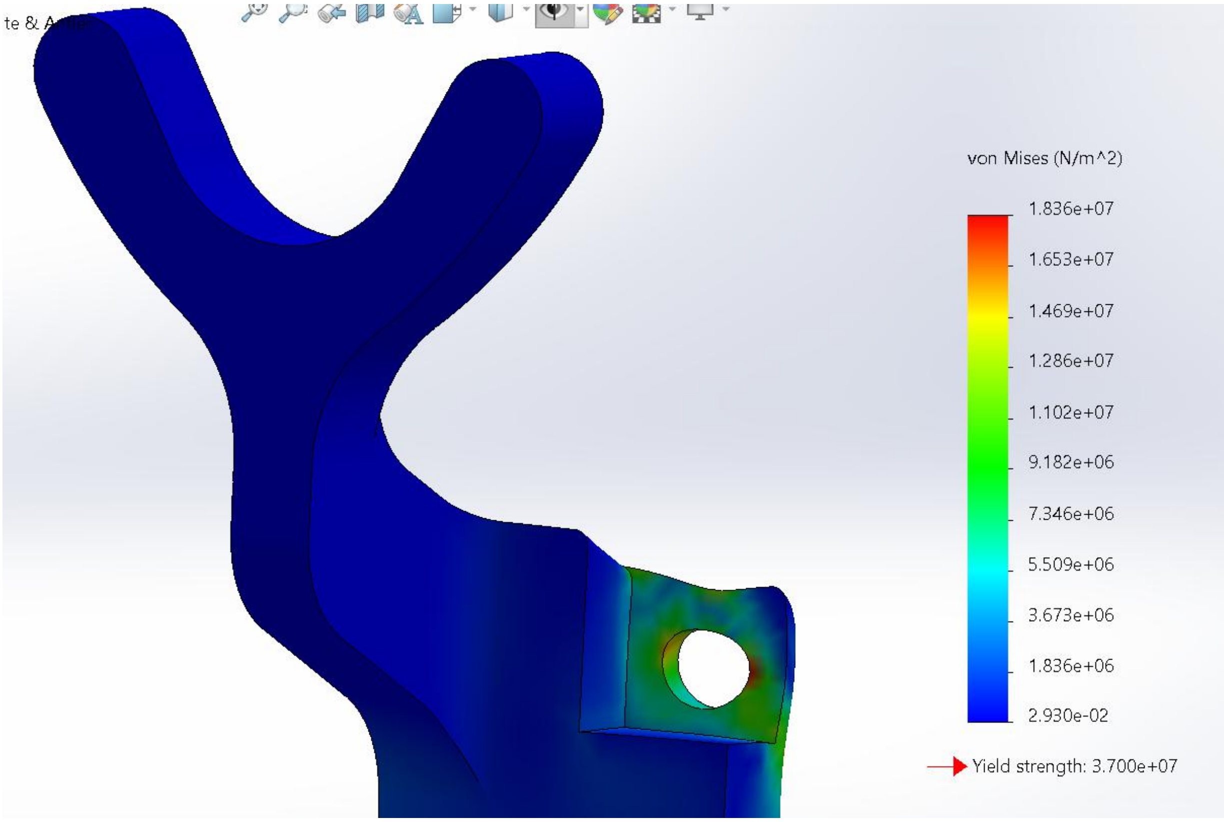

Figure 4. Pulley Plate Stress. The pulley plate developed the largest stress concentration at the outer edge of the center of the cavity in which the load was applied due to the cavity wanting to collapse.

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 [1]. 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 place. 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 [1]. 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.

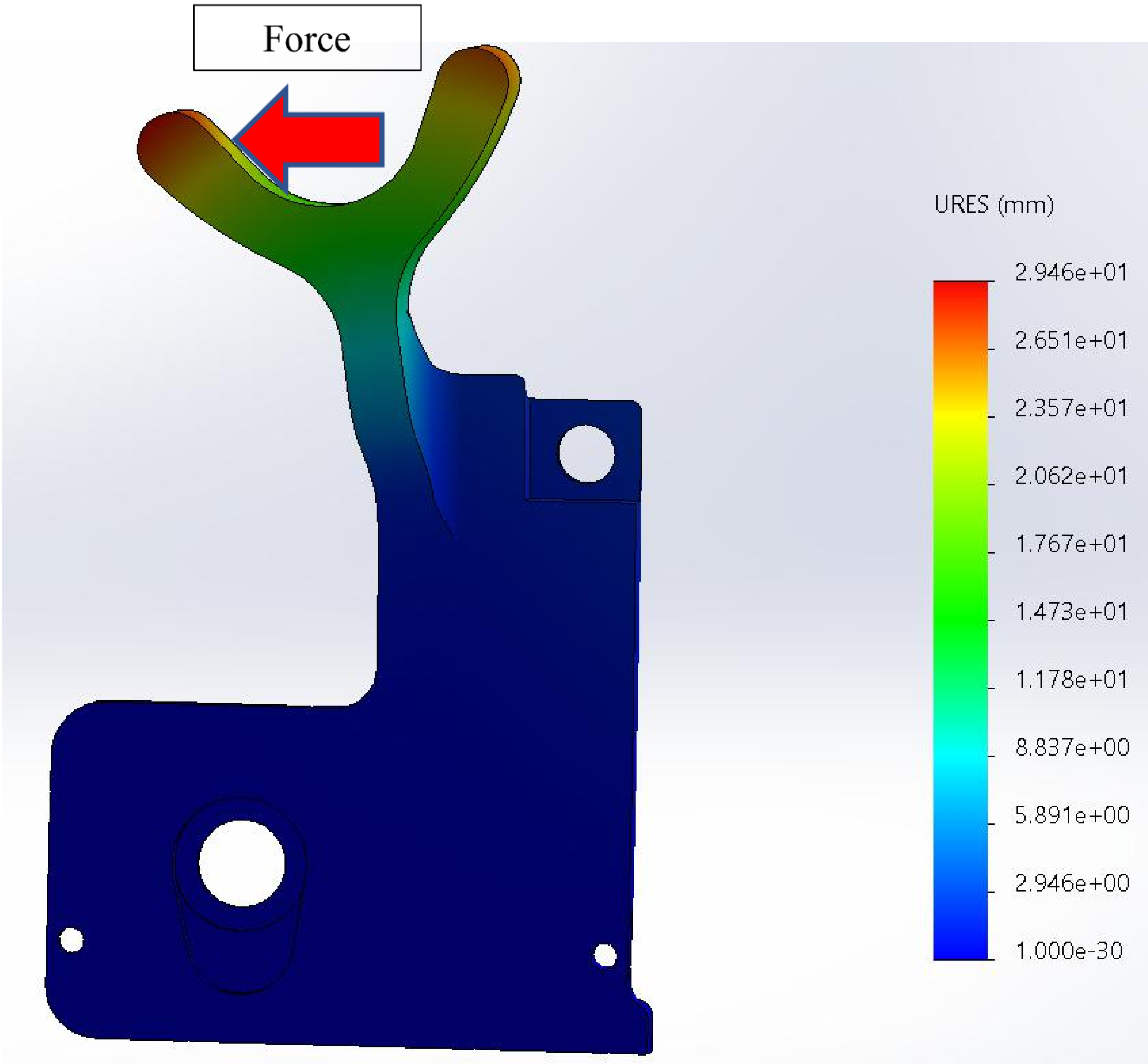

Figure 5. Antler Standard Side Deformation. The antler deflects almost 30 mm towards the standard side of the rower when subject to a very high and extreme load.

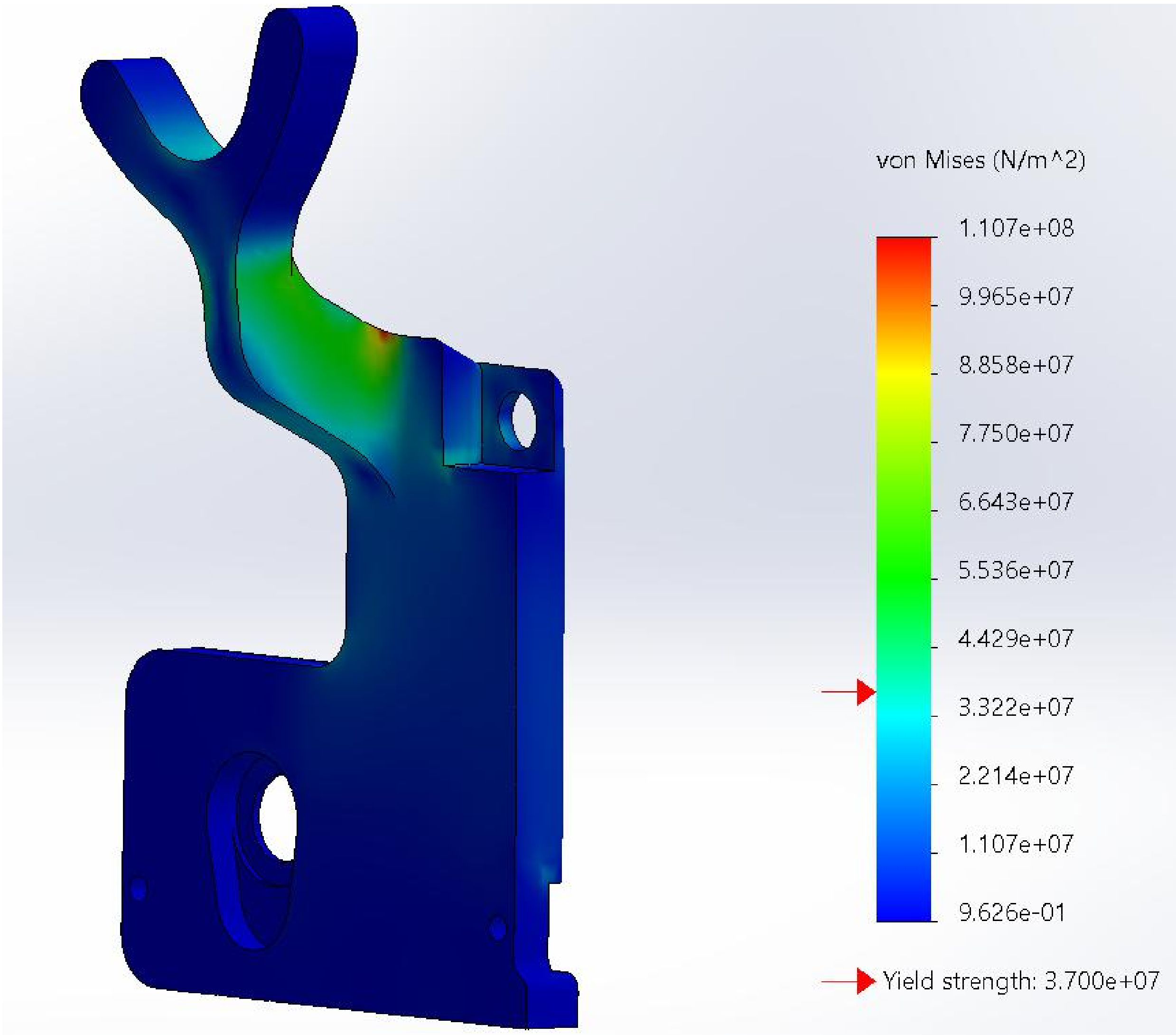

Figure 6. Antler Standard Side Max Stress. The antler develops significant stress in the arm of the antler support under extremely high and excessive loading, causing the structure to fail under this given loading scenario.

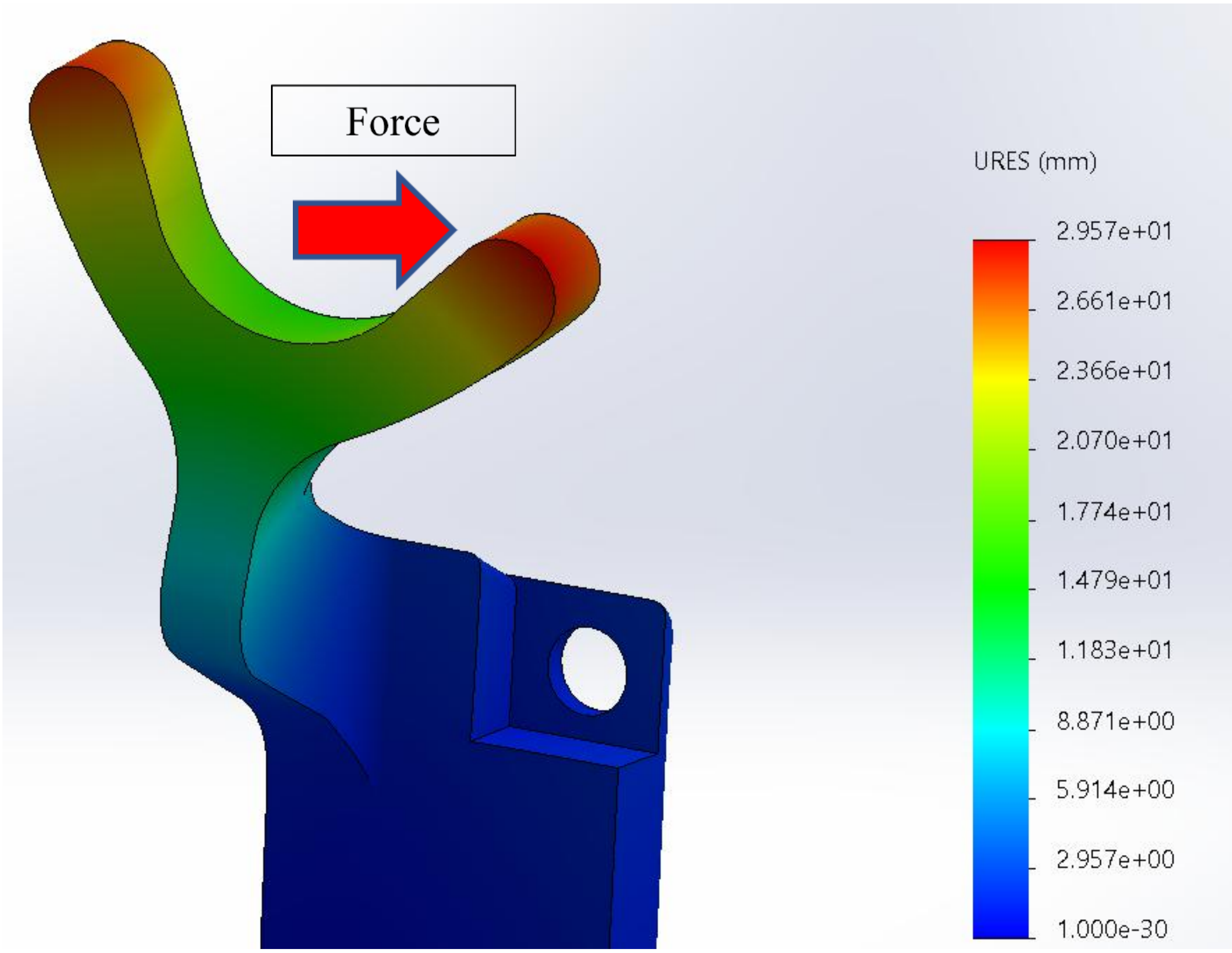

Figure 7. Antler Adaptive Side Deformation. The antler deflects almost 30 mm towards the adaptive side of the rower when subject to a very high and extreme load.

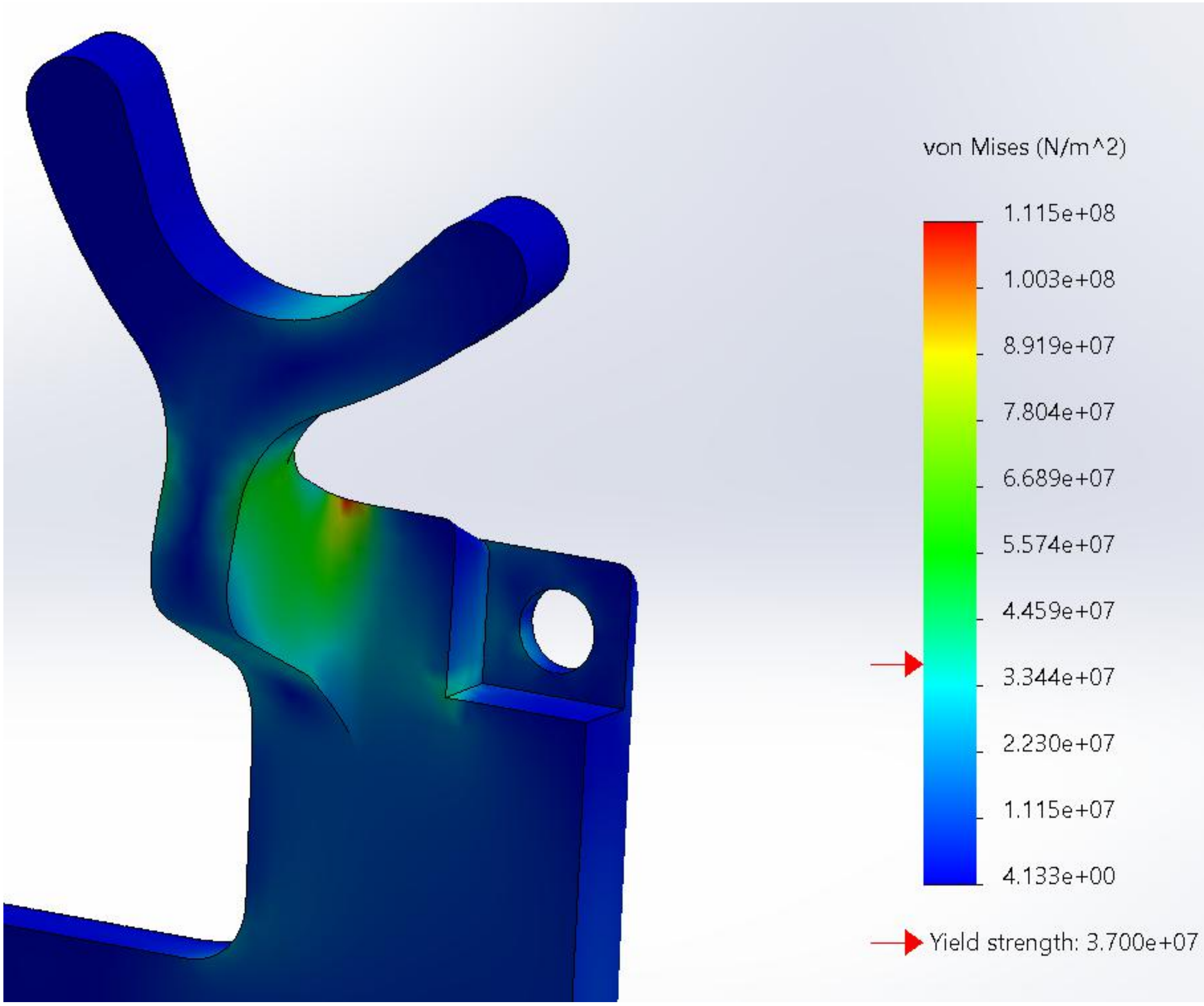

Figure 8. Antler Adaptive Side Max Stress. The antler develops significant stress in the arm of the antler support under extremely high and excessive loading, causing the structure to fail under this given loading scenario.

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 [1]. 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.

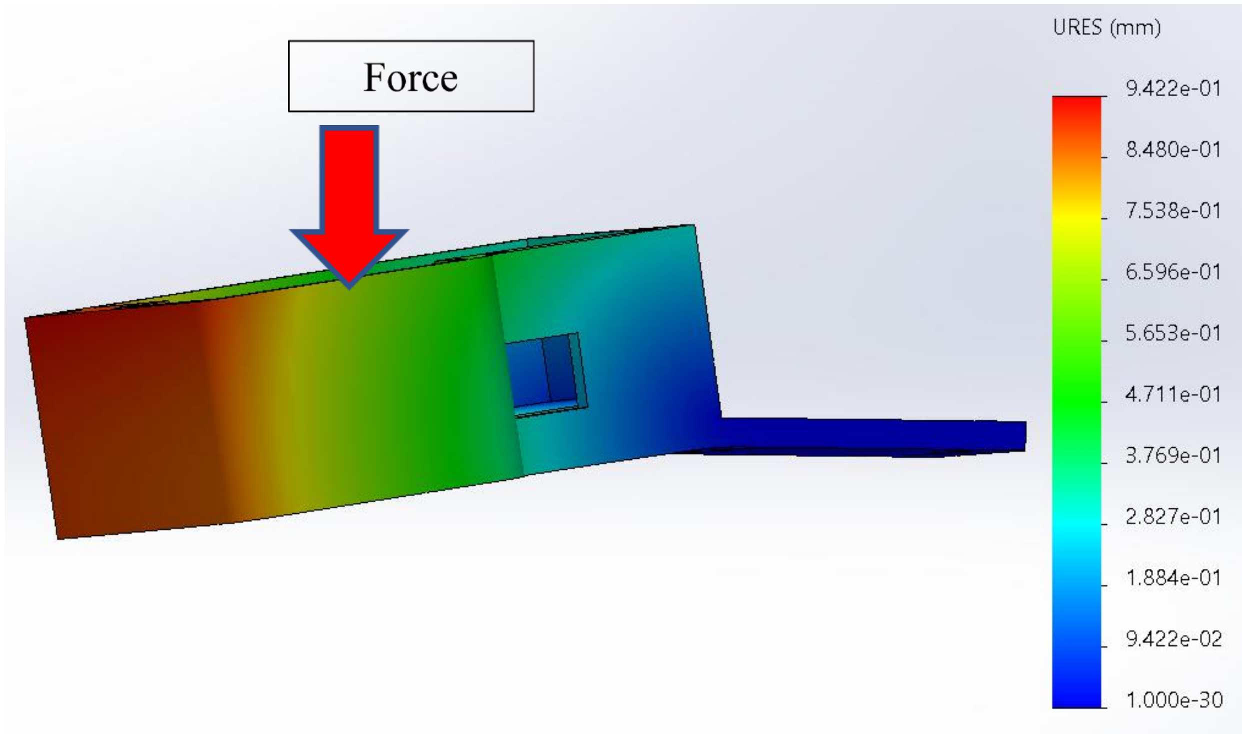

Figure 9. Electronics Box Deformation. The electronics box deflects less than 1 mm under a worst case loading, proving it is likely to succeed in holding the weight of the designed circuit.

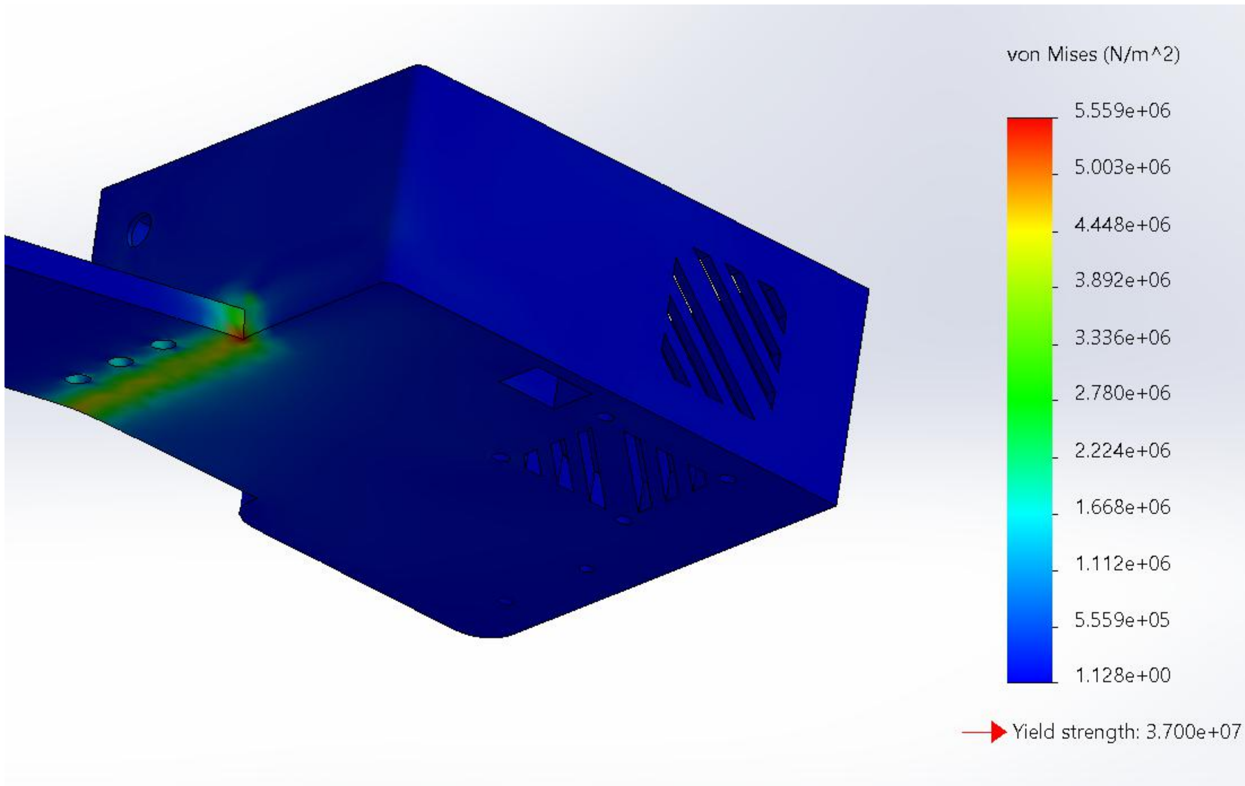

Figure 10. Electronics Box Max Stress. The electronics box has a higher likelihood to fail right at the location where it begins to bend and is no longer rigidly connected to the underside of the pulleys. However, these developed stresses are much less than the yield stress of Tough PLA, so the box is 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.

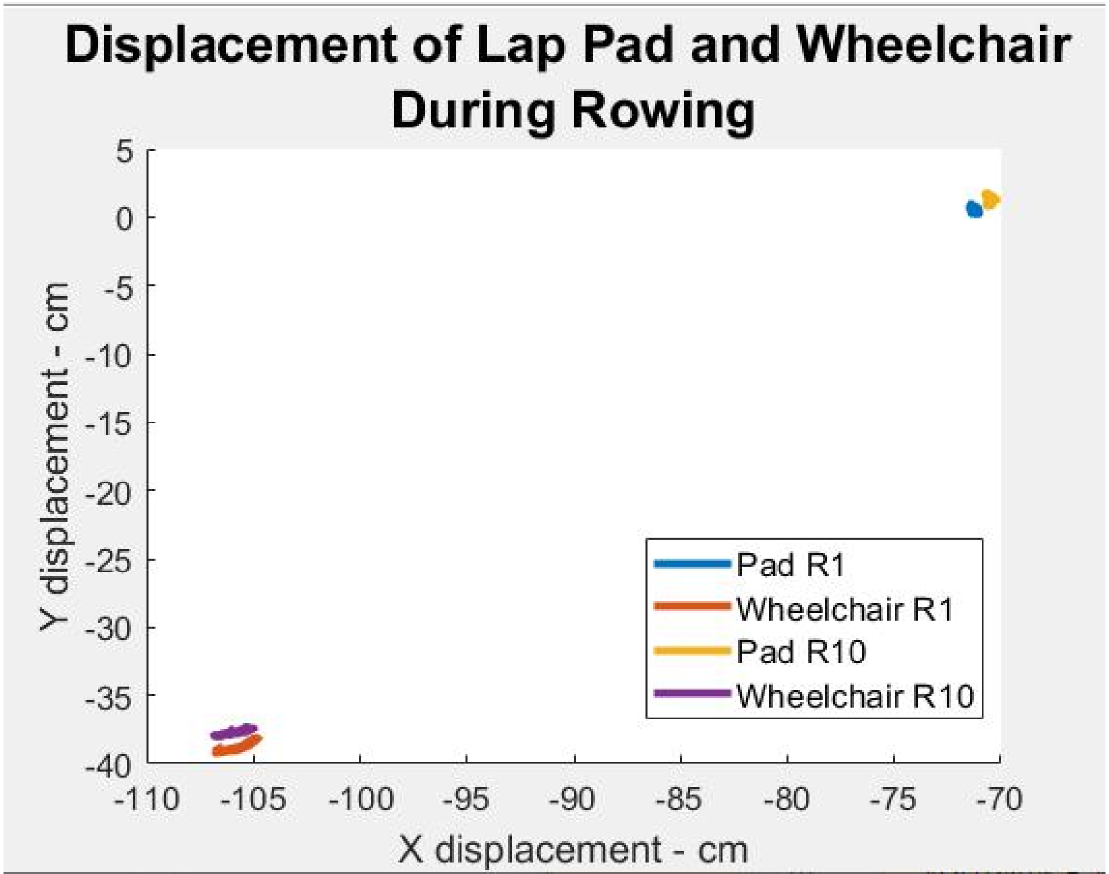

Figure 11. Diagram of Lap Pad and Wheelchair Motion. Motion of the wheelchair and lap pad during the rowing trials are represented with the four different lines. The axes are not centered at 0, due to the coordinate system originating from the calibration line.

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 I:

[1] “Ultimaker Tough PLA TDS.” https://support.makerbot.com/s/article/1667411002379 (accessed Dec. 11, 2022).
[2] N. Découfour, F. Barbier, P. Pudlo, and P. Gorce, “Forces Applied on Rowing Ergometer Concept2®: a Kinetic Approach for Development (P94),” p. 8.

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 be more manufacturable so that Johnson Health Tech could fabricate the parts out of metal, specifically Plain Carbon Steel. This helped 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 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 as 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**).

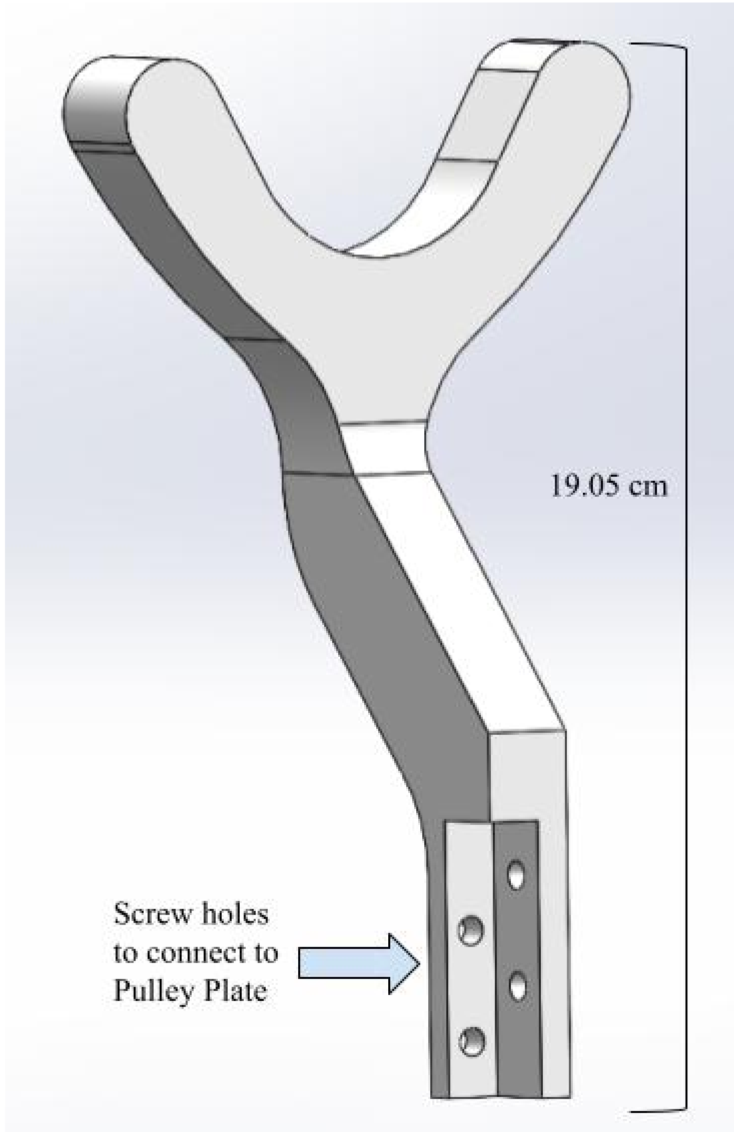

Figure 1. Separated Antler. The separated Antler has four screw holes that can rigidly connect to the Pulley Plate via the corner crevice that will mate with the corresponding corner on the Pulley Plate.

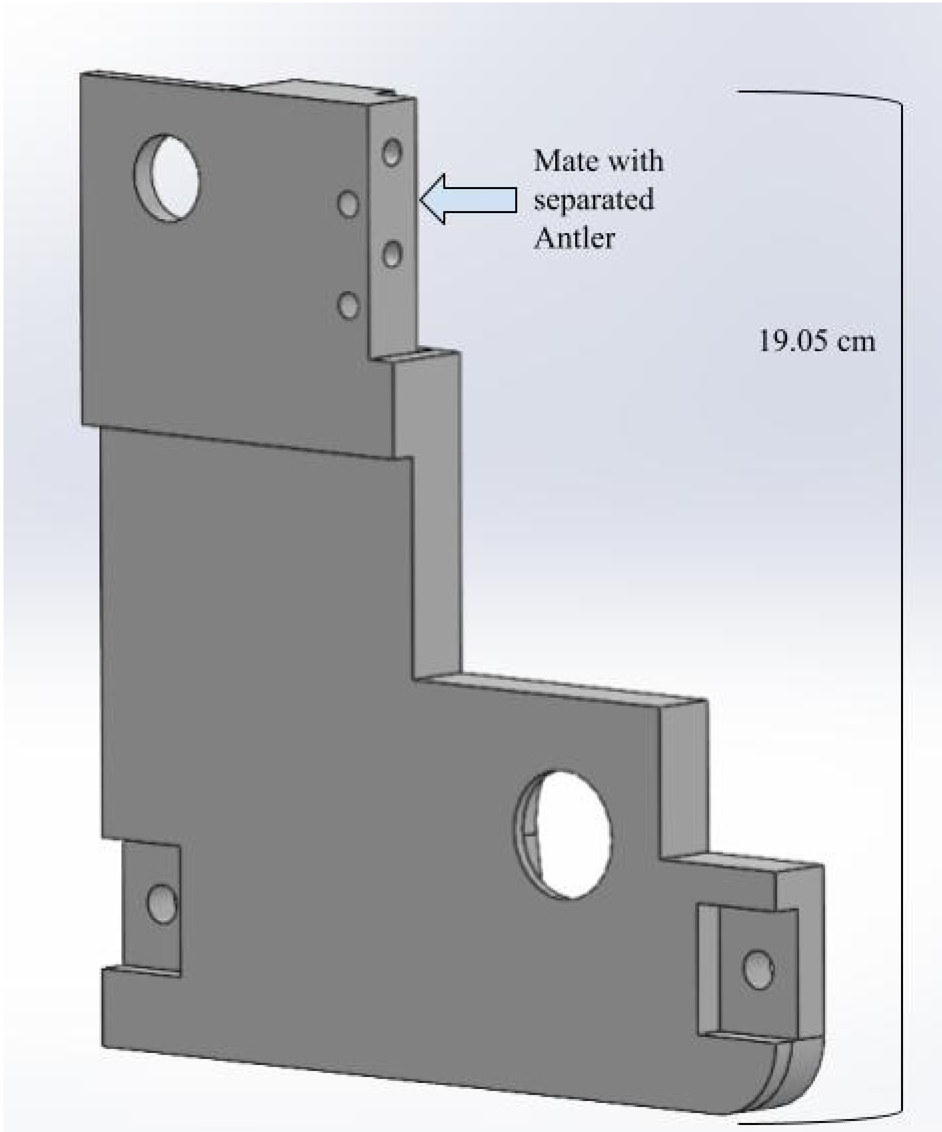

Figure 2. Separated Pulley Plate. The separated Pulley Plate has a mating corner with screw holes that will fit snugly with the separated Antler. No other features on the Pulley Plate were modified.

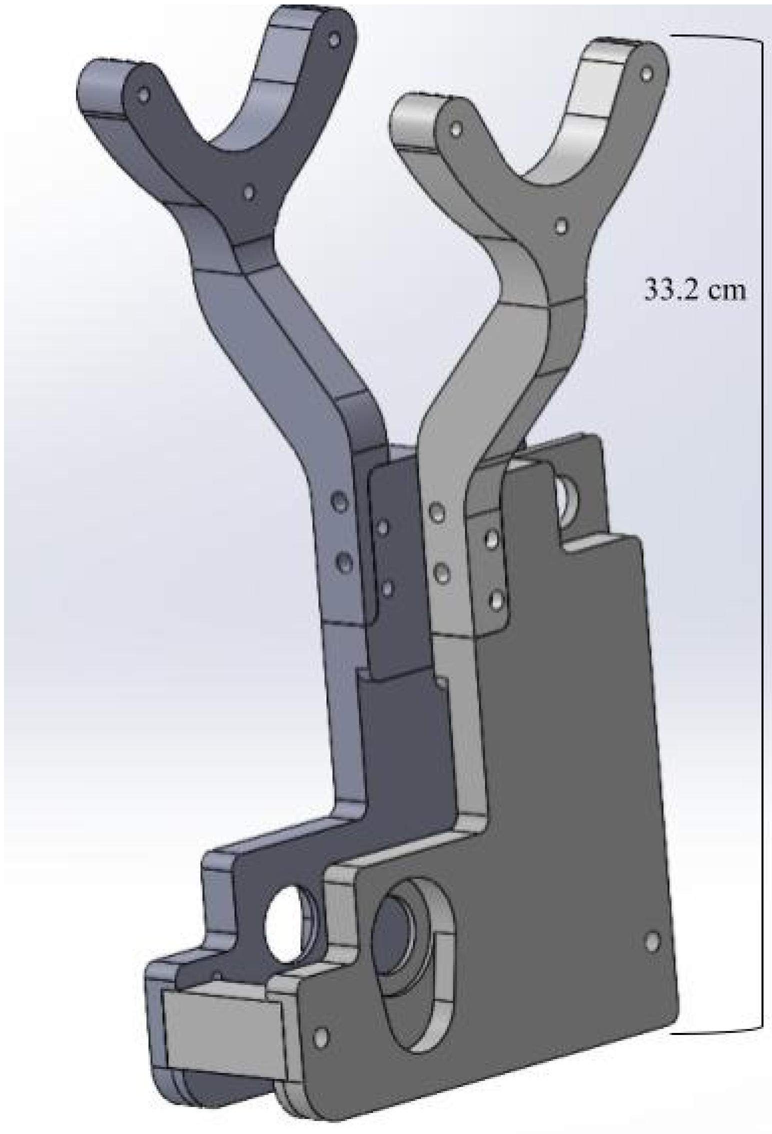

Figure 3. Johnson Health Tech modified Two-Piece Initial Design Assembly. Johnson Health Tech added fillets to all the sharp corners on the antlers and pulley plate based on what dimension of fillet their machines can create. Johnson Health Tech also added three mounting holes to each antler to secure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

Pulley Plate and Antler design is fabricated from 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 were drilled in the side of the plates that align with the two holes on the rower neck support arms. Previously, only the top hole had been used, as this is the hole that the original pulley was rigidly attached to. On the rower neck support arms, there was a second unused hole directly below the pulley attachment hole that was used to attach the new plates to the rower neck support arms. Thus, by having two rigid connection points (**Figure 4**), the plate was not able to rotate or translate once attached.

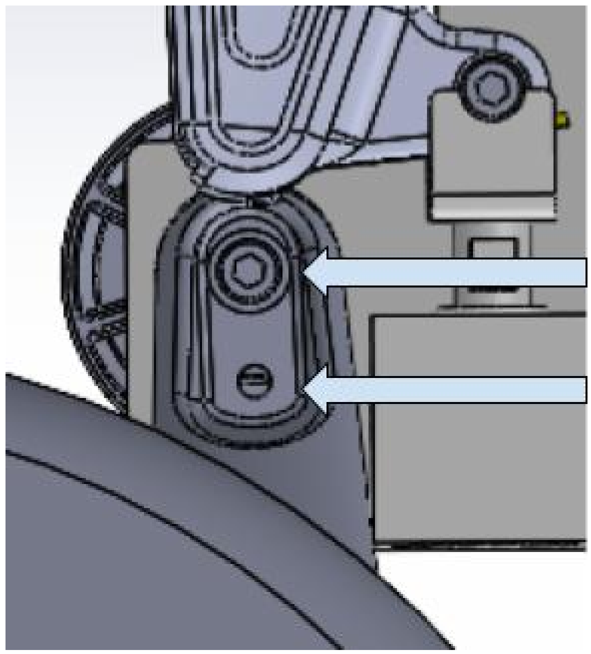

Figure 4. New Pulley Plate Connection to Rower Neck Support Arms. The Pulley Plate is now screwed into both holes on each of the rower neck support arms to prevent rotations and translations during rowing.

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 the thinned plates are 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 insert a screw from the bottom face. To fix this issue, a rectangular cut was made in the bottom front corner of each plate. Then, a block of metal was welded to the two plates. Within this block, two corner screws were placed that secured the box containing the console rotation mechanism 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 also made 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. 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 rotating under the handlebar when completely vertical. To fix this problem, the antlers were made 1.5 inches taller than the original design. The updated thinned Pulley Plate and Antler assembly (**Figure 5**), and full rower assembly **(Figure 6**) can be seen below.

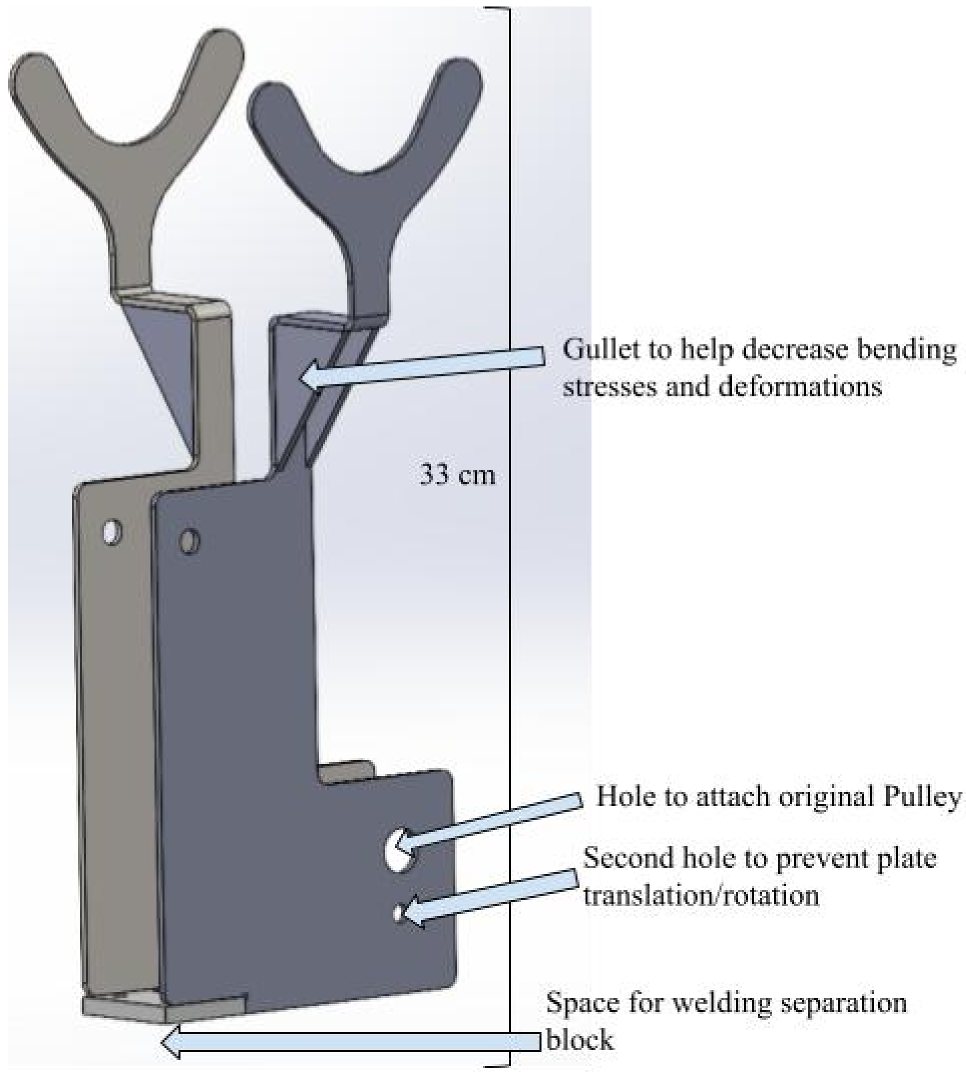

Figure 5. Thinned Pulley Plate and Antler Part. The Pulley Plate and Antler were thinned and combined as one part. The Antler has two 90° bends and is 1.5 inches taller than the original Antler design. Two holes were drilled in the plates to rigidly attach the rower neck support arms to prevent translation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

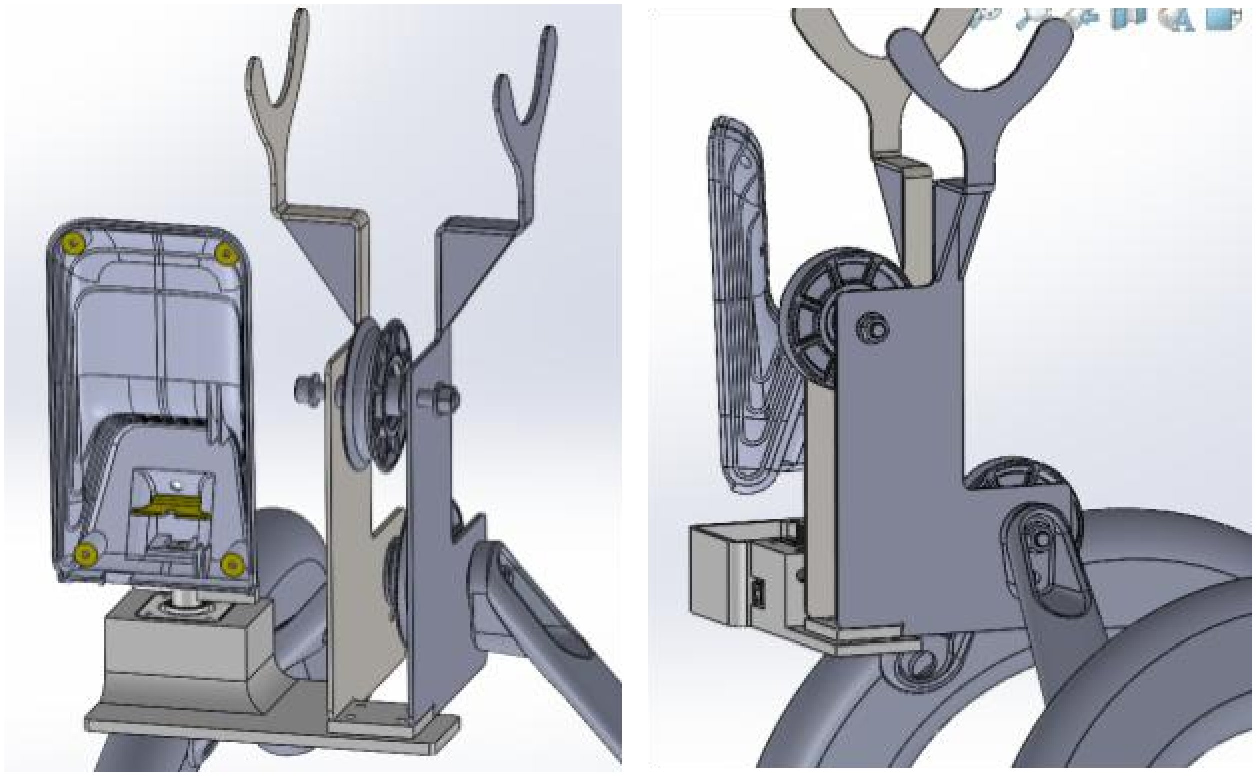

Figure 6. Tinned Pulley Plate and Antler Assembly on Rower. The front (left) and side (right) views of the updated and thinned Pulley Plate and Antler assembly show the new design on the rower. This new design allows for complete rotation of the console under the handlebar and still allows for attachment to the console rotation mechanism box.

The manufacturing process for this updated design was much easier and more cost-effective. To create this part, Johnson Health Tech used a laser cutter to cut out the flattened profile of the Pulley Plate and Antler. Then, they used a machine to bend the Antler and give it its two 90° bends. Lastly, the front block was welded to the underside cavity of the two plates to allow connection of the console rotation mechanism box. After fabrication, this assembly was integrated with the rest of the rower. Additionally, once the parts were finalized, one final SolidWorks Simulation was run using the updated 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, 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 were physically fabricated from. In BME 301 and BME 400 simulations, loads of 1050 N were used for all simulations because it 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, this load value was an inappropriate choice for running simulations on the manufactured plate/antler, which was confirmed when running simulations with the 1050 N load. Stresses would be several orders of magnitude 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 of the 1050 N load. Based on 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.

As can be seen in the figures below, a maximum displacement of 1.914 cm occurs when a 400 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, and it is unlikely that these forces will develop while the handlebar rests within the antler cavities. Therefore, although these loading conditions predict a slight displacement and 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. 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.

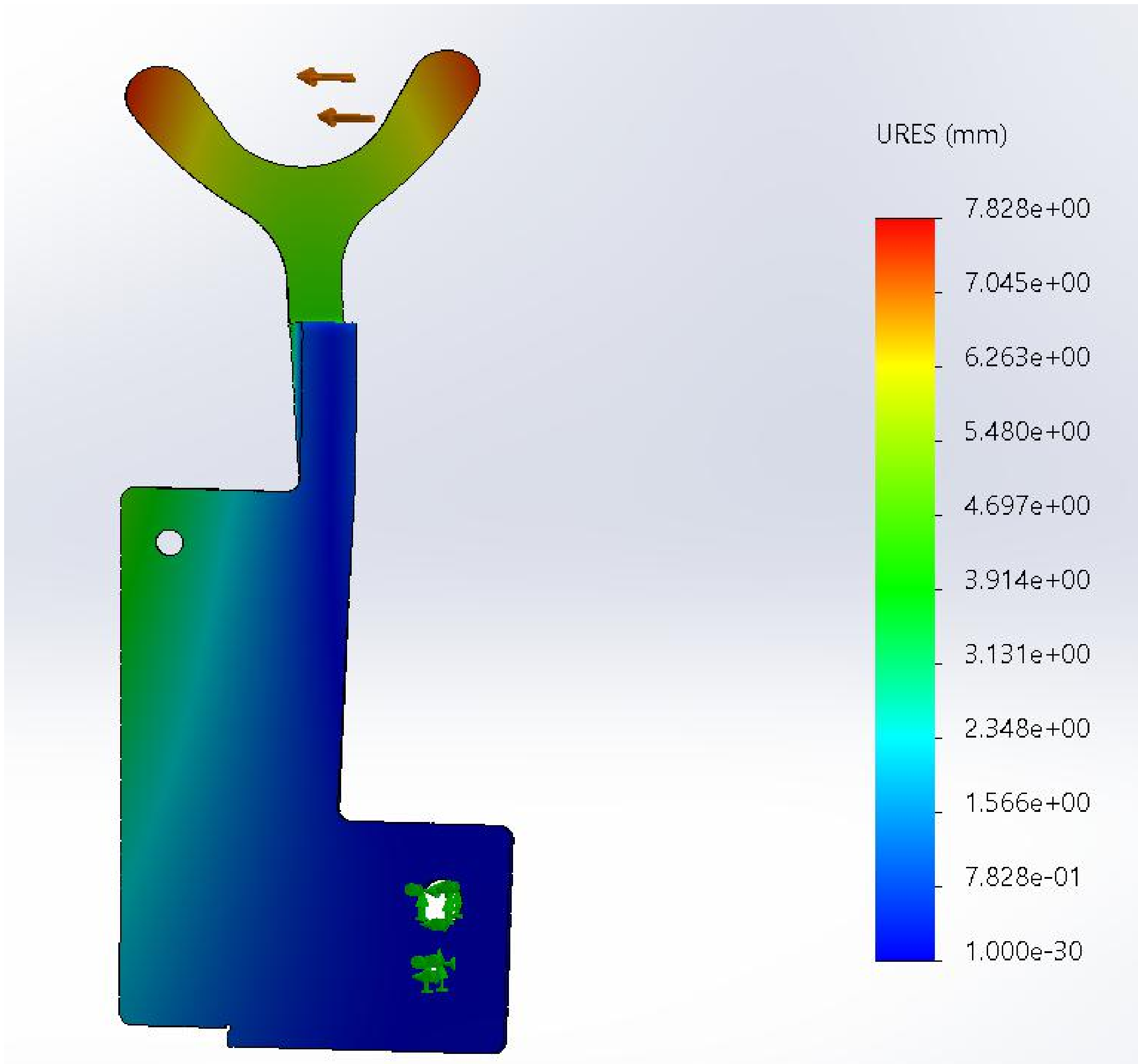

Figure 1. 300 N Load Adaptive Side Deformation. Under a 300 N load applied towards the adaptive side of the rower, the Pulley Plate and Antler experience a max displacement of 1.955 cm at the distal tip of the Antler.

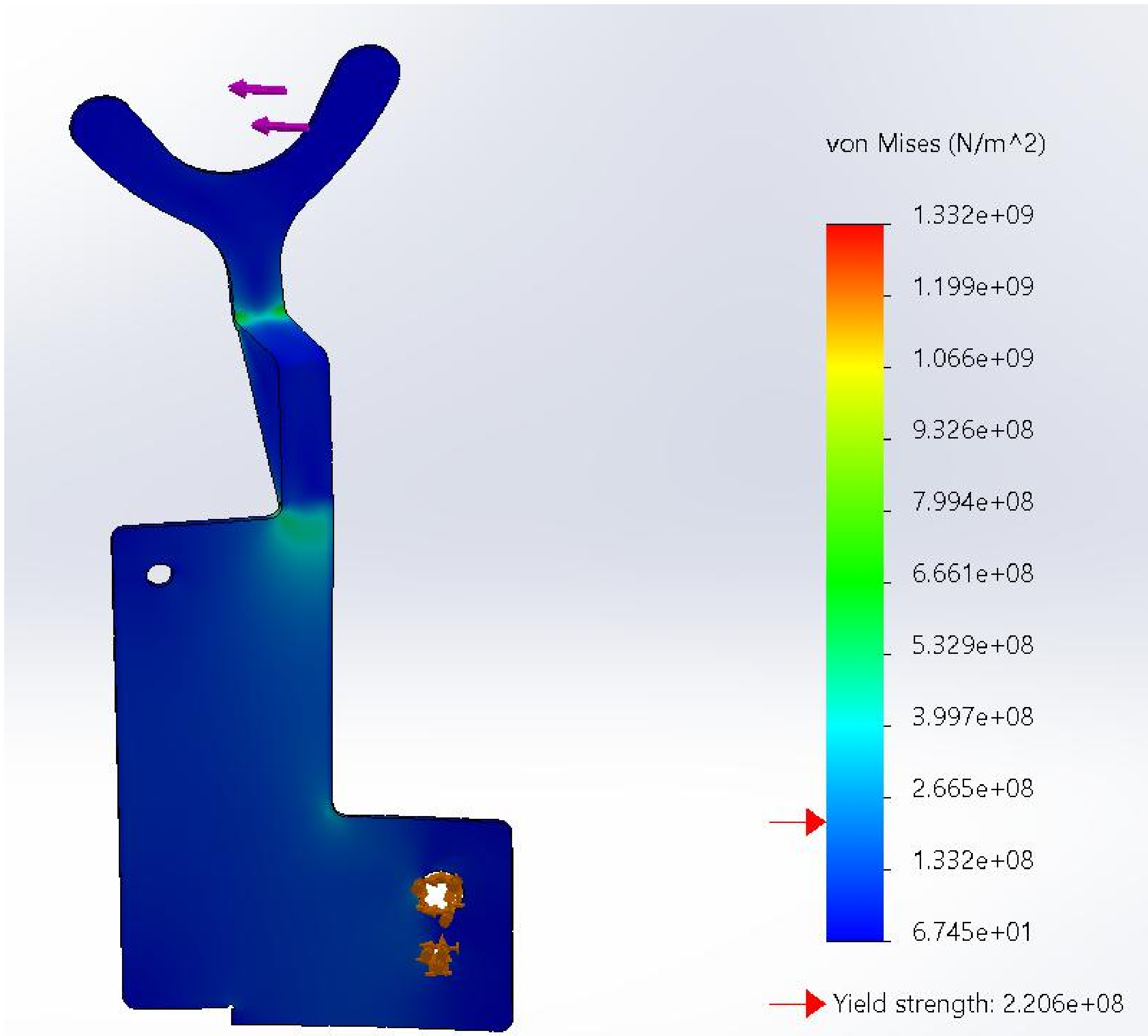

Figure 2. 300 N Load Adaptive Side Stress. Under a 300 N load applied towards the adaptive side of the rower, the Pulley Plate and Antler experience a max stress of 1450 MPa at the corner between the gullet and the vertical portion of the Antler.

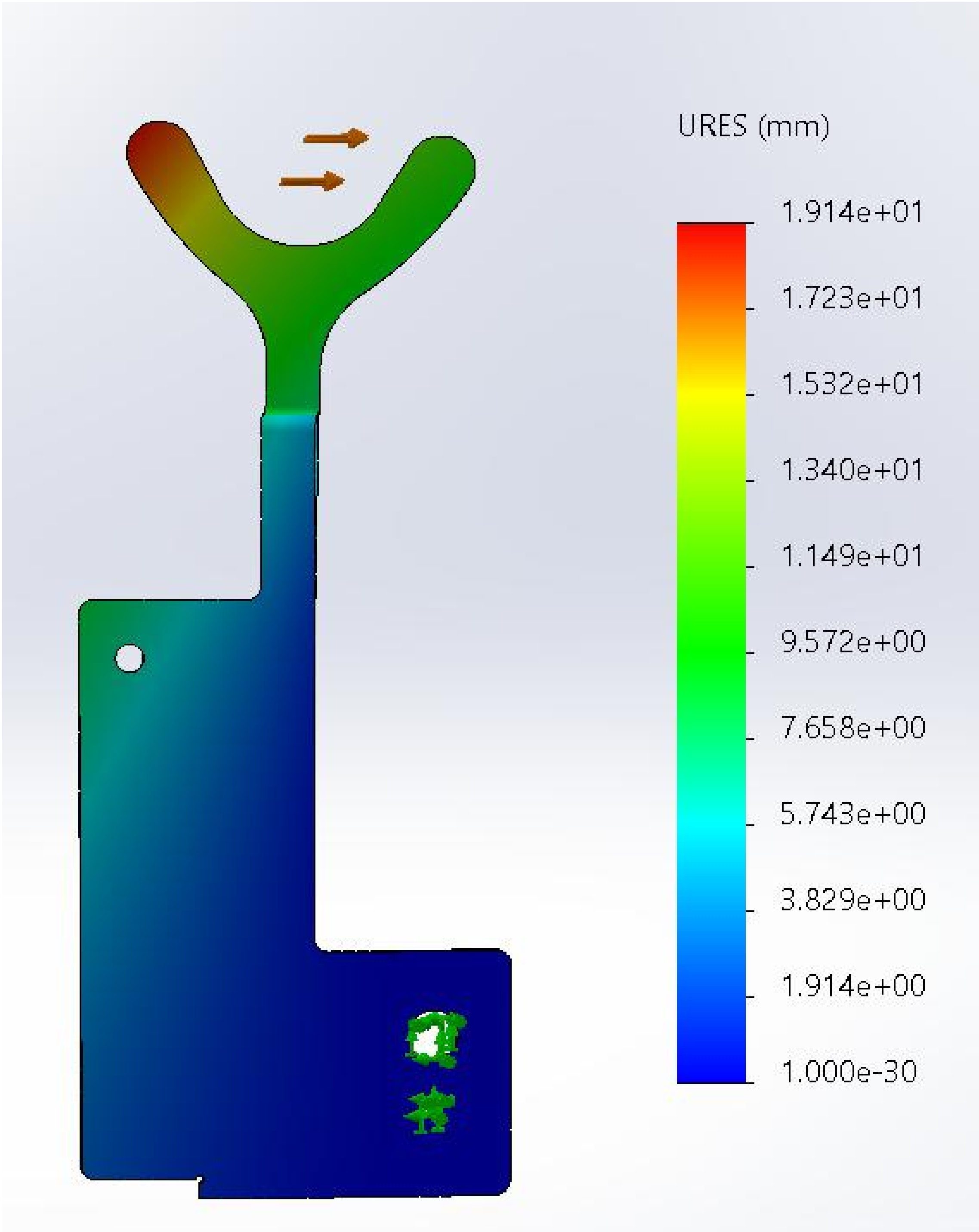

Figure 3. 400 N Load Standard Side Deformation. Under a 400 N load applied towards the standard side of the rower, the Pulley Plate and Antler experience a max displacement of 2.643 cm at the distal tip of the Antler.

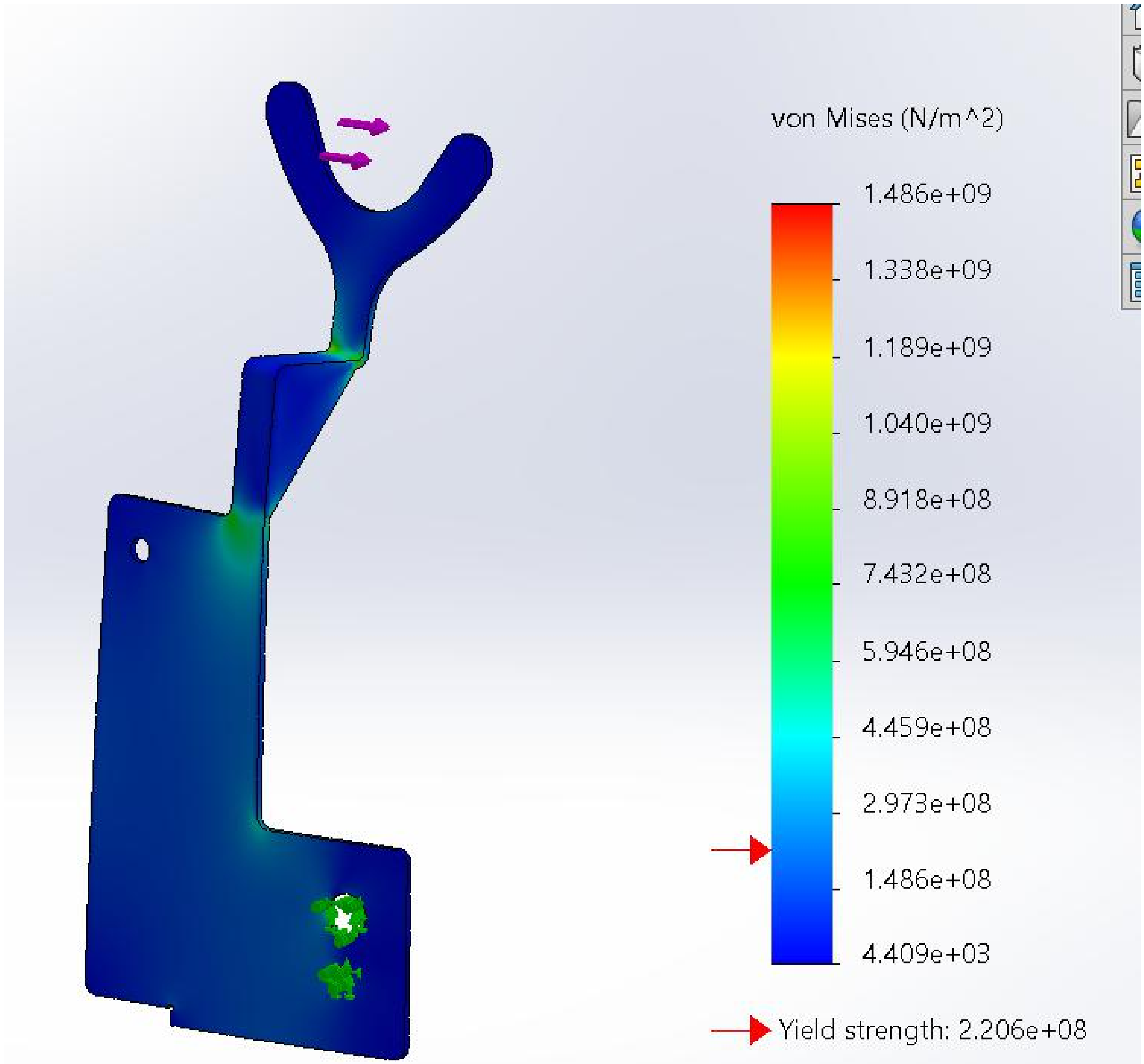

Figure 4. 400 N Load Standard Side Stress. Under a 400 N load applied towards the standard side of the rower, the Pulley Plate and Antler experience a max stress of 1960 MPa at the corner between the gullet and the vertical portion of the Antler.

Appendix L: BME 402 Updates to Stabilization Frame

The main goal for the stabilization frame this semester was to improve its manufacturability and aesthetic appeal. 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, which also improved the strength of the frame. The vertical support bar was shifted to be in plane with the two horizontal support bars (**Figure 1**). This change increased the strength of the frame in addition to improving its silhouette. The previous method for providing rotation to the lap pad restraint, a bolt and screw stop, was 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 design 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.

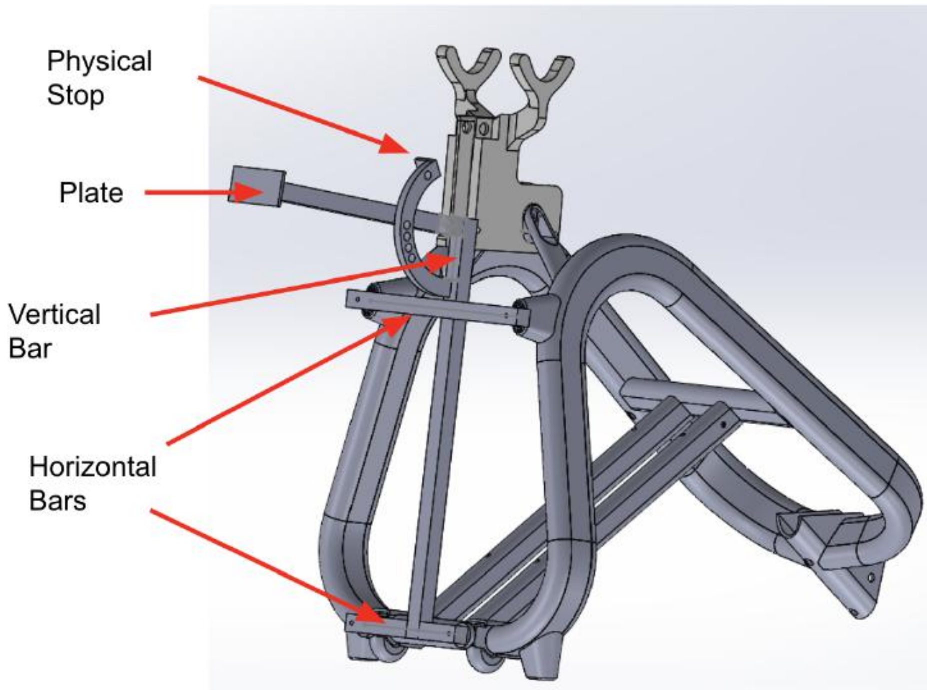

Figure 1. SolidWorks Model of Updated Stabilization Frame. The updated stabilization frame has the vertical bar in plane with the horizontal support bars. Additionally, the pin-adjustment mechanism has been incorporated to limit the lap pad movement to discrete increments.

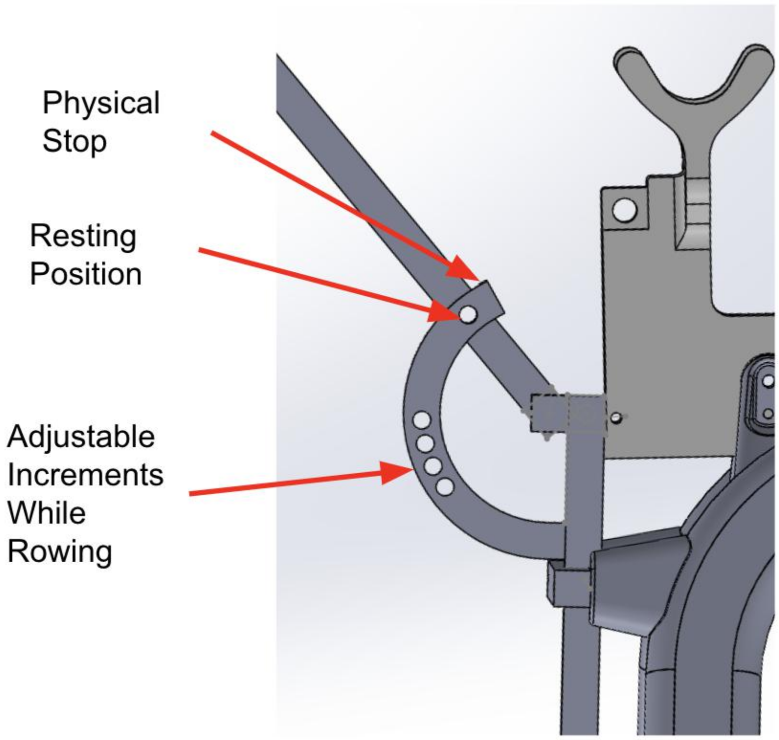

Figure 2. Pin-adjustment Mechanism. The pin-adjustment mechanism allows for the lap pad bar to rotate and lock into discrete positions along the arc. The top hole is the resting position for the lap pad while the other holes are positions that the user can utilize to lock the lap pad during the rowing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

After sending the SolidWorks models of the stabilization frame to Johnson Health Tech for fabrication, a few design changes were made (see **Appendix U)**. First, the lower horizontal bar was completely removed from the design. Additionally, the vertical bar was made significantly shorter, and only extended upward from the upper horizontal bar. For the pin adjustment mechanism, two additional holes were drilled into the plate to increase the number of adjustability levels for the stabilization frame.

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 of 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 pad 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 was 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 was replaced by an electronic design. A NEMA17 stepper motor adjusts the overlap between the magnet and the flywheel by rotating clockwise (in reference to the left view of the rower) to increment the resistance level and counterclockwise to decrement the resistance level. An Arduino Mega, DRV8825 motor driver, and +12 Volt power supply control the stepper motor's position according to feedback from several switches within the circuit. Each side of the machine has 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 orients the system at the onset of power application. The first task that the program completes is to rotate the stepper motor in the counterclockwise direction until the limit switch is depressed. The position of the limit switch is 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**.

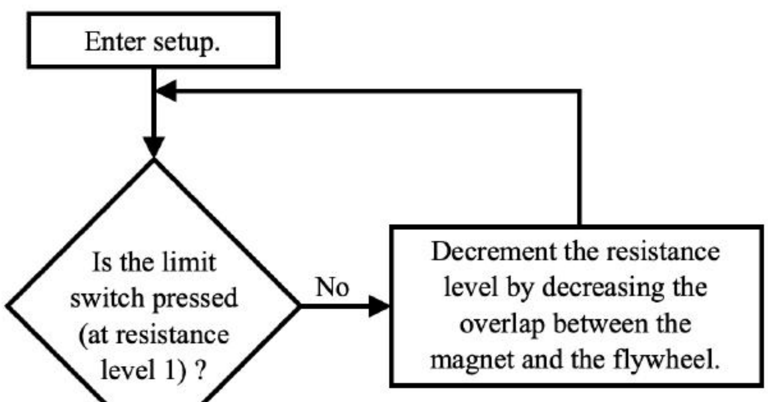

Figure 1. Resistance Dial Setup Coding Flowchart. At the beginning of the program (i.e., when the device is first powered on), check the state of the resistance dial limit switch. If it is not depressed, rotate the stepper motor that controls the overlap between the magnet and the flywheel such that 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 rotates 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 rotates counterclockwise by a set number of degrees that correlate to one decrement of the resistance level. It was determined that the magnet housing moved approximately three degrees every resistance level increment with the original mechanical mechanism. Based on measurements using a protractor, the selected NEMA17 stepper motor moves approximately three degrees per one step. Consequently, the program rotates the motor one step for every singular increment/decrement in the resistance level, assuming that the value ranges between one and ten. A pair of two digit seven segment LED displays present on both sides of the machine display the current resistance level to the user. After each press of a button, the display automatically updates 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.

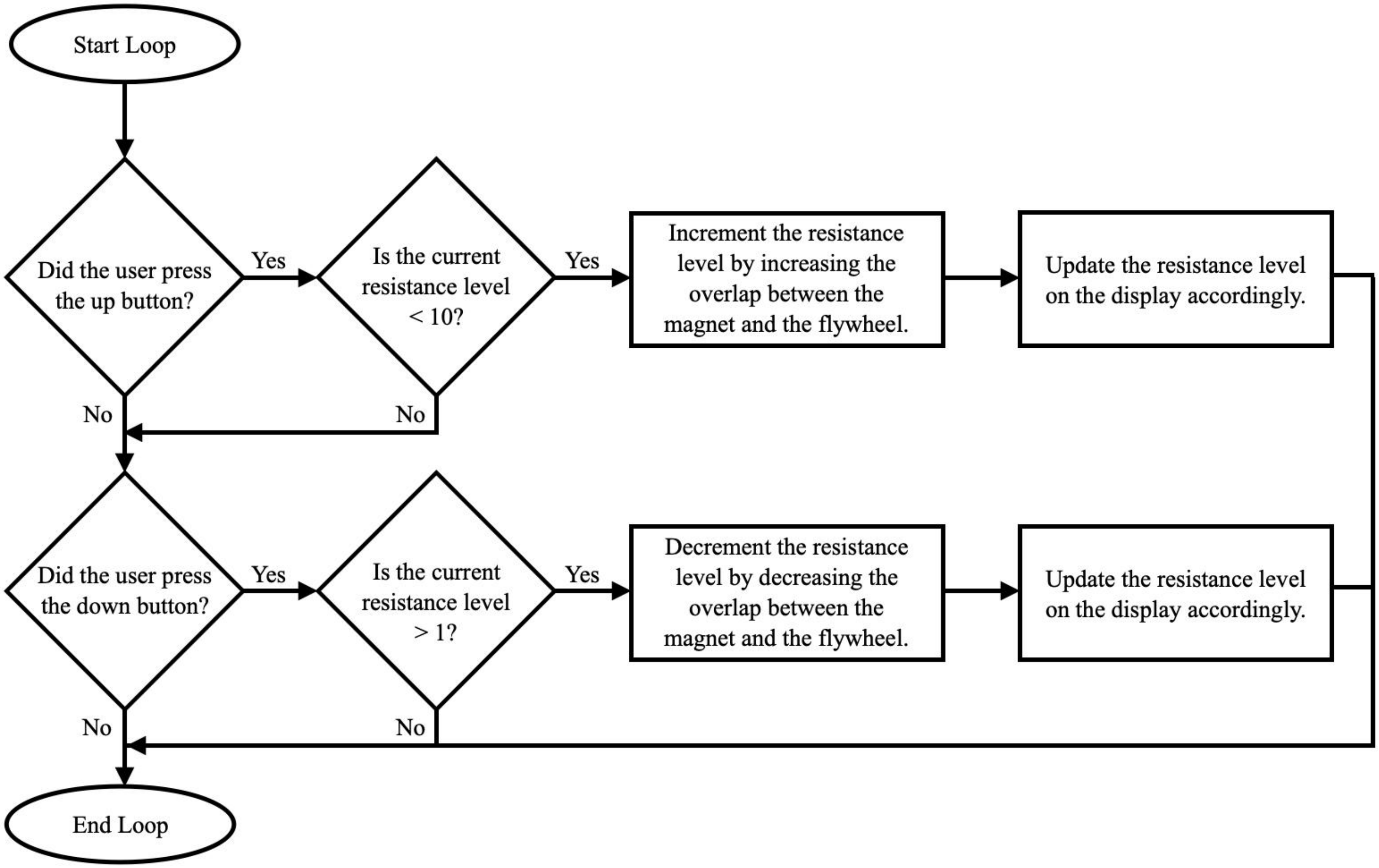

Figure 2. Resistance Dial Void Loop Coding Flowchart. Each loop iteration, the code checks the state of the up and down resistance level buttons. If the up button is pressed and the current resistance level is less than 10, rotate the stepper motor that controls the overlap between the magnet and the 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 was constructed according to the schematic shown in **Figure 3**. An Arduino Mega was necessary because the Arduino Uno did not have enough digital pins to implement the proposed design. The Arduino Mega was purchased from the MakerSpace at the University of Wisconsin-Madison. An Arduino Mega screw terminal board was also purchased to strengthen the connections within the design and improve durability [1]. The NEMA 17 [2] stepper motor and DRV8825 motor controllers [3] were purchased from the same vendor that sold the one used in the console rotation mechanism. One 100 μF capacitor required to protect the DRV8225 from power surges was sourced from the BME storage closet. The limit switch was taken from materials supplied by JHT. Two sets of up/down arrow buttons [4] and two 2-digit seven LED [5] displays were purchased from online vendors.

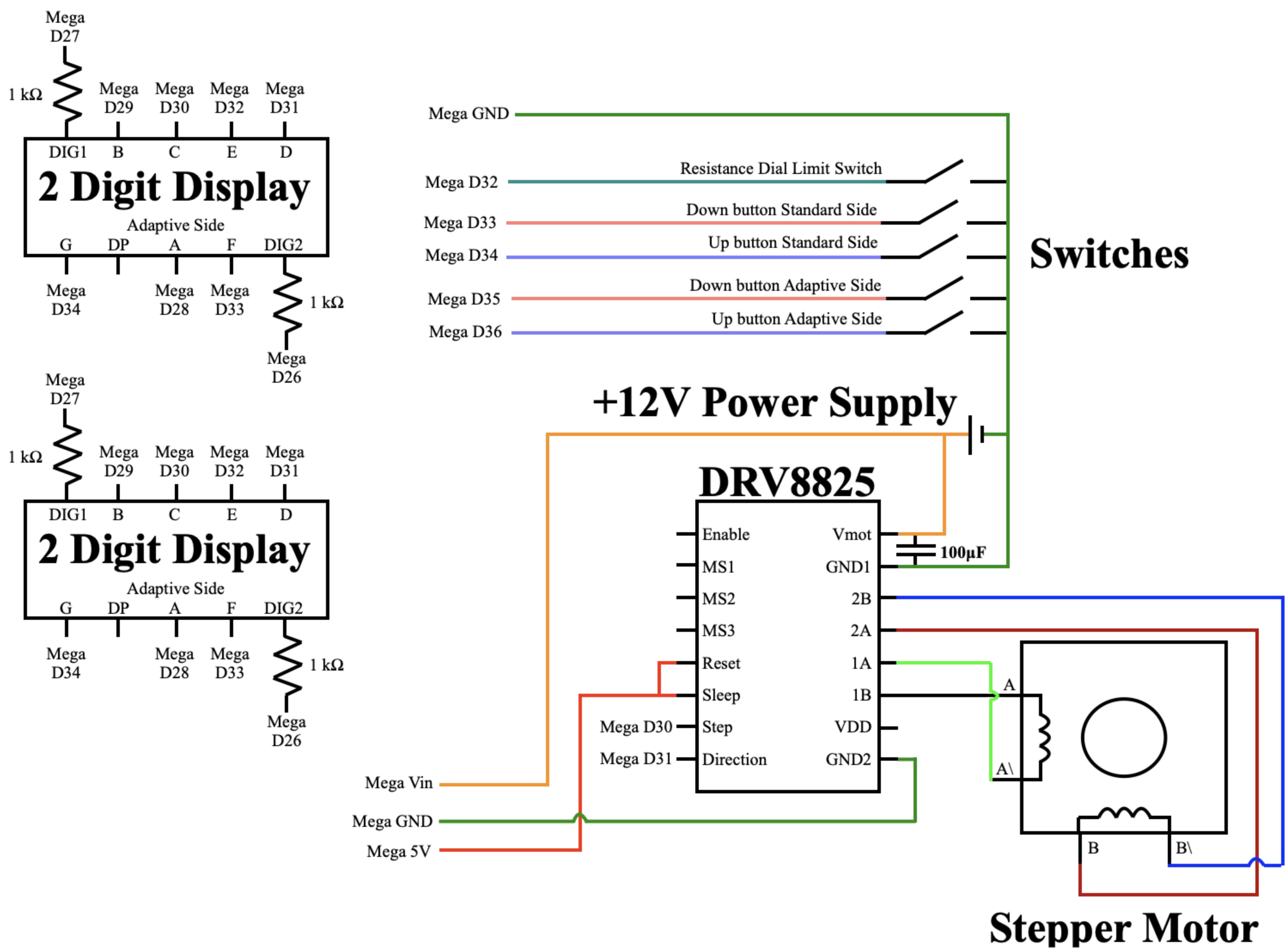

Figure 3. Resistance Dial Circuit Schematic. The resistance dial circuit consists of an Arduino Mega, DRV8825, NEMA17 stepper motor, +12V power supply, 100 µF capacitors, two 2 digit 7 segment displays, four press buttons, and NO limit switch. The colored lines represent the wire connections present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

Assembly Integration with Matrix Rower

The magnets from the mechanical resistance mechanism were kept in their original position (**Figure 4**), and the spring mechanism was removed. A stepper motor attached to the side of the rower frame via a 3D printed housing rotates the magnets to change the resistance level. Prior to unscrewing the magnet housing, a calibration was done to determine how much the magnets rotate between each change in resistance level. It was found that there is about a 3 degree change for every increment or decrement in resistance level. Given this degree of rotation, the stepper motor was calibrated to produce the same amount of rotation once connected with the magnet housing.

Figure 4. Previous Resistance Mechanism The magnet housing was originally 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 new resistance dial mechanism keeps this entire structure intact.

To physically attach the magnet housing to the stepper motor, a mechanism was developed that fits between the shaft of the stepper motor and the bolt through hole in the magnet housing (**Figure 6**) that acts as the magnet housing's pivot point. To simplify the design, this connector piece mimics the bolt that was already in place and connects the stepper motor to the magnet housing. On one end, the component has a press-fit cavity that secures the connector piece to the D-shaft of the stepper motor. Threads were 3D printed on the other end of the component to allow tightening of the connector to the magnet housing using the washer and nut that were previously used with the bolt. Next, a housing chamber was developed to hold the stepper motor in place (**Figure 7**). This small piece has a cavity that the stepper motor can be screwed into. A flag sticks out and allows the piece to be screwed into the current magnet housing. This ensures that the magnet housing stays rigidly connected to the stepper motor and that the stepper motor housing is rigidly connected to the rower frame itself. Then, whenever the stepper motor rotates, it rotates the magnet housing and the magnets about the flywheel.

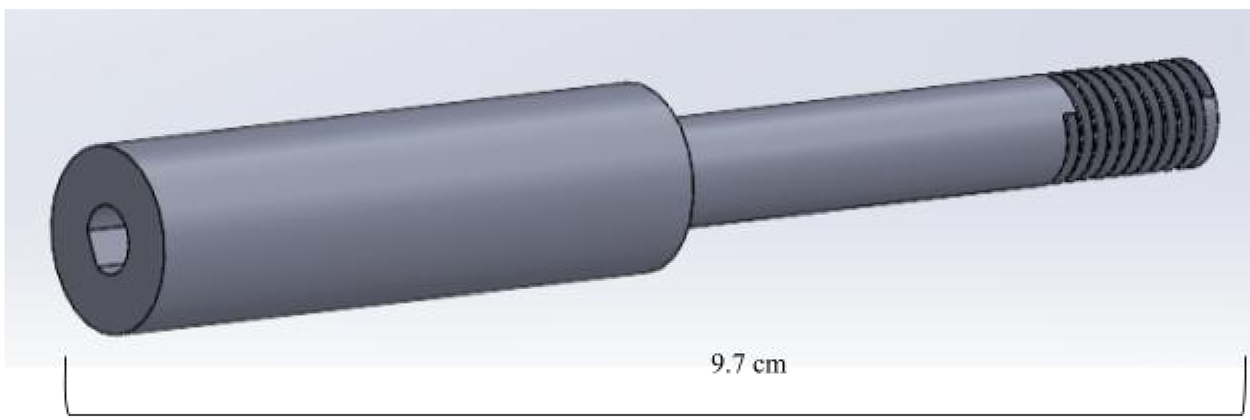

Figure 6. Stepper Motor - Magnet Housing Connection. The connector includes a press-fit cavity to fit on the D-shaft of the stepper motor, and 3D printed threads that allow for attachment to the magnet housing. This connector will allow the stepper motor to rotate the magnet housing to change the resistance level.

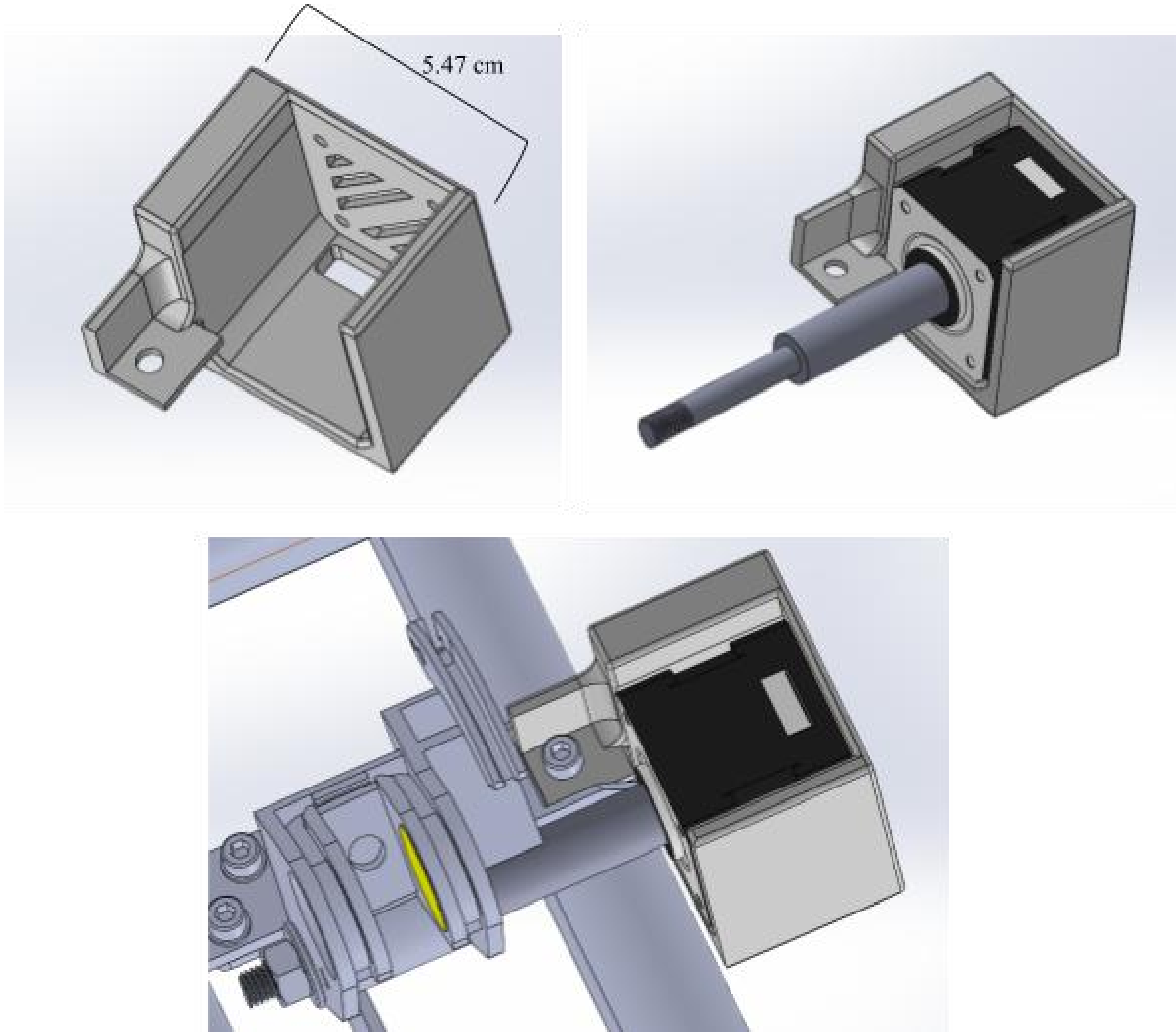

Figure 7. Stepper Motor Housing. The stepper motor housing (top left) allows the stepper motor to be screwed into the housing (top right). Additionally, the flag on the housing is used to screw this piece into the rower frame (bottom). Thus, whenever the shaft rotates, the motor does not rotate with the shaft.

The box that sits on the floor and holds both the electronics for the resistance dial mechanism and the console rotation mechanism was designed (**Figure 8**). Due to spatial limitations near the base of the rower, it was easier to have this box be freely-floating on the ground, rather than screwed into a connection point on the rower’s base. This box has a hole in the front and back walls to allow wires from the stepper motor in the resistance dial mechanism and the stepper motor for console rotation to enter the box. Because this new box holds all electrical components (except the stepper motors), the console rotation electronics box only contains the stepper motor and console. Therefore, this box was updated to only have the cavity for the stepper motor (**Figure 9**). The final component of the resistance adjustment mechanism was a small encasement that holds the two 2-digit seven segment displays showing which resistance level the machine is currently set to. This component includes a base tray that the display can rest in, and a cover that sits on top to enclose the electronics included on the solder board (**Figure 10**). The screw holes on the solder board were tapped out on both the base and cover, and all three pieces were sandwiched and screwed together.

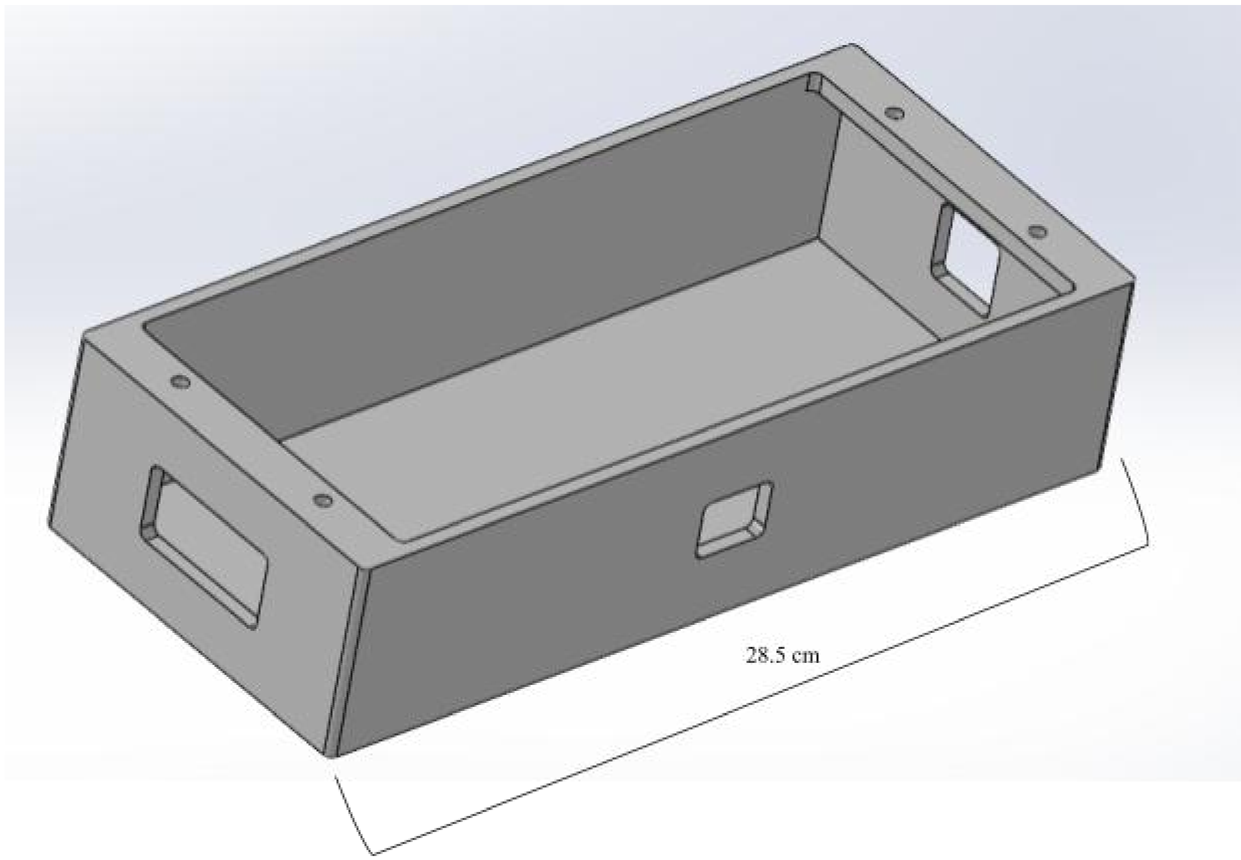

Figure 8. Electronics Box. The electronics box includes the Arduino Mega and the motor controller. It has holes on the front and back walls for wires to be threaded in and out of. There is also a side hole to allow for easy access to the power supply cord. This box sits flat on the ground near the rower's base.

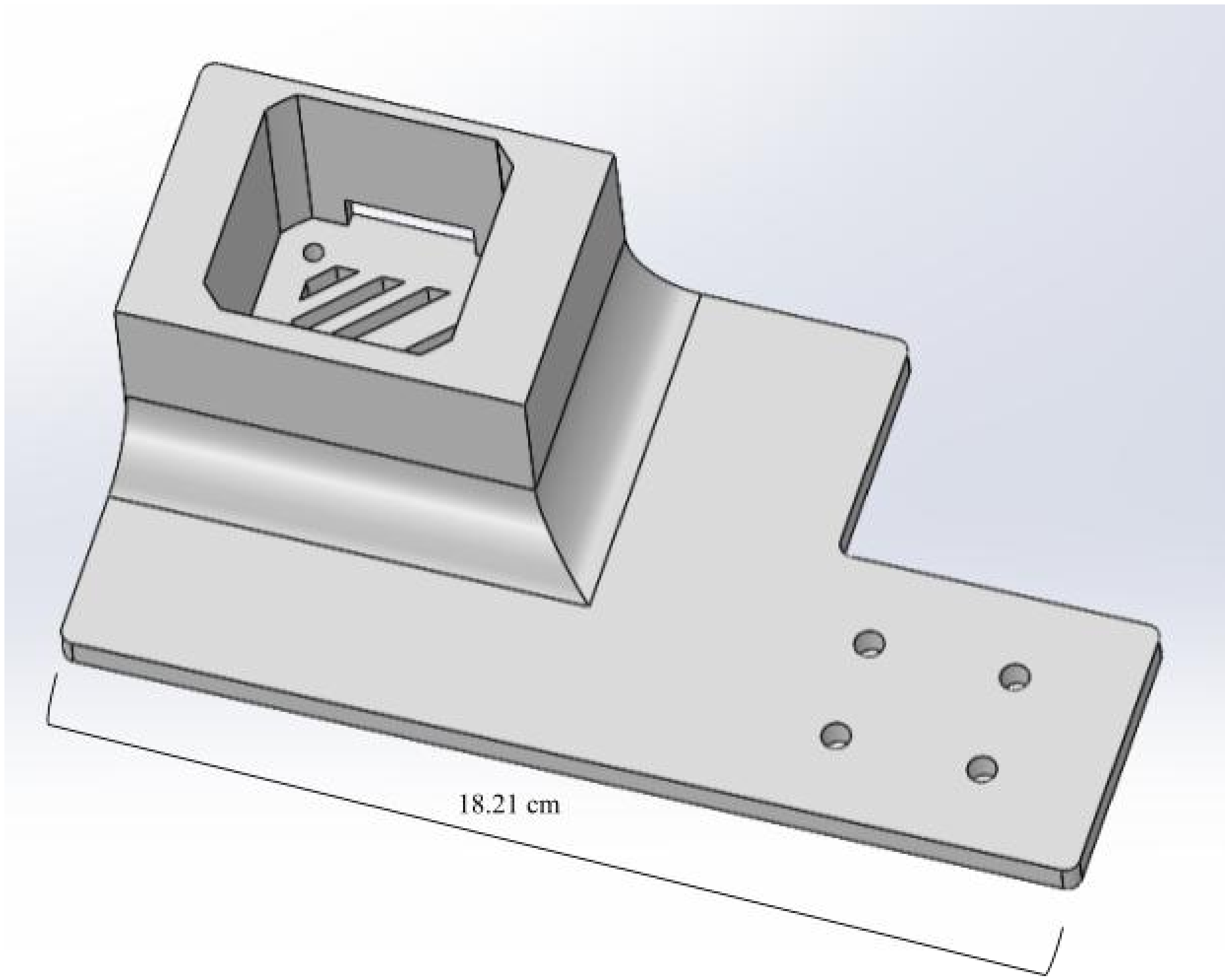

Figure 9. Updated Console Rotation Box. The updated console rotation box only includes a cavity for the stepper motor to sit in and be screwed in place. Since the Arduino and motor controller were moved to the electronics box at the rower's base, their cavities were removed in the updated box design (as compared to the previous design iteration).

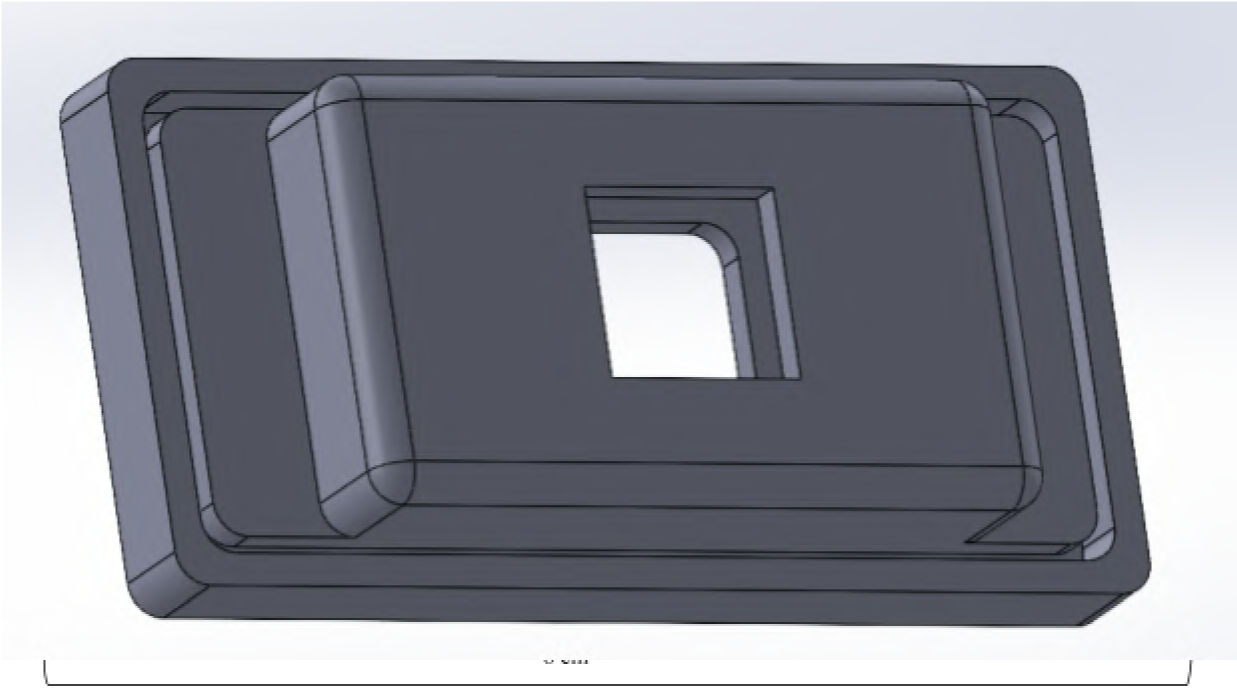

Figure 10. LCD Display Assembly. The 2-digit seven segment display assembly includes a base plate for the solder board to sit on, and a cover to enclose the open resistors. There is a hole on the top to allow visibility of the 2-digit seven segment display itself.

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 (accessed Dec. 11, 2022).

[3] “Amazon.com: Songhe 3D Printer Parts DRV8825 Stepper Motor Driver Module with Heat Sink for Ramps 1.4 StepStick A4988 (5pcs) : Industrial & Scientific.” https://www.amazon.com/gp/product/B07XF2LYC8/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1 (accessed May 01, 2023).

[4] “QCQIANG 4pcs 22mm Waterproof Momentary Green Mushroom Head Push Button Switch, 3A/3V-220V Screw Feet Wiring: Amazon.com: Industrial & Scientific.” https://www.amazon.com/QCQIANG-Waterproof-Momentary-Mushroom-3V-220V/dp/B0B1PGMK9F/ref=sr_1_82_sspa?keywords=mushroom%2Bhead%2Bpush%2Bbutton&qid=167907879

9&s=industrial&sr=1-82-spons&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUExM1JBVjFUSTNaSktFJmVuY3J5cHRlZElkPUEwMDUyODk2MzFUUlZORDROMVdHMiZlbmNyeXB0ZWRBZElkPUEwMjEyMjY3MjVGTzNKOUZINjdIMiZ3aWRnZXROYW1lPXNwX21ZiZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU&th=1 (accessed May 01, 2023).

[5] 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 Final Circuit Schematic

The final circuit, consisting of the components described previously for the console rotation mechanism and the resistance adjustment mechanism, was constructed according to the schematic shown in Figure 1. After first modeling the circuit using breadboards and jumper wires, the final circuit was fabricated using solder boards and screw terminals that increased the durability and connection stability of the design. Once the other components of the adaptive rower were fabricated, the electronics were integrated into the overall design.

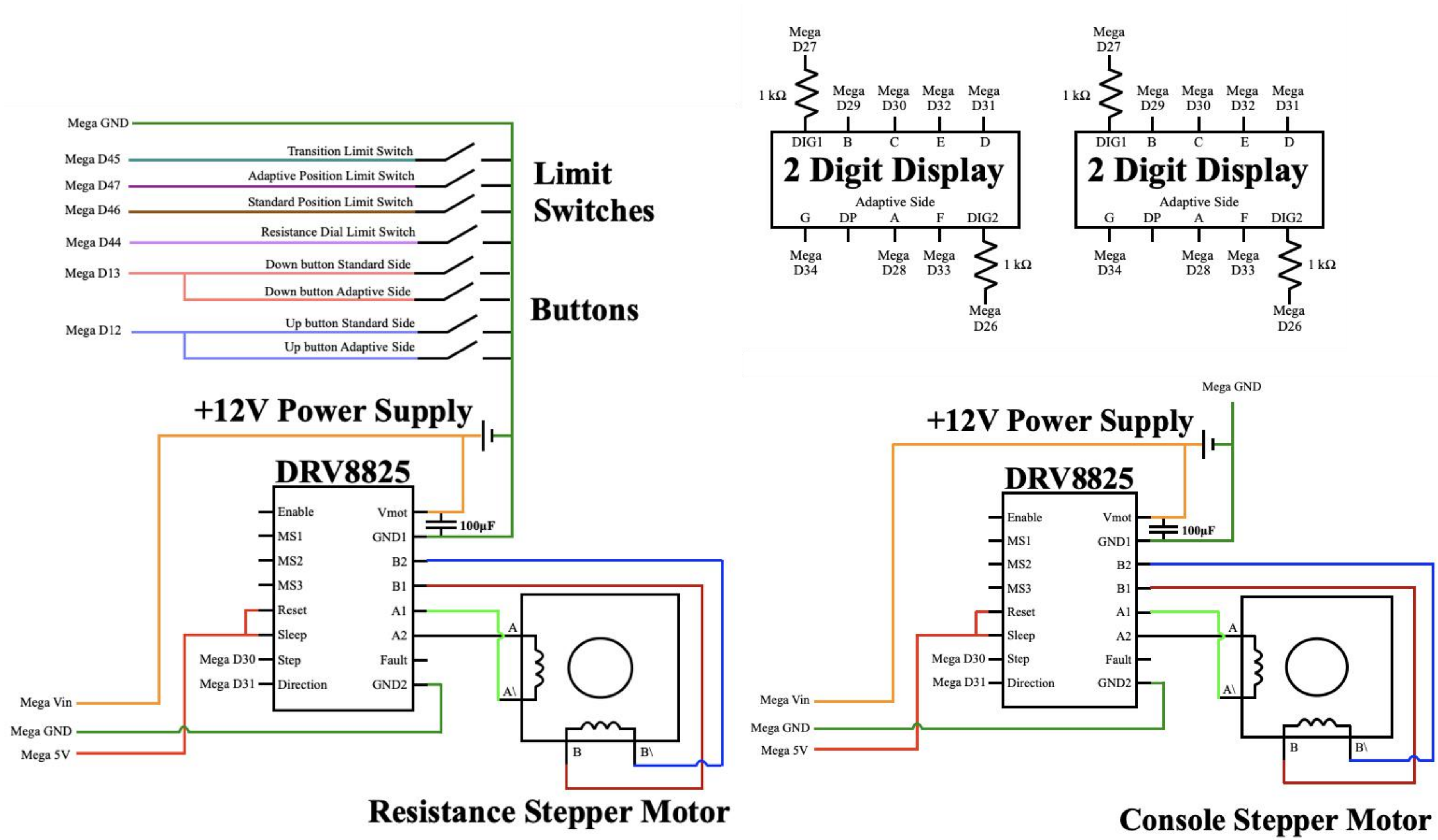

Figure 1. Final Circuit Schematic. The final circuit consists of an Arduino Mega, two DRV8825, two NEMA17 stepper motors, a +12V power supply, two 100 μF capacitors, four 1 kΩ resistors, four NO limit switches, four push buttons, and two 2-digit seven segment displays. The colored lines represent the wire connections present between each physical component.

Appendix O: BME 402 Final Coding Flowcharts

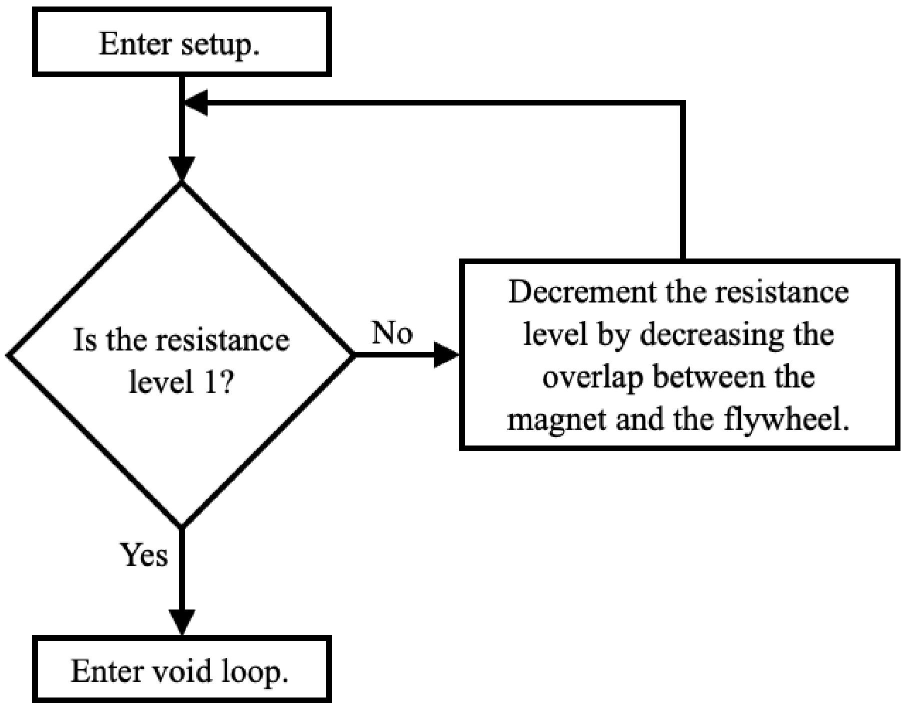

Figure 1. Resistance Dial Setup Coding Flowchart. At the beginning of the program (i.e., when the device is first powered on), check the state of the resistance dial limit switch. If it is not depressed, rotate the stepper motor that controls the overlap between the magnet and the flywheel such that 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.

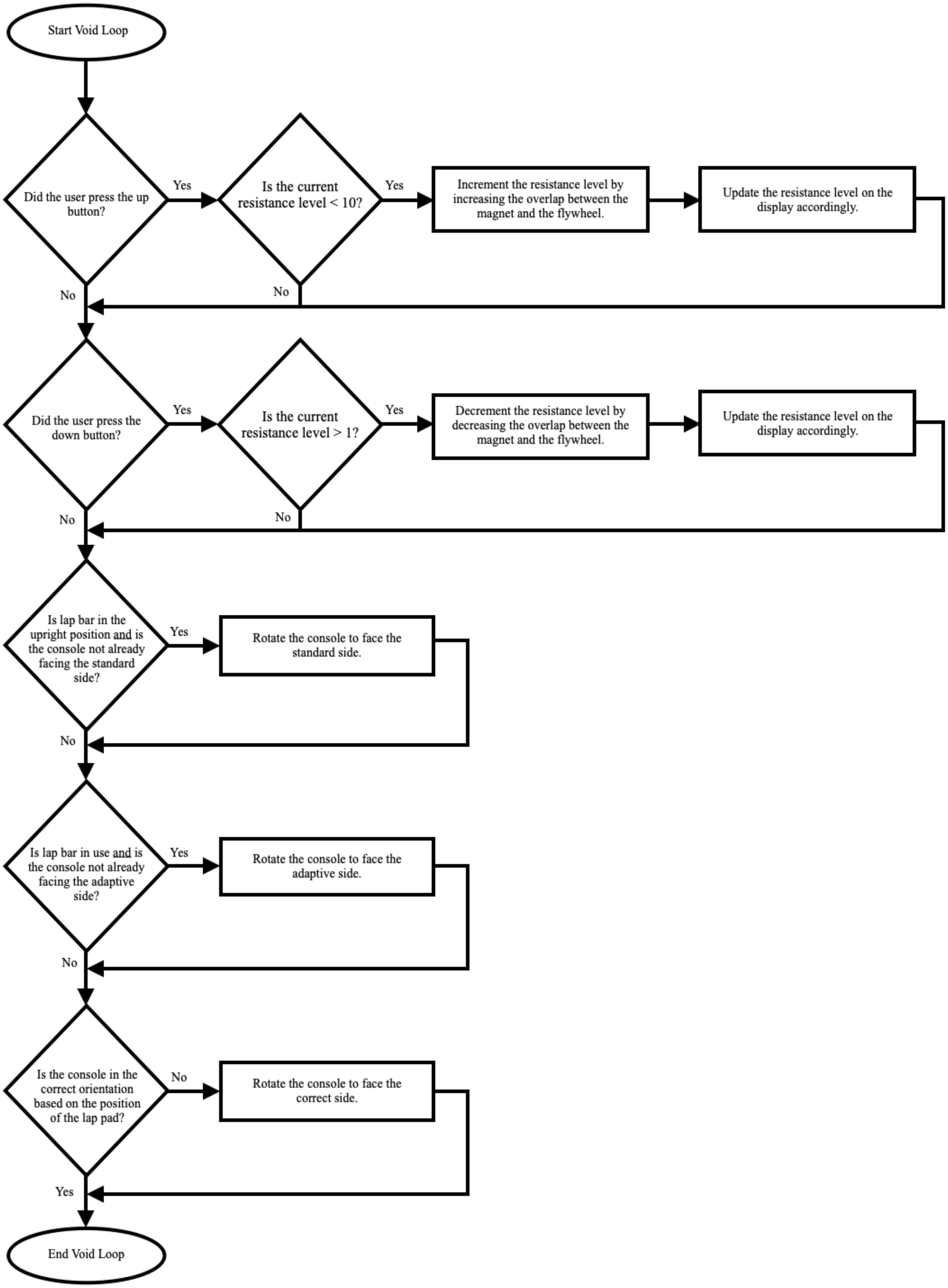
Start Void Loop
Did the user press the up button?
Yes
Is the current resistance level < 10?
Yes
Increment the resistance level by increasing the overlap between the magnet and the flywheel.
Update the resistance level on the display accordingly.
No
No
Did the user press the down button?
Yes
Is the current resistance level > 1?
Yes
Decrement the resistance level by decreasing the overlap between the magnet and the flywheel.
Update the resistance level on the display accordingly.
No
No
Is lap bar in the upright position and is the console not already facing the standard side?
Yes
Rotate the console to face the standard side.
No
Is lap bar in use and is the console not already facing the adaptive side?
Yes
Rotate the console to face the adaptive side.
No
Is the console in the correct orientation based on the position of the lap pad?
No
Rotate the console to face the correct side.
Yes
End Void Loop

Figure 2. Final 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. 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.

Appendix P: BME 402 Final Arduino Code

```
// Written by:  Annabel Frake

// Class:       BME 402

// Purpose:     Rotate the console of a Matrix rowing machine between the standard and adaptive sides. Change the rowing resistance level (between 1 and 10) using up and down buttons. This change modifies the position of the magnet over the flywheel to change the rowing resistance level and updates identical 2 digit 7 segment displays that output the current resistance level.


// Include the necessary libraries.

#include "SevSeg.h"

#include <ezButton.h>;


// Declare digital pins for the up/down buttons. Note: there are two buttons for each, but they are tied to the same pin because their functionality is identical.

byte const upButtonPin = 12;

byte const downButtonPin = 13;


// Declare digital pins for the limit switches.

byte const resistanceLimitSwitchPin = 44; // This limit switch is placed near the magnet fixture such that, when it is depressed, the resistance level is 1.
```

byte const transitionSwitchPin = 45; // This limit switch is placed near the stabilization lap pad bar. When its state changes, the rower transitioned between adaptive and standard use or vice versa. When this limit switch is depressed, the console should be on the standard side and when it is not depressed, the console should be on the adaptive side.

byte const standardSwitchPin = 46; // 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 = 47; // This limit switch is placed near the console on the adaptive side. When it is pressed, the console is facing the wheelchair user.

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

byte const resistanceDirPin = 6;

byte const resistanceStepPin = 7;

byte const consoleDirPin = 8;

byte const consoleStepPin = 9;

// Create ezButton objects for the up and down buttons and the transition limit switch.

ezButton transitionSwitch(transitionSwitchPin);

ezButton upButton(upButtonPin);

ezButton downButton(downButtonPin);

// Create a SevSeg object for the display.

SevSeg sevseg;

// Define the number of steps for one increment of the stepper motor. Note: one rotation is achieved with 200 steps.

int stepsPerIncrement = 1; // Step - corresponds to roughly 3 degrees.

// Define the time delay for the manual PWM of the stepper motors.

```
int resistanceSpeedDelay = 30000; // microseconds 30000

int consoleSpeedDelay = 30000; // microseconds


// Declare a variable for the resistance level. The resistance level is set to 1 at the beginning of the program.

int resistanceLevel = 1;


void setup()

{

  // Initialize the serial port.

  Serial.begin(9600);


  // Set the stepper motor pinmodes to OUTPUT.

  pinMode(resistanceDirPin, OUTPUT);

  pinMode(resistanceStepPin, OUTPUT);

  pinMode(consoleDirPin, OUTPUT);

  pinMode(consoleStepPin, OUTPUT);


  // Set the limit switch pins to INPUT_PULLUP. Note: An internal pull-up 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(resistanceLimitSwitchPin, INPUT_PULLUP);

  pinMode(standardSwitchPin, INPUT_PULLUP);

  pinMode(adaptiveSwitchPin, INPUT_PULLUP);


  // Assign the up and down buttons and the transition limit switch with a debounce time of 50 milliseconds
```

```
  transitionSwitch.setDebounceTime(50);
  upButton.setDebounceTime(50);
  downButton.setDebounceTime(50);

  // Define pins for the two 2 digit 7 segment displays. Because they display the same output, they are connected to the same digital out pins.
  byte numDigits = 2;
  byte digitPins[] = {27, 26}; // {D2, D1}
  byte segmentPins[] = {28, 29, 30, 31, 32, 33, 34}; // {A, B, C, D, E, F, G}

  // Define characteristics for the two 2 digit 7 segment displays.
  bool resistorsOnSegments = true;
  bool updateWithDelaysIn = true;
  byte hardwareConfig = COMMON_ANODE;
  sevseg.begin(hardwareConfig, numDigits, digitPins, segmentPins, resistorsOnSegments);
  sevseg.setBrightness(90);

  // Set the resistance level to 1.
  setResistance();
}

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

```
 transitionSwitch.loop();


  // If the up button is pressed and the resistance level is less than 10, increment the resistance level. Note: .isReleased() must be used instead of .isPressed() or the code will implement twice.
 if (upButton.isReleased() && resistanceLevel < 10)
 {
   // Call the function that increments the position of the magnet over the flywheel.
   resistanceLevel = increment();


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


   // If the down button is pressed and the resistance level is greater than 1, decrement the resistance level. Note: .isReleased() must be used instead of .isPressed() or the code will implement twice.
 if (downButton.isReleased() && resistanceLevel > 1)
 {
   // Call the function that decrements the position of the magnet over the flywheel.
   resistanceLevel = decrement();


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


  // 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())
  {
     // Blank the displays so that they do not behave abnormally due to the delays within the motor logic. Also signifies to the user that they cannot change the resistance during that time
    sevseg.blank();

    // 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())
  {
     // Blank the displays so that they do not behave abnormally due to the delays within the motor logic. Also signifies to the user that they cannot change the resistance during that time
    sevseg.blank();

    // 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 and ensure it is in the correct orientation.
  else
  {
    //sevseg.blank();
```

```
    checkConsolePosition();
  }

  // Update the output of the display to accurately portray the current resistance level.
  sevseg.setNumber(resistanceLevel);
  sevseg.refreshDisplay(); // Refresh the display so that the change is registered.
}

// A function to rotate the magnet such that the resistance level is incremented once.
int increment()
{
  // Specify the direction the motor will rotate: counterclockwise.
  digitalWrite(resistanceDirPin, LOW);

  // Rotate the motor by stepsPerIncrement.
  for (int i = 0; i < stepsPerIncrement; i++)
  {
    // Manually perform PWM.
    digitalWrite(resistanceStepPin, HIGH);
    delayMicroseconds(resistanceSpeedDelay); // Determines speed of stepper motor.
    digitalWrite(resistanceStepPin, LOW);
    delayMicroseconds(resistanceSpeedDelay); // Determines speed of stepper motor.
  }

  // Increment the resistance level by one.
  return resistanceLevel += 1;
```

```
}

// A function to rotate the magnet such that the resistance level is decremented once.
int decrement()
{
  // Specify the direction the motor will rotate: clockwise.
  digitalWrite(resistanceDirPin, HIGH);

  // Rotate the motor by stepsPerIncrement.
  for (int i = 0; i < stepsPerIncrement; i++)
  {
    // Manually perform PWM.
    digitalWrite(resistanceStepPin, HIGH);
    delayMicroseconds(resistanceSpeedDelay); // Determines speed of stepper motor.
    digitalWrite(resistanceStepPin, LOW);
    delayMicroseconds(resistanceSpeedDelay); // Determines speed of stepper motor.
  }

  // Decrement the resistance level by one.
  return resistanceLevel -= 1;
}

// A function to set the resistance level to 1. Note: This code only implements once in void setup to ensure that the resistance level is known when the program starts.
void setResistance()
{
```

```
  // Specify the direction the motor will rotate: clockwise.
  digitalWrite(resistanceDirPin, HIGH);

  // Rotate the motor in the specified direction until the limit switch is depressed, indicating a resistance level of 1.
    while (digitalRead(resistanceLimitSwitchPin)) // Note: logic is flipped because of INPUT_PULLUP.
  {
    // Manually perform PWM.
    digitalWrite(resistanceStepPin, HIGH);
    delayMicroseconds(resistanceSpeedDelay); // Determines speed of stepper motor.
    digitalWrite(resistanceStepPin, LOW);
    delayMicroseconds(resistanceSpeedDelay); // Determines speed of stepper motor.
  }

  Serial.println("Resistance Level Set to 1");

  // Update the output of the display to accurately portray the current resistance level.
  sevseg.setNumber(resistanceLevel);
  sevseg.refreshDisplay(); // Refresh the display so that the change is registered.
}

// 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(consoleDirPin, LOW);
```

```
  // 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(consoleStepPin, HIGH);
    delayMicroseconds(consoleSpeedDelay); // Determines speed of stepper motor.
    digitalWrite(consoleStepPin, LOW);
    delayMicroseconds(consoleSpeedDelay); // Determines speed of stepper motor.
  }

  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(consoleDirPin, HIGH);

  // 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(consoleStepPin, HIGH);
```

```
    delayMicroseconds(consoleSpeedDelay); // Determines speed of stepper motor.
    digitalWrite(consoleStepPin, LOW);
    delayMicroseconds(consoleSpeedDelay); // Determines speed of stepper motor.
  }

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

// A function that checks the current position of the console and corrects its orientation if a discrepancy is detected.
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.
  {
     // Blank the displays so that they do not behave abnormally due to the delays within the motor logic. Also signifies to the user that they cannot change the resistance during that time.
    sevseg.blank();

    // 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.
  {
    // Blank the displays so that they do not behave abnormally due to the delays within the motor logic. Also signifies to the user that they cannot change the resistance during that time.
    sevseg.blank();


    // Call the function that rotates the console to face the adaptive side.
    rotateToAdaptive(adaptiveSwitchPin);
  }
}
```

Appendix Q: Electronic Testing Protocols and Results

Console Testing Protocol:

- To test the functionality of the console circuit and code, induce the following edge cases and record the rotation (or lack thereof) of the console. Record “pass” if the circuit operates according to the expected outcome. Otherwise, record “fail”. Repeat each edge case three times.
- Ignore the behavior of the resistance mechanism; that will be tested in the adaptive resistance mechanism testing protocol.
    - Edge Case 1:
        - 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.
        - Apply power.
        - Expected outcome: The console rotates to adaptive side.
        - Recorded observation: The console rotates to adaptive side.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 2:

        - 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.
        - Apply power.
        - Expected outcome: The console rotates to standard side.
        - Recorded observation: The console rotates to standard side.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 3:
        - 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.
        - Apply power.
        - Expected outcome: 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.
        - Recorded observation: 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.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 4:
        - 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.
        - Apply power.
        - Expected outcome: 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 adaptive side.
        - Recorded observation: 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 adaptive side.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 5:

        - 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.
        - Apply power.
        - Expected outcome: The console rotates to standard side.
        - Recorded observation: The console rotates to standard side.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 6:
        - 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.
        - Apply power.
        - Expected outcome: The console rotates to adaptive side.
        - Recorded observation: The console rotates to adaptive side.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 7:
        - Apply power.
        - 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.
        - Expected outcome: 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.
        - Recorded observation: 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.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 8:
        - Apply power.
        - 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.

- Expected outcome: 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.
- Recorded observation: 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.
- Pass/Fail: Pass, Pass, Pass

<u>Adaptive Resistance Mechanism Testing Protocol:</u>

- To test the functionality of the adaptive resistance mechanism circuit and code, induce the following edge cases and record the system's behavior. Record pass if the circuit operates according to the expected outcome. Otherwise, record fail. Repeat each edge case 3 times.
- Ignore the behavior of the console; that will be tested in the console protocol.
    - Edge Case 1:
        - Before power application: Manually rotate the magnet fixture such that the resistance level is greater than one (a.k.a. the adaptive resistance mechanism limit switch is not pressed).
        - Apply power.
        - Expected outcome: The magnet fixture rotates clockwise (relative to the motor side) until it triggers the adaptive resistance mechanism limit switch, at which point, the fixture stops moving. The display outputs a value of "1."
        - Recorded observation: The magnet fixture rotates clockwise (relative to the motor side) until it triggers the adaptive resistance mechanism limit switch, at which point, the fixture stops moving. The display outputs a value of "1."
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 2:

        - Before power application: Manually rotate the magnet fixture such that the resistance level is at one (a.k.a. the adaptive resistance mechanism limit switch is pressed).
        - Apply power.
        - Expected outcome: The magnet fixture remains stationary. The display outputs a value of "1."
        - Recorded observation: The magnet fixture remains stationary. The display outputs a value of "1."
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 3:
        - Apply power.
        - After power application: Increment the resistance by pressing the up arrow on the standard side of the machine. Ensure that the display outputs values "1" through "10" and that the resistance cannot be incremented above a value of "10." Decrement the resistance by pressing the down arrow on the standard side of the machine. Ensure that the display outputs values "10" down to "1" and that the resistance cannot be incremented below a value of "1."
        - Expected outcome: The display outputs the following sequence: "1 2 3 4 5 6 7 8 9 10 9 8 7 6 5 4 3 2 1."
        - Recorded observation: The display outputs the following sequence: "1 2 3 4 5 6 7 8 9 10 9 8 7 6 5 4 3 2 1." The display cannot be increased past 10 nor decrease below 1.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 4:
        - Apply power.
        - After power application: Increment the resistance by pressing the up arrow on the adaptive side of the machine. Ensure that the display outputs values "1" through "10" and that the resistance cannot be incremented above a value of "10." Decrement the resistance by pressing the down arrow on the adaptive side of the machine. Ensure that the display outputs values "10" down to "1" and that the resistance cannot be incremented below a value of "1."

        - Expected outcome: The display outputs the following sequence: "1 2 3 4 5 6 7 8 9 10 9 8 7 6 5 4 3 2 1."
        - Recorded observation: The display outputs the following sequence: "1 2 3 4 5 6 7 8 9 10 9 8 7 6 5 4 3 2 1." The display cannot be increased past 10 nor decreased below 1.
        - Pass/Fail: Pass, Pass, Pass
    - Edge Case 5:
        - Apply power.
        - After power application: Increment the resistance by pressing the up arrow on either the standard or adaptive side of the machine. Ensure that the magnet fixture rotates counterclockwise (relative to the motor side) by roughly 3 degrees each button press. Decrement the resistance by pressing the down arrow on either the standard or adaptive side of the machine. Ensure that the magnet fixture rotates clockwise (relative to the motor side) by roughly 3 degrees each button press.
        - Expected outcome: The motor rotates roughly 27 degrees (9 increments at 3 degrees each) clockwise. The motor then rotates roughly 27 degrees (9 increments at 3 degrees each) counterclockwise.
        - Recorded observation:
            - resistance 1 to 2: incremented 1 degree
            - resistance 2 to 3: incremented 4 degrees
            - resistance 3 to 4: incremented 1 degree
            - resistance 4 to 5: incremented 2 degrees
            - resistance 5 to 6: incremented 1 degree
            - resistance 6 to 7: incremented 2 degrees
            - resistance 7 to 8: incremented 1 degree
            - resistance 8 to 9: incremented 2 degrees
            - resistance 9 to 10: incremented 2 degrees
            - average: 1.78 degrees
            - standard deviation: 0.97 degrees
        - Pass/Fail: Fail, Fail, Fail
        - Note: The reason for the wide variation is currently unknown. Such inconsistency should be addressed in future iterations of the design.

- Edge Case 6:
  - Apply power.
  - After power application: Increment/decrement the resistance by pressing the up arrow/down on either the standard or adaptive side of the machine while the flywheel is in motion.
  - Expected outcome: The motor rotates the appropriate amount (in degree increments) in the appropriate direction based on the input to the system regardless of whether the flywheel is in motion or not.
  - Recorded observation: N/A ** In hindsight, this is essentially the same as edge case 5, so we did not complete this edge case separately **
  - Pass/Fail: N/A ** In hindsight, this is essentially the same as edge case 5, so we did not complete this edge case separately **

<u>Combined Circuitry Testing Protocol:</u>

- To test the functionality of the overall circuit and code, induce the following edge cases and record the behavior of the system. Record pass if the circuit operates according to the expected outcome. Otherwise, record fail. Repeat each edge case 3 times.
- This protocol only tests the interaction between the console system and the adaptive resistance mechanism. To test the individual functionality of the independent systems, see the previous protocols.
  - Edge Case 1:
    - Apply power.
    - After power application: Increment/decrement the resistance by pressing the up arrow/down on either the standard or adaptive side of the machine. Immediately after an up/down button is pressed (assuming the button press is not outside the bounds of the system - i.e. 1 through 10), induce rotation of the console.
      - Note: It may be difficult to induce rotation of the console immediately after an up/down button press (ideally while the magnet fixture is still in motion) because the magnet fixture moves quickly. Try your best to achieve the ideal testing parameters, but this edge case is unlikely to occur in standard use of the device, so it is not the most important edge case to study.

        - Expected outcome: The magnet fixture increments/decrements appropriately and the correct value is outputted on the displays. The console rotates appropriately based on the input to the system.
        - Recorded observation: N/A **Unable to test because the motor moved too quickly for human reaction times **
        - Pass/Fail: N/A **Unable to test because the motor moved too quickly for human reaction times **
    - Edge Case 2:
        - Apply power.
        - After power application: Induce rotation of the console and while it is rotating, try to change the resistance level.
        - Expected outcome: The displays are blank while the console is rotating. The magnet fixture remains stationary.
        - Recorded observation: The displays are blank while the console is rotating. The magnet fixture remains stationary.
        - Pass/Fail: Pass, Pass, Pass

Appendix R: BME 402 Participant 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 Human SpikerBox EMG machine into a power source/outlet. Plug the three electrode cable into the channel input of the Human SpikerBox device.
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 body in the anatomical position. Place two electrodes on the muscle belly of the bicep in a tangential position relative to each other. Place the third electrode on the forearm of the user, removed from the two other electrodes.
9. Connect the 2 red leads to the two tangential electrodes. Connect the black lead to the forearm electrode
10. Adjust the settings on the console to display stroke rate.
11. Turn on the Human SpikerBox EMG machine. Adjust the bandpass filter in order to record the full electric signal.
12. Have the user turn the resistance dial to level 1.
13. Have the user grab the handlebar with both hands and lift vertically upward to remove the handlebar from the supports.
14. 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 15 seconds.
    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.
    b. Give user 3 strokes to get in rhythm before recording the EMG signals.
15. Once the time trial is complete, slowly and gently place the handlebar back within the supports.
16. Rest for 30 seconds.
17. Repeat steps 11-15 at resistance levels 5 and 10.
18. 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.
19. Repeat steps 6-17 two more times to record EMG signals of the deltoid and latissimus dorsi. Electrode position will vary in step 8.
    a. Lattisimus doris: 2 recording tangential electrodes following the direction of the muscle fibers in the muscle belly. Reference electrode on shoulder blade.
    b. Deltoid: 2 recording tangential electrodes following the direction of the muscle fibers in the muscle belly. Reference electrode on the tricep.
20. Turn off the EMG machine and unplug from the power supply.
21. 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.
22. Unlock the wheelchair wheels and have the user slowly roll away from the rower.
23. 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 15-30 seconds.
    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 time trial is complete, slowly and gently place the handlebar back within the supports.
10. Rest for 30 seconds.
11. Repeat steps 6-10 at resistance levels 5 and 10 (or the highest resistance the participant is comfortable with).
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 Human SpikerBox EMG machine into a power source/outlet. Plug the three electrode cable into the channel input of the Human SpikerBox device.
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 body in the anatomical position. Place two electrodes on the muscle belly of the bicep in a tangential position relative to each other. Place the third electrode on the forearm of the user, removed from the two other electrodes.
8. Connect the 2 red leads to the two tangential electrodes. Connect the black lead to the forearm electrode
9. Adjust the settings on the console to display the stroke rate.
10. Turn on the Human SpikerBox EMG machine. Adjust the bandpass filter in order to record the full electric signal.
11. Set resistance dial to 1.
12. Have the user lean forward to grab the handlebar with two hands from its position in the original Matrix rower handlebar resting position.
13. 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 15 seconds.
    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.
    b. Give user 3 strokes to get in rhythm before recording the EMG signals.
14. Once the time trial is complete, slowly and gently place the handlebar back in the supports.
15. Rest for 30 seconds.
16. Repeat steps 11-14 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 5-17 two more times to record EMG signals of the deltoid and latissimus dorsi. Electrode position will vary in step 7.
    a. Lattisimus doris: 2 recording tangential electrodes following the direction of the muscle fibers in the muscle belly. Reference electrode on shoulder blade.
    b. Deltoid: 2 recording tangential electrodes following the direction of the muscle fibers in the muscle belly. Reference electrode on the tricep.
19. Turn off the EMG machine and unplug from the power supply.

20. 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.
21. 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.
22. 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 15-30 seconds.
    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 time trial is complete, slowly and gently place the handlebar back in the supports.
9. Rest for 30 seconds.
10. Repeat steps 5-9 at resistance levels 5 and 10 (or the highest resistance the participant is comfortable with).
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 S: 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
☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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
☐ 1	☐ 2	☐ 3	☐ 4	☐ 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 T: BME 402 IRB Miscellaneous Documents

1. **Consent Form**

University of Wisconsin-Madison
Consent to Participate in Research

TITLE OF STUDY: Matrix Adaptive Rowing Assessment

PRINCIPAL INVESTIGATOR
Tracy Jane Puccinelli
UW-Madison Department of Biomedical Engineering
(608) 265-8267
tracy.puccinelli@wisc.edu

Institution: University of Wisconsin

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.

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. We invite you to take part in the research study because you are capable of using the Matrix rowing machine.

What will I need to do in this study?
The research team will ask you to use the Matrix Adaptive Rowing Machine and provide feedback about the experience via a survey. You will row on either the standard, adaptive, or both sides of the rower depending on your physical capabilities (i.e., if you require the use of a wheelchair or not). You will perform three trials per side, if applicable, for one minute each on different resistances and a break in between trials. Some participants which are capable of utilizing both sides of the rower (no wheelchair use) will wear electromyogram (EMG) leads to detect muscle group activation on both sides of the rowing machine. We expect that you will be in this research study for 1-2 hours in a single day.

What are some reasons I might – or might not – want to be in this study?

You may want to be in this study if you are:	You may NOT want to be in this study you are:
· Willing to give 1-2 hours of your time for the study with no immediate benefit. · Interested in contributing to scientific knowledge even though you won't benefit directly from the study. · Interested in the development of adaptive exercise equipment which increases gym inclusivity by accommodating individuals in wheelchairs.	· Not comfortable performing a moderate rowing workout. · May not have time to complete study questionnaires. · Not willing to experience possible temporary soreness after exercise, depending on your fitness level at the time of the study.

Do I have to be in the study?
No, you do not have to be in this study. Participation in this research study is voluntary, and it is your choice whether or not to take part in this research. If you decide not to be in this study, your choice will not affect your healthcare or any services you receive. There will be no penalty to you. You can ask all the questions you want before you decide. Participation in this study will not affect your grade, class standing, or status in your program.

Detailed Information

How is research different from healthcare?
When you take part in a research study you are helping to answer a research question. Study tests and procedures are not for your health care.

Who can I talk to about this study?

If you have questions, concerns, or complaints, or think that participating in the research has hurt you, can contact Tracy Jane Puccinelli, the Principal Investigator, whose contact information is listed on the first page of the consent form.

If you have any questions about your rights as a research participant or have complaints about the research study or study team, call the confidential research compliance line at 1-833-652-2506. Staff will work with you to address concerns about research participation and assist in resolving problems.

If I take part in the study, what will I do?
This study will be collecting user feedback on the newly developed Matrix Adaptive Rowing Machine which accommodates individuals in and out of wheelchairs. This study will be conducted at the University of Wisconsin-Madison in the Engineering Centers Building.
While participating in this study, you will follow the printed protocol to interact with the rowing machine and complete three one-minute trials on different resistances. The research team may take photos of you while using the rowing machines for a final report of the study, and some participants which are able to use both the standard and adaptive sides of the rower may utilize EMG leads during testing. No data will be collected while rowing. Following the completion of the trials, data collection will occur via survey feedback from participants about their experience using the machine. The study will take 1-2 hours at most to complete.

What happens if I say yes, but I change my mind later?
You can leave the research at any time. If you choose to leave the study, your choice will not affect your healthcare or any services you receive. Your grade, class standing, or status in your program will not be affected by your choice to participate in the study or not. No matter what decision you make, and even if your decision changes, there will be no penalty to you. You will not lose medical care or any legal rights.

Will being in this study help me in any way?
Being in this study will not help you directly. Your participation in the study may benefit other people in the future by helping us learn more about adaptive exercise equipment.

What are the study risks?
The most common discomfort associated with rowing activity is potential muscle fatigue and soreness depending on the fitness and activity levels of each individual participant.

Participants which will use electromyogram (EMG) leads with surface electrodes have potential electrical safety hazards. The most common risk is minor irritation of the skin where the electrode was placed.

The adaptive side use also poses risk of wheelchair tipping while exercising, although there is a stabilization frame to secure the user and their wheelchair. This could result in head or limb injuries and bruising, although unlikely.

What happens to the information collected for the research?

We have strict rules to protect your personal information. We will limit the use and disclosure of your personal information, including research study and medical records, to people who have a need to review this information.

However, we cannot promise complete confidentiality. Federal or state laws may permit or require us to show information to university or government officials (and to study sponsors) responsible for monitoring this study. This includes University of Wisconsin and its representatives and affiliates, including those responsible for monitoring or ensuring compliance, such as the Human Research Protection Program. We may also have to tell appropriate authorities, such as health care providers, if we learn during the study that you or others are at risk of harm.

Will information from this study go in my medical record?

None of the information we collect for this study will go in your medical record.

What else do I need to know?

What happens if I am injured or get sick because of this study?

If you are injured because of this study, medical care is available to you through UW Health, your local provider, or emergency services, as it is to all sick or injured people.

• If it is an emergency, call 911 right away or go to the emergency room.

• For non-emergency medical problems, please contact your regular health care provider.

• Call the Lead Researcher, Tracy Jane Puccinelli at (608) 265-8267 to report your sickness or

injury.

Here are some things you need to know if you are injured because of this research:

• If the sickness or injury requires medical care, the costs for the care will be billled to you or your insurance, just like any other medical costs.

• Your health insurance company may or may not pay for this care.

• No other compensation (such as lost wages or damages) is usually available.

• UW-Madison and UW Health do not have a program to pay you if you get sick or are injured because of this study.

• By signing this consent form and taking part in this study, you are not giving up any legal rights you may have. You keep your legal rights to seek payment for care required because of a sickness or injury resulting from this study.

Will I receive anything for participating?

Participants will not be paid for participating.

How many people will be in this study?

We expect about 7–15 people will be in this research study.

Agreement to participate in the research study

You do not have to sign this form. If you refuse to sign, however, you cannot take part in this research study. If you sign the line below, it means that:

● You have read this consent and authorization form.

● You have had a chance to ask questions about the research study, and the researchers have answered your questions.

● You want to be in this study.

Signature of participant ____ Date______

Printed name of participant ____

Signature of person obtaining consent _____________________________Date ______

Printed name of person obtaining consent_____________________________________

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.

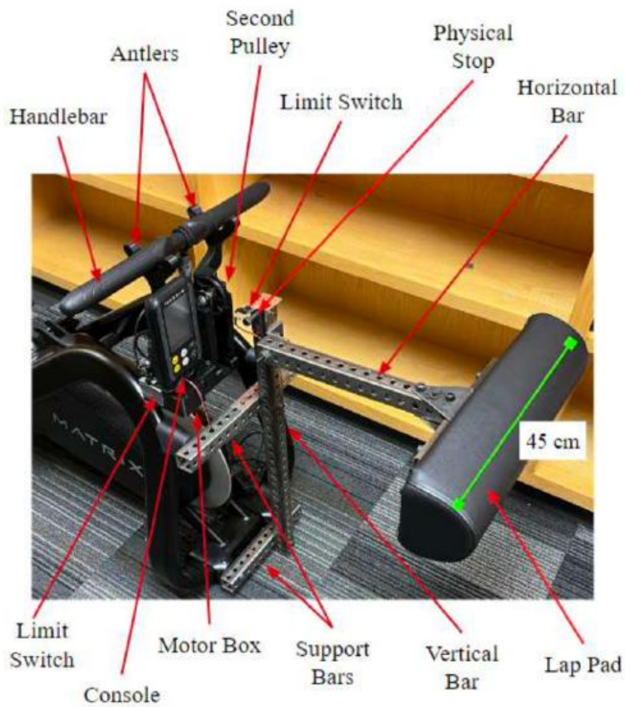

Figure 1. Prototype Assembly. The prototype assembly includes the pulley support plates with antlers, the console rotation mechanism and electronics box, and the metal adjustable stabilization frame. Please note that in the final product (will be fabricated in the coming weeks), the stabilization frame 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.

Appendix U: BME 402 Final Prototype Images

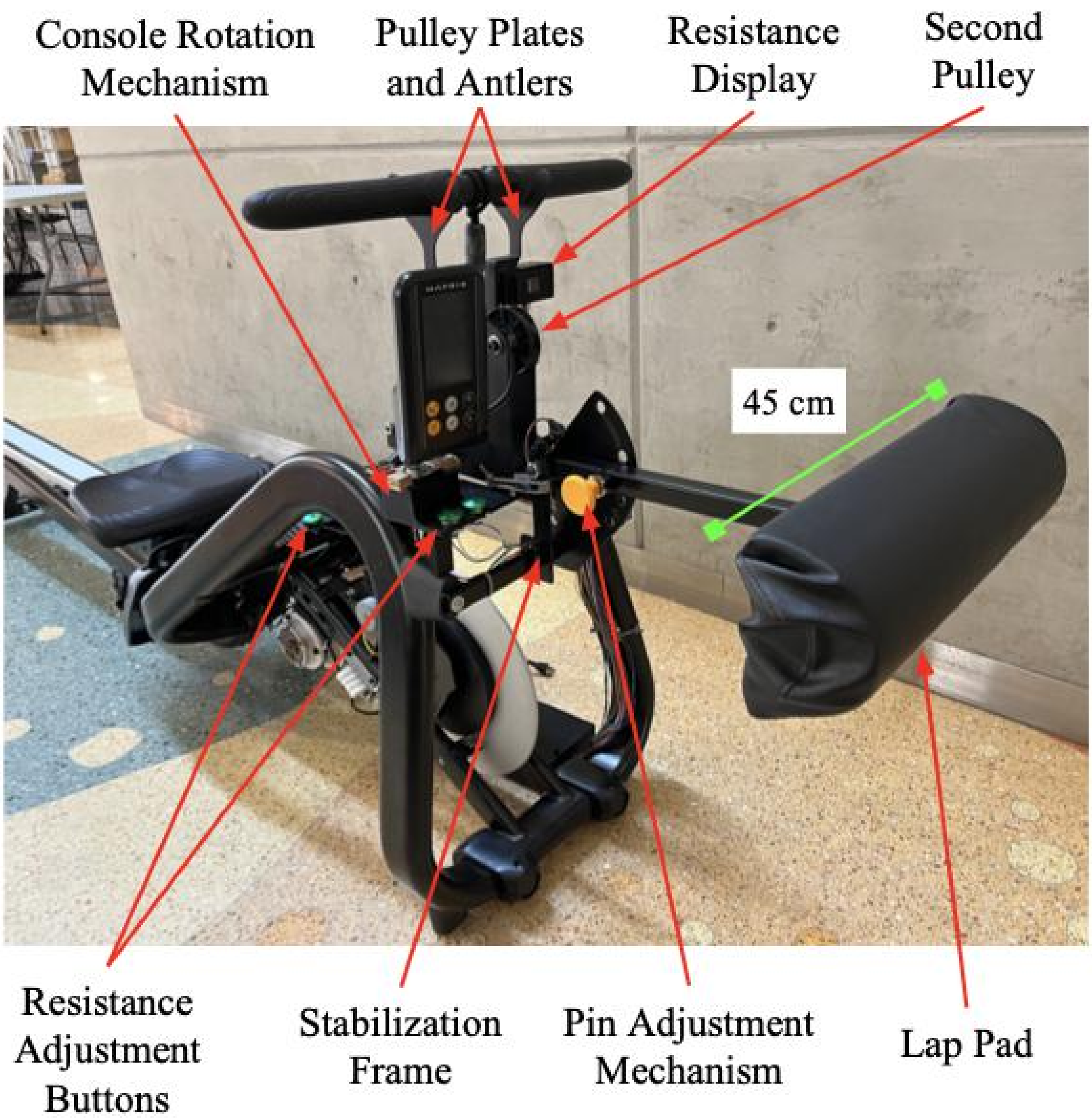

Figure 1. Full Assembly Isometric View. The final design consists of two antler-like structures and associated second pulley, a stabilization frame, a console rotation mechanism, and a resistance adjustment mechanism. All labels call out design components that were either created entirely from scratch or modified from the original version for the purposes of this project.

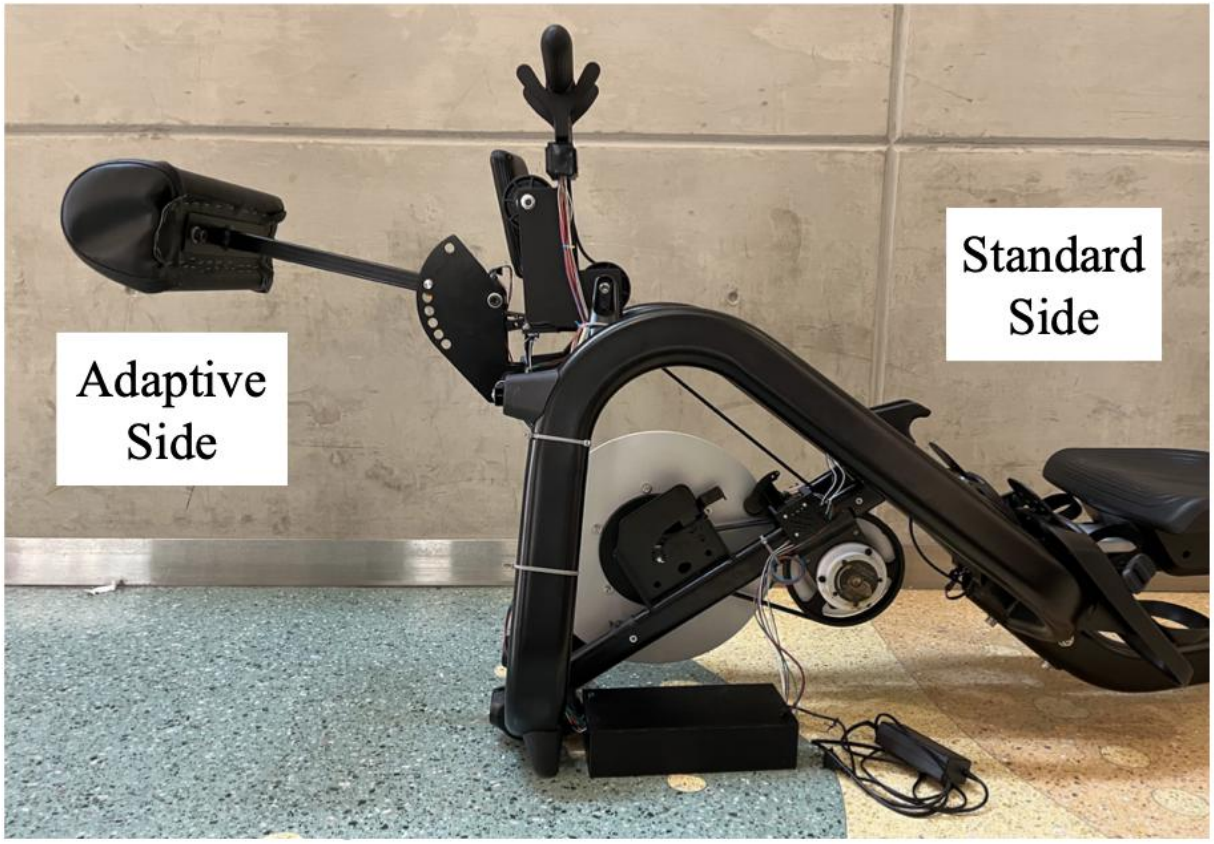

Figure 2. Full Assembly Side View. The final design consists of two antler-like structures and associated second pulley, a stabilization frame, a console rotation mechanism, and a resistance adjustment mechanism. The standard side of the machine is defined as the side with the sliding seat while the adaptive side of the machine is defined as the one with the stabilization frame.

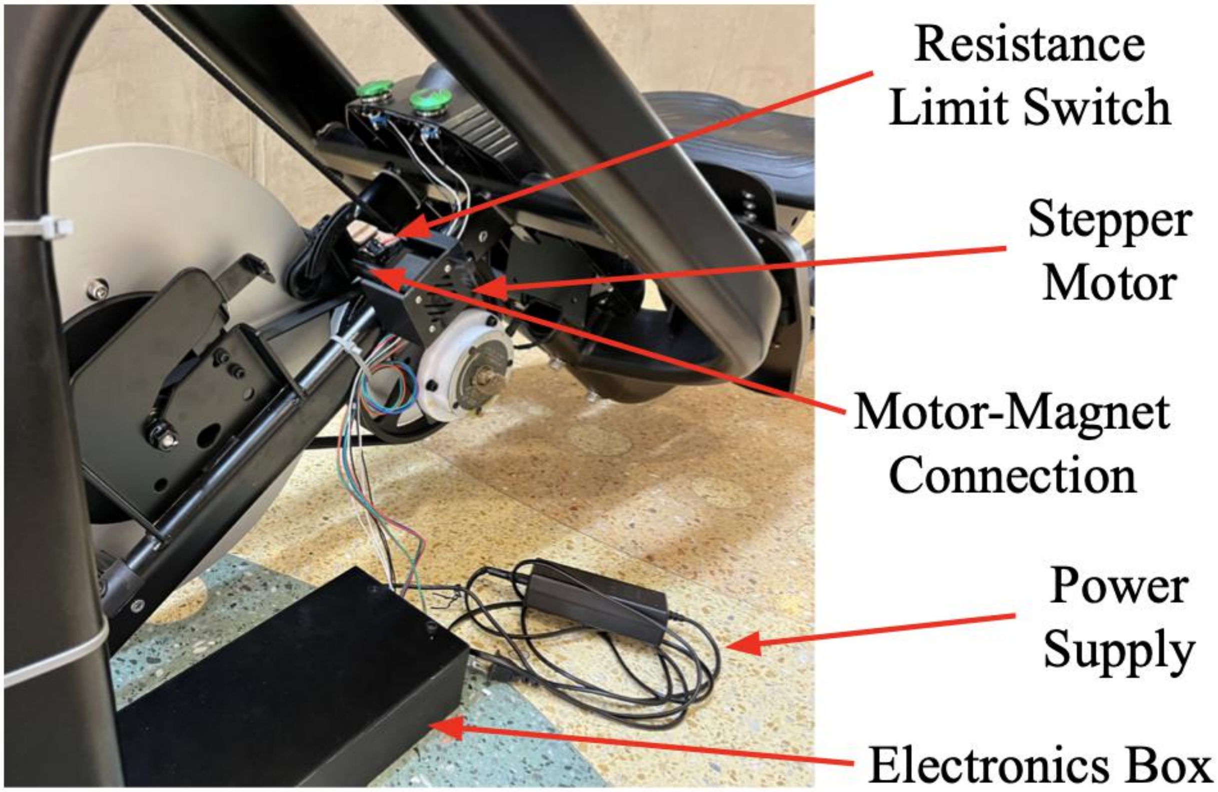

Figure 3. Resistance Adjustment Mechanism. The resistance adjustment mechanism consists of a stepper motor and associated housing, a limit switch, and the pre-existing magnet housing. At the onset of power, the system resets the resistance level to one, and that value can subsequently be changed via push buttons on the standard and adaptive sides of the machine. The electronic components controlling the behavior of this mechanism are housed within the electronics box. All labels call out design components that were either created entirely from scratch or modified from the original version for the purposes of this project.

Appendix V: BME 402 EMG Testing and Results

In an attempt to compare the levels of muscle activation on both the standard and adaptive sides of the adaptive rowing machine, EMG testing was performed on one subject using the Human SpikerBox. As noted in the PDS, similar levels of muscle activation are desired between the standard and adaptive sides of the rowing machine to confirm that comparable upper body workouts can be achieved on both sides. The bicep, rear deltoid, and latissimus dorsi muscle groups were examined during testing. The protocol followed for the EMG testing can be found in **Appendix R**. Muscle group activation profiles were first captured on the standard side of the rowing machine, and then on the adaptive side.

After the muscle activation profiles were collected for each respective muscle group on both sides of the machines, the images were analyzed using the Spike Recorder analysis software (see **Appendix W**). For each activation profile, a frequency filter between 10-500 Hz was utilized to remove noise (**Figure 1)**. Additionally, for each activation profile, the approximate maximum amplitude was calculated from the average waveform. The results from the EMG testing and analysis showed that there was a fairly consistent increase in exertion when increasing the resistance for the following: standard side bicep, standard side latissimus dorsi, and adaptive side latissimus dorsi. The adaptive side bicep, standard side rear deltoid, and adaptive side rear deltoid did not have notable relationships between resistance and maximum amplitude of activation. Between both sides of the machine, the latissimus dorsi muscle group had higher levels of activation on the standard side than on the adaptive side for each respective resistance level. The same trend was not observed for the other experimental conditions.

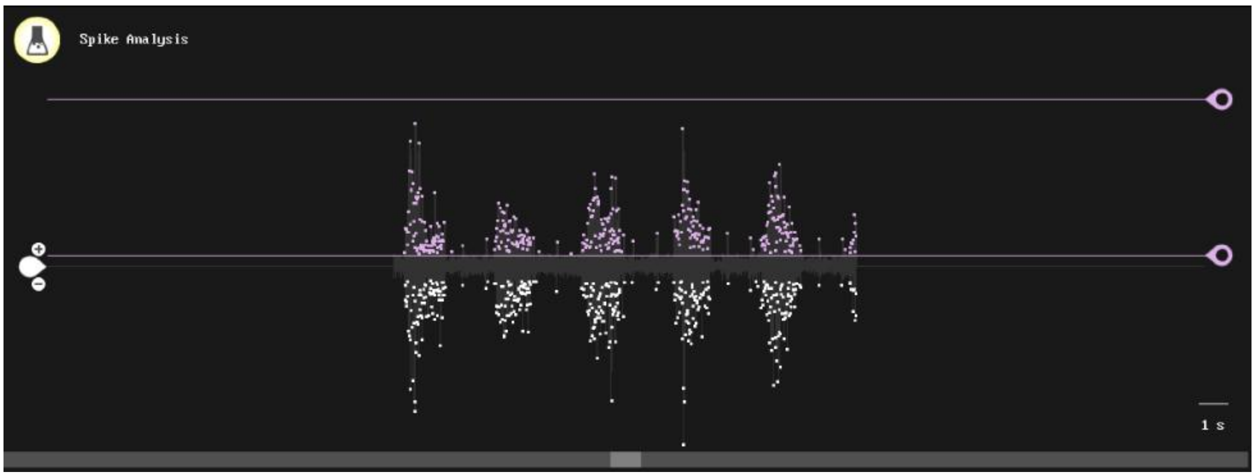

Figure 1. Muscle Activation Profile. For each trial, muscle activation profiles were recorded. Frequency filters of greater than 10 Hz and less than 500 Hz were utilized to remove noise from each profile.

There could have been a few errors associated with the procedure. First, only one individual was tested, which is not representative of the general population. Additionally, there may have been inconsistencies with the rowing rate and level of exertion output by the testing subject over the course of a given trial. Lastly, for the analysis, utilizing improper frequency filters when using the EMG machine could have led to data points being cut out during the analysis that were important to the average waveform calculation.

In order to improve the EMG testing and analysis, more users could be included to increase the amount of data and information collected. Additionally, the duration of each trail could be increased to improve the consistency between rowing strokes. This change would also improve the consistency regarding the rowing rate performed for each trial. To ensure that all vital data points are included for the calculation of average waveforms, more specific frequency filters could be utilized specific for each muscle group.

Appendix W: BME 402 EMG Average Waveform Graphs

Standard Bicep

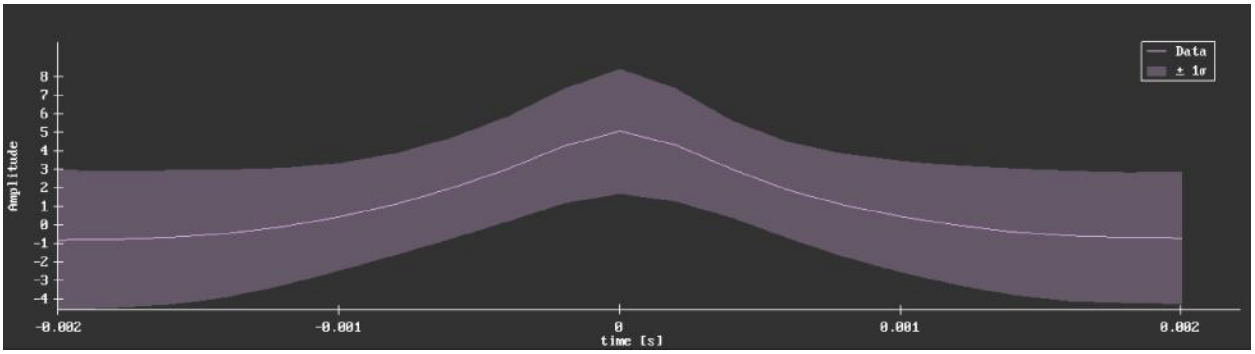

Figure 1. Standard Side Bicep Resistance 1 Average Waveform. The standard side bicep waveform on resistance 1 had a maximum amplitude around 5.

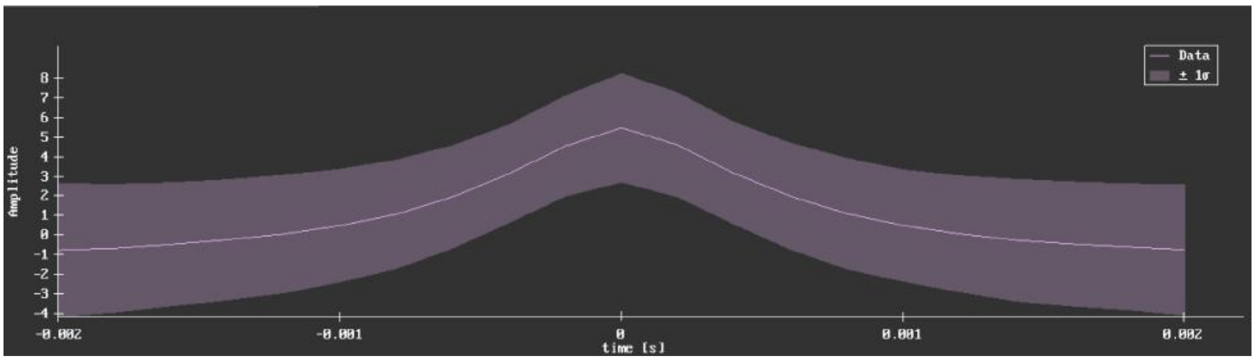

Figure 2. Standard Side Bicep Resistance 3 Average Waveform. The standard side bicep waveform on resistance 3 had a maximum amplitude around 5.5.

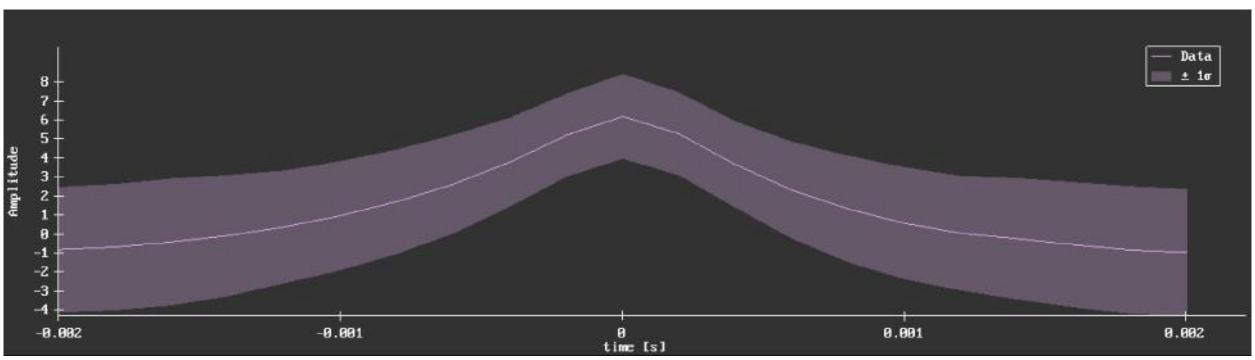

Figure 3. Standard Side Bicep Resistance 5 Average Waveform. The standard side bicep waveform on resistance 5 had a maximum amplitude around 6.

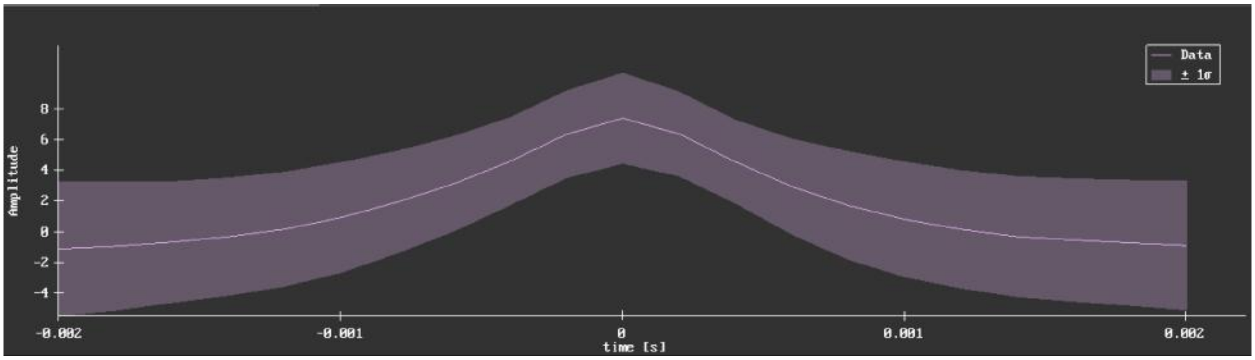

Figure 4. Standard Side Bicep Resistance 7 Average Waveform. The standard side bicep waveform on resistance 7 had a maximum amplitude around 7.5.

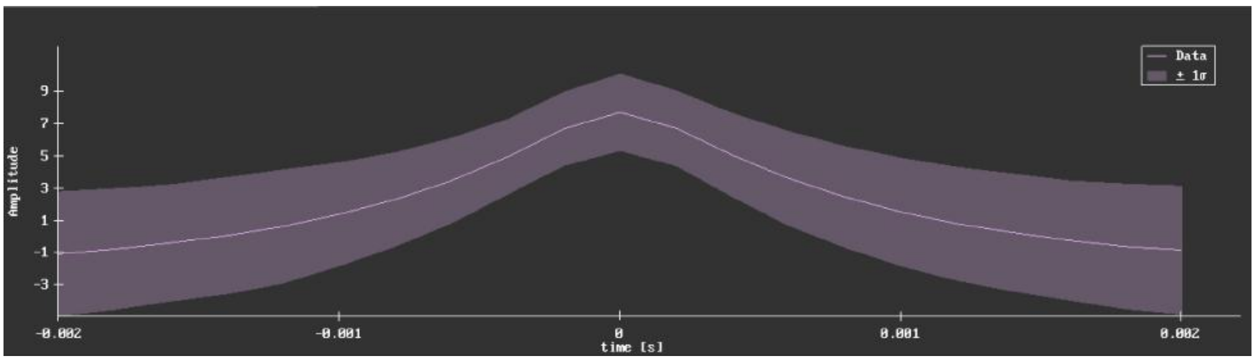

Figure 5. Standard Side Bicep Resistance 9 Average Waveform. The standard side bicep waveform on resistance 9 had a maximum amplitude around 8.

<u>Adaptive Bicep</u>

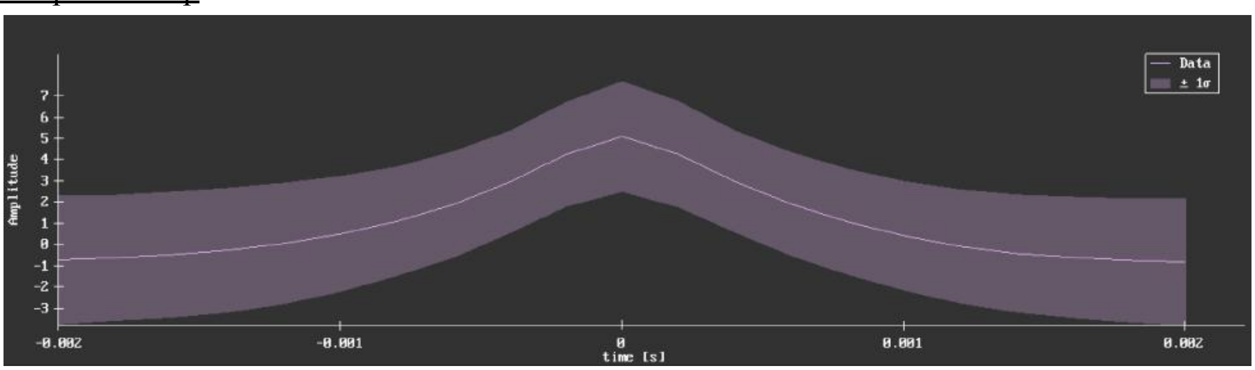

Figure 6. Adaptive Side Bicep Resistance 1 Average Waveform. The adaptive side bicep waveform on resistance 1 had a maximum amplitude around 5.

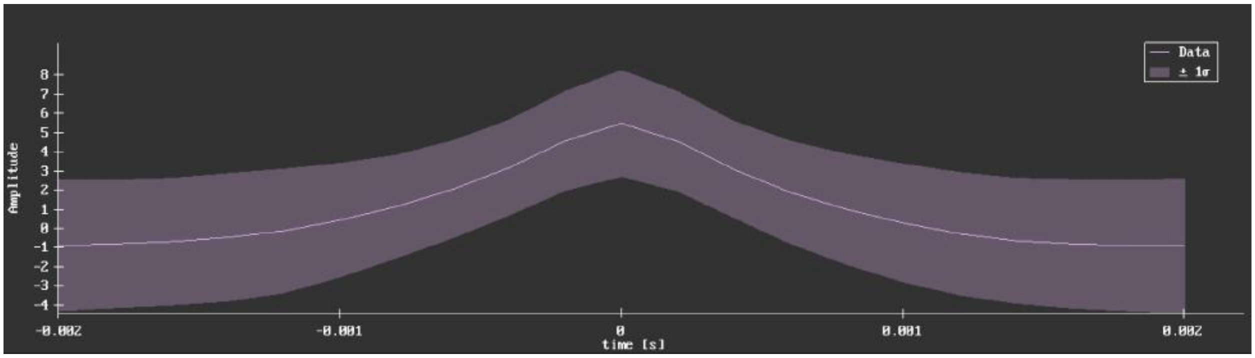

Figure 7. Adaptive Side Bicep Resistance 3 Average Waveform. The adaptive side bicep waveform on resistance 3 had a maximum amplitude around 5.5.

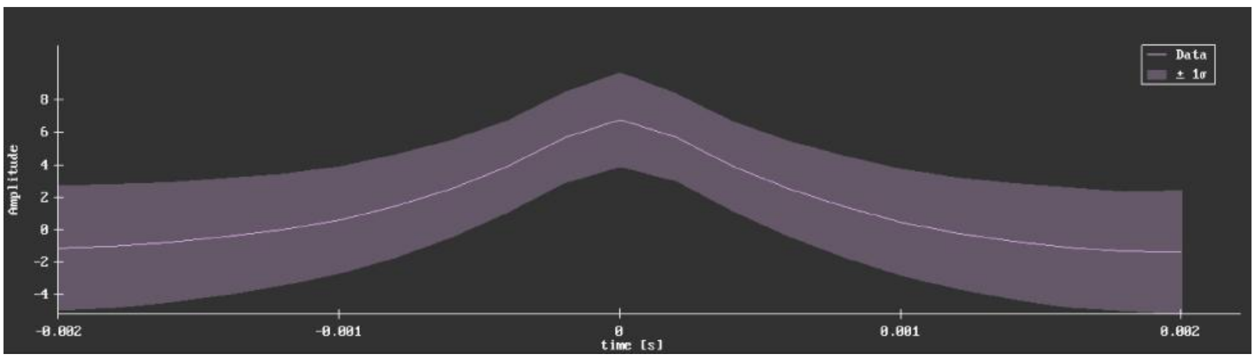

Figure 8. Adaptive Side Bicep Resistance 5 Average Waveform. The adaptive side bicep waveform on resistance 5 had a maximum amplitude around 7.

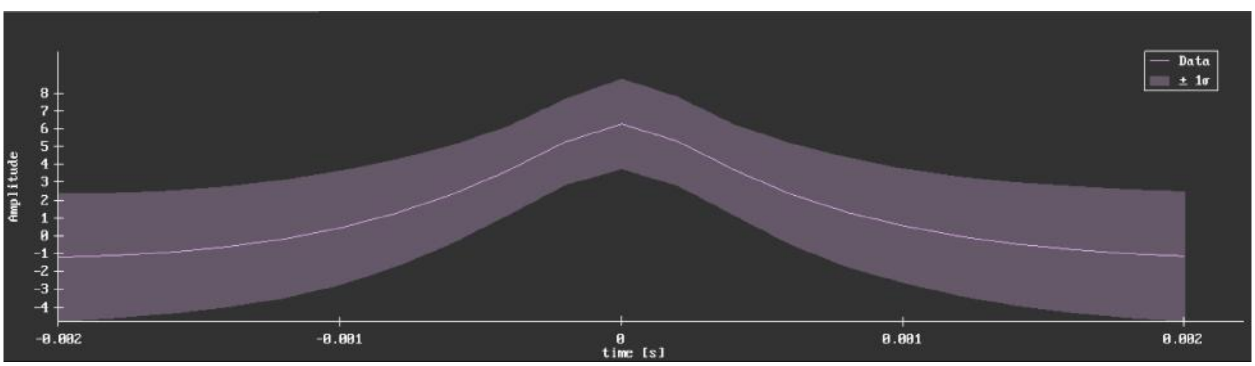

Figure 9. Adaptive Side Bicep Resistance 7 Average Waveform. The adaptive side bicep waveform on resistance 7 had a maximum amplitude around 6.5.

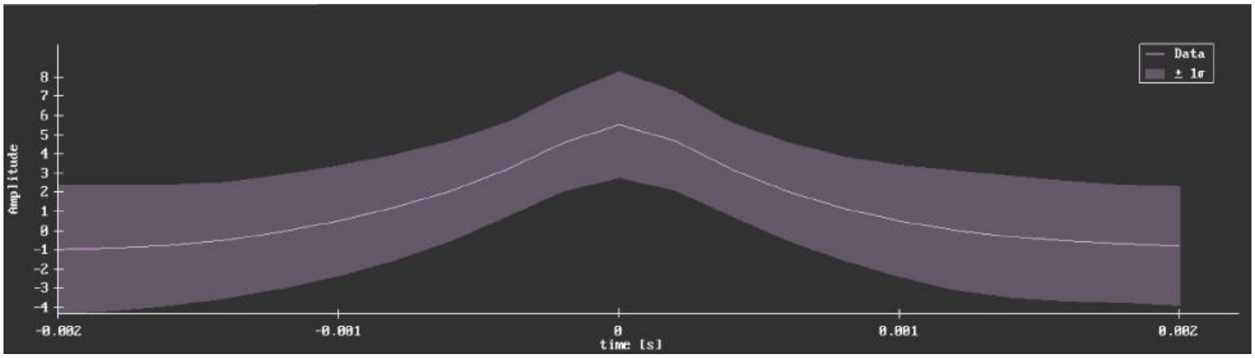

Figure 10. Adaptive Side Bicep Resistance 9 Average Waveform. The adaptive side bicep waveform on resistance 9 had a maximum amplitude around 6.

Standard Rear Deltoid

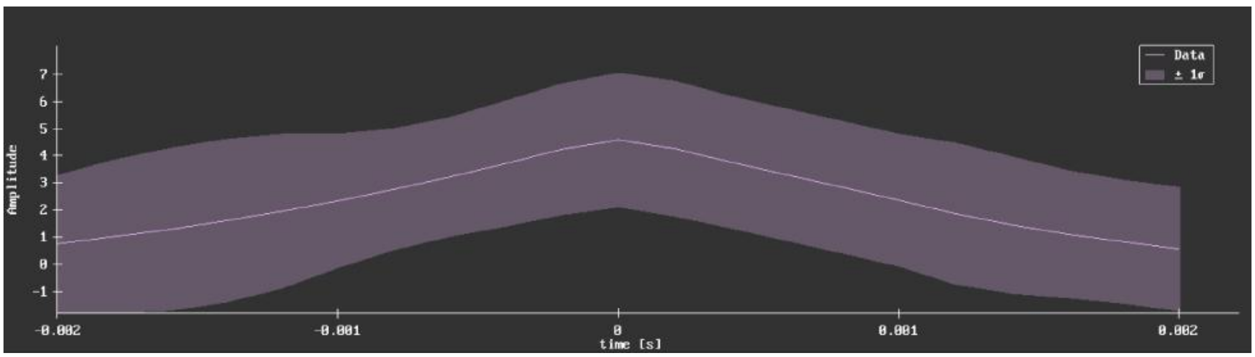

Figure 11. Standard Side Rear Deltoid Resistance 1 Average Waveform. The standard side rear deltoid waveform on resistance 1 had a maximum amplitude around 4.5.

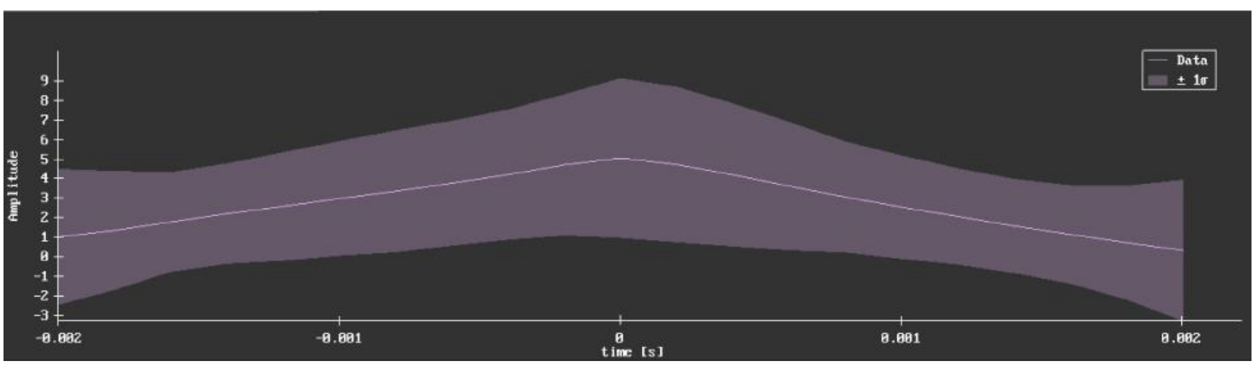

Figure 12. Standard Side Rear Deltoid Resistance 3 Average Waveform. The standard side rear deltoid waveform on resistance 3 had a maximum amplitude around 5.

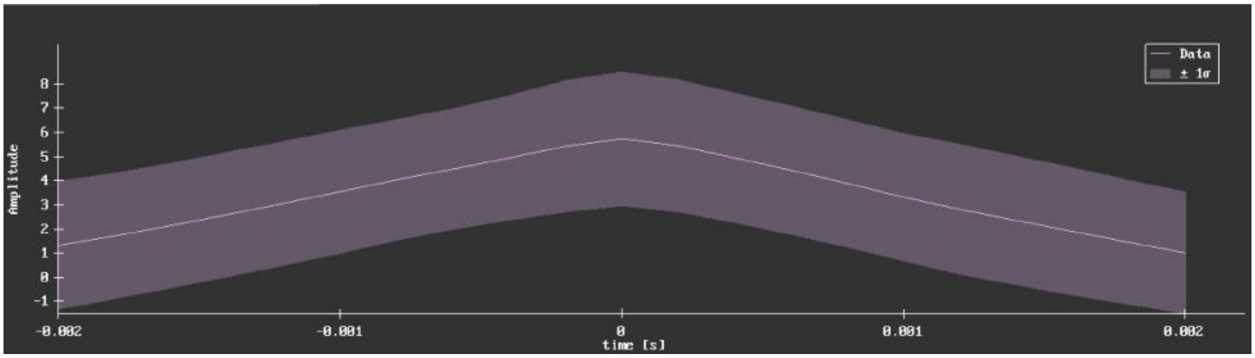

Figure 13. Standard Side Rear Deltoid Resistance 5 Average Waveform. The standard side rear deltoid waveform on resistance 5 had a maximum amplitude around 6.

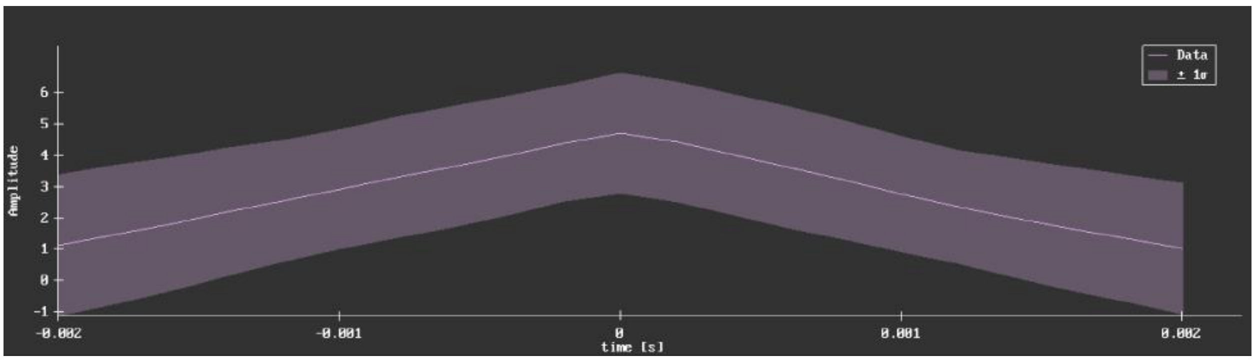

Figure 14. Standard Side Rear Deltoid Resistance 7 Average Waveform. The standard side rear deltoid waveform on resistance 7 had a maximum amplitude around 5.

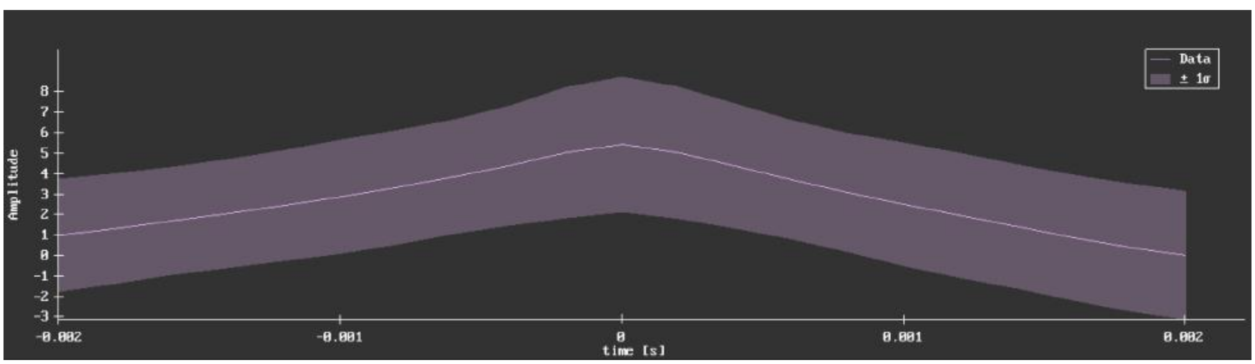

Figure 15. Standard Side Rear Deltoid Resistance 9 Average Waveform. The standard side rear deltoid waveform on resistance 9 had a maximum amplitude around 6.

Adaptive Rear Deltoid

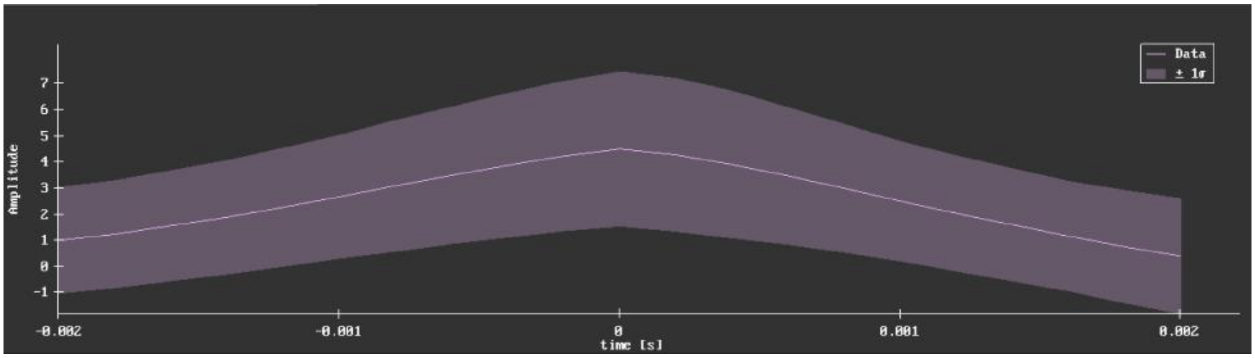

Figure 16. Adaptive Side Rear Deltoid Resistance 1 Average Waveform. The adaptive side rear deltoid waveform on resistance 1 had a maximum amplitude around 4.5.

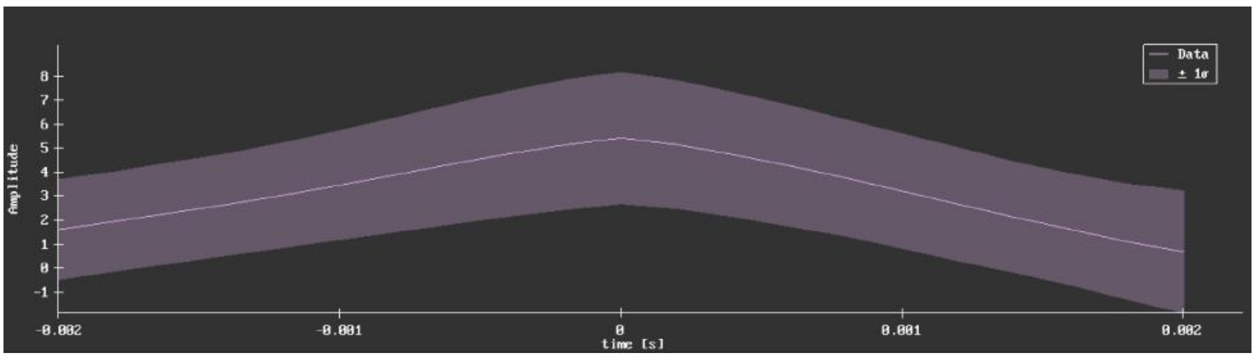

Figure 17. Adaptive Side Rear Deltoid Resistance 3 Average Waveform. The adaptive side rear deltoid waveform on resistance 3 had a maximum amplitude around 5.5.

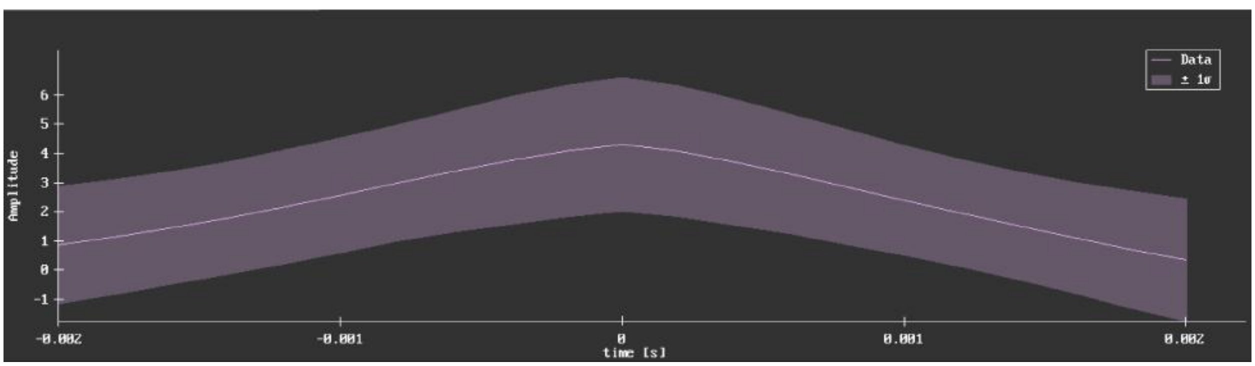

Figure 18. Adaptive Side Rear Deltoid Resistance 5 Average Waveform. The adaptive side rear deltoid waveform on resistance 5 had a maximum amplitude around 4.5.

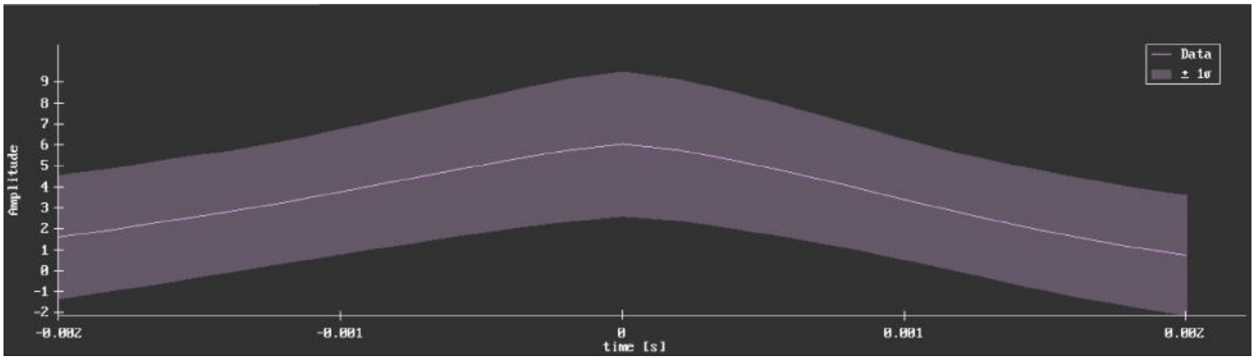

Figure 19. Adaptive Side Rear Deltoid Resistance 5 Average Waveform. The adaptive side rear deltoid waveform on resistance 5 had a maximum amplitude around 6.

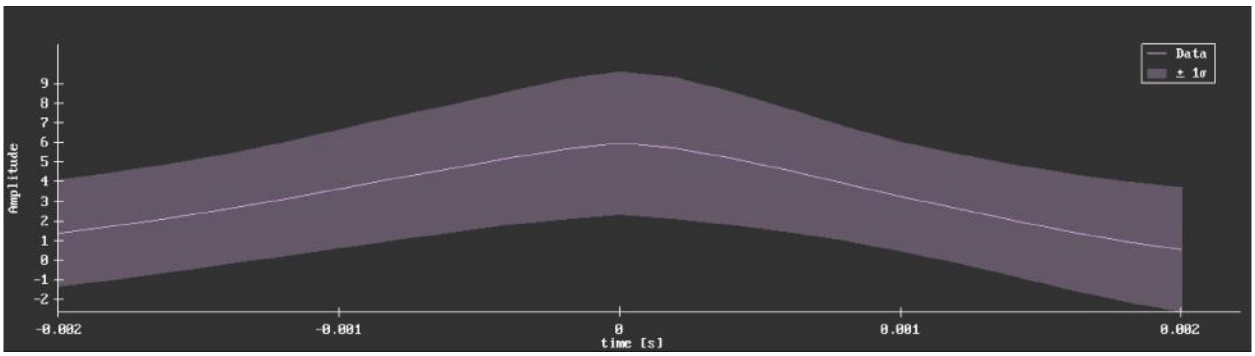

Figure 20. Adaptive Side Rear Deltoid Resistance 7 Average Waveform. The adaptive side rear deltoid waveform on resistance 7 had a maximum amplitude around 6.

Standard Latissimus Dorsi

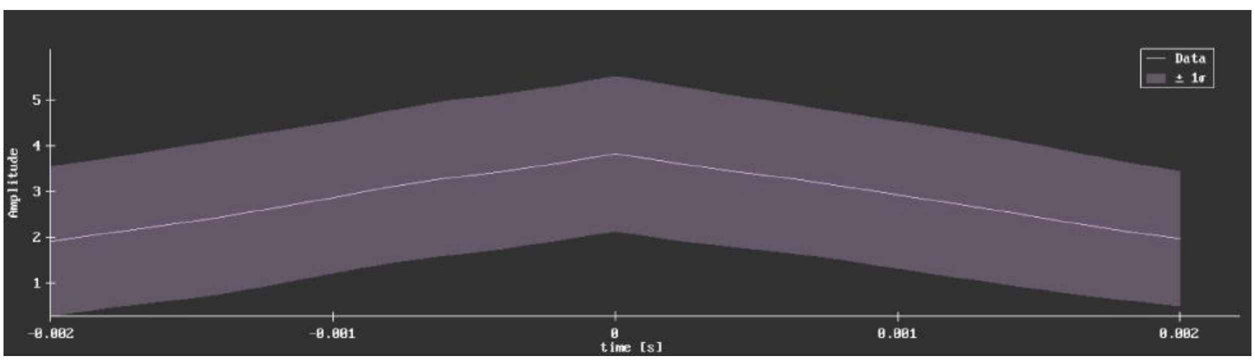

Figure 21. Standard Side Latissimus Dorsi Resistance 1 Average Waveform. The standard side latissimus dorsi waveform on resistance 1 had a maximum amplitude around 4.

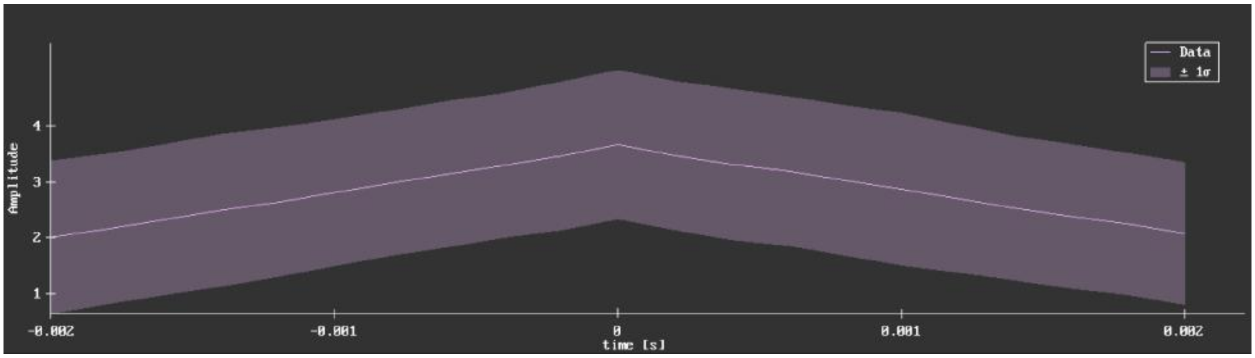

Figure 22. Standard Side Latissimus Dorsi Resistance 3 Average Waveform. The standard side latissimus dorsi waveform on resistance 3 had a maximum amplitude around 3.5.

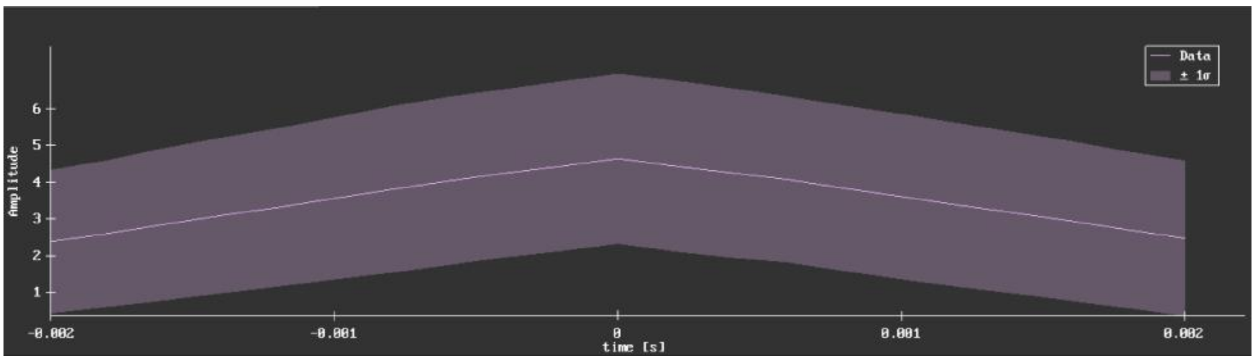

Figure 23. Standard Side Latissimus Dorsi Resistance 5 Average Waveform. The standard side latissimus dorsi waveform on resistance 5 had a maximum amplitude around 4.5.

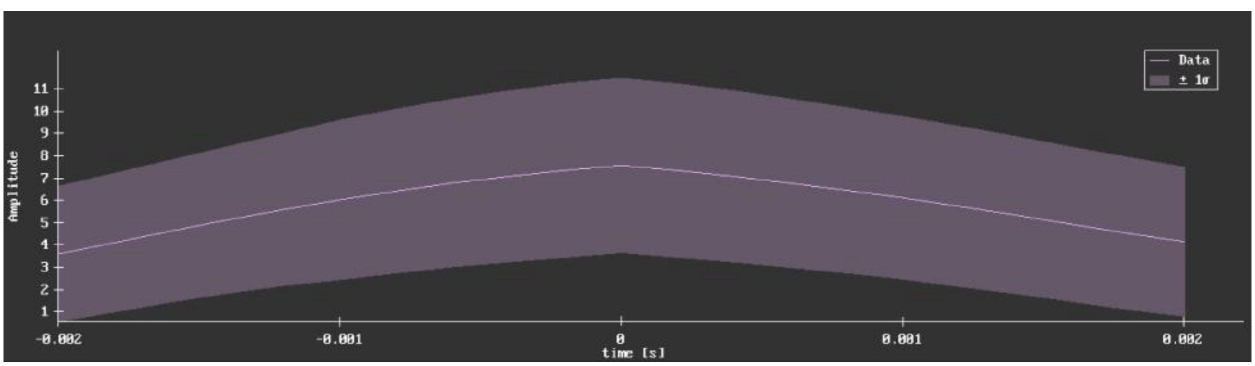

Figure 24. Standard Side Latissimus Dorsi Resistance 7 Average Waveform. The standard side latissimus dorsi waveform on resistance 7 had a maximum amplitude around 7.5.

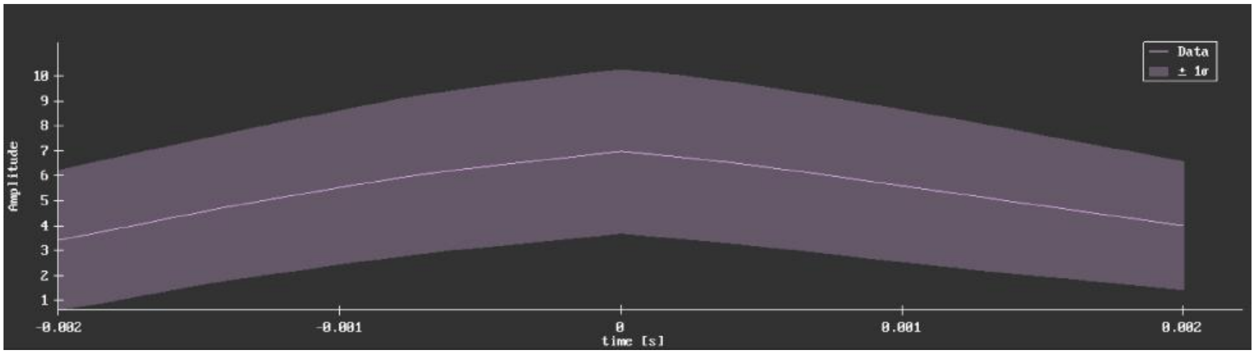

Figure 25. Standard Side Latissimus Dorsi Resistance 9 Average Waveform. The standard side latissimus dorsi waveform on resistance 9 had a maximum amplitude around 7.5.

Adaptive Latissimus Dorsi

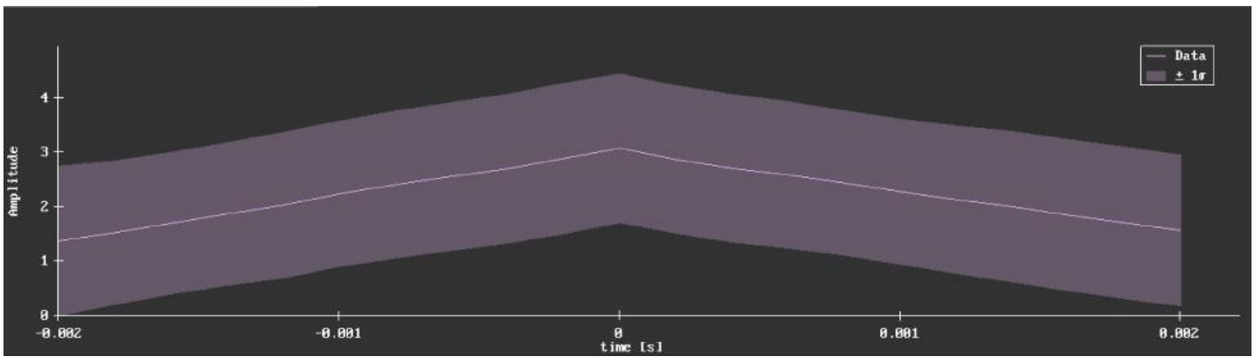

Figure 26. Adaptive Side Latissimus Dorsi Resistance 1 Average Waveform. The adaptive side latissimus dorsi waveform on resistance 1 had a maximum amplitude around 3.

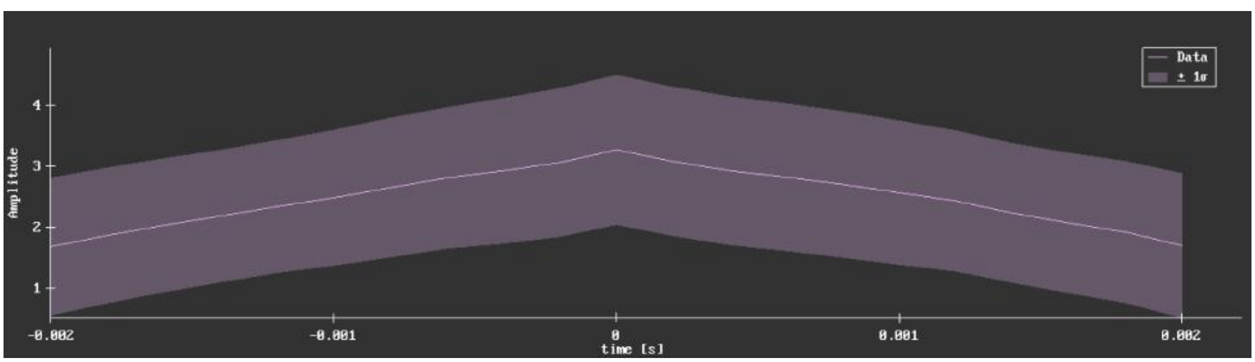

Figure 27. Adaptive Side Latissimus Dorsi Resistance 3 Average Waveform. The adaptive side latissimus dorsi waveform on resistance 3 had a maximum amplitude around 3.

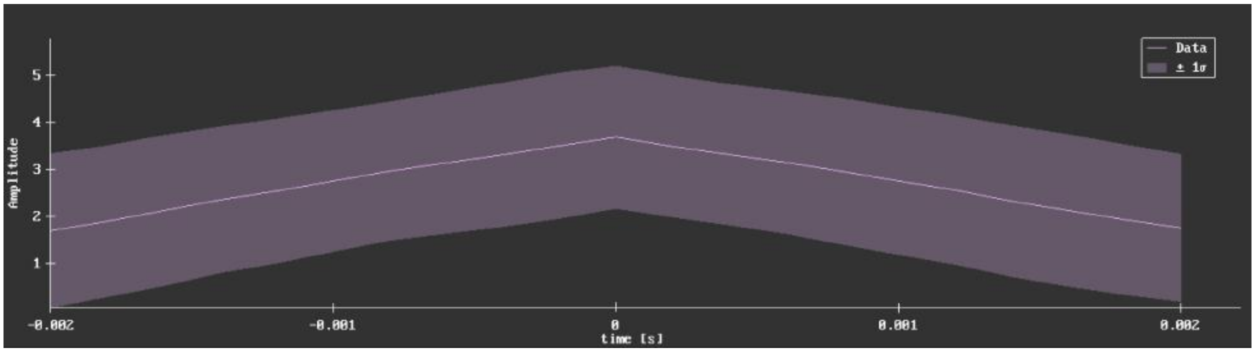

Figure 28. Adaptive Side Latissimus Dorsi Resistance 5 Average Waveform. The adaptive side latissimus dorsi waveform on resistance 5 had a maximum amplitude around 4.

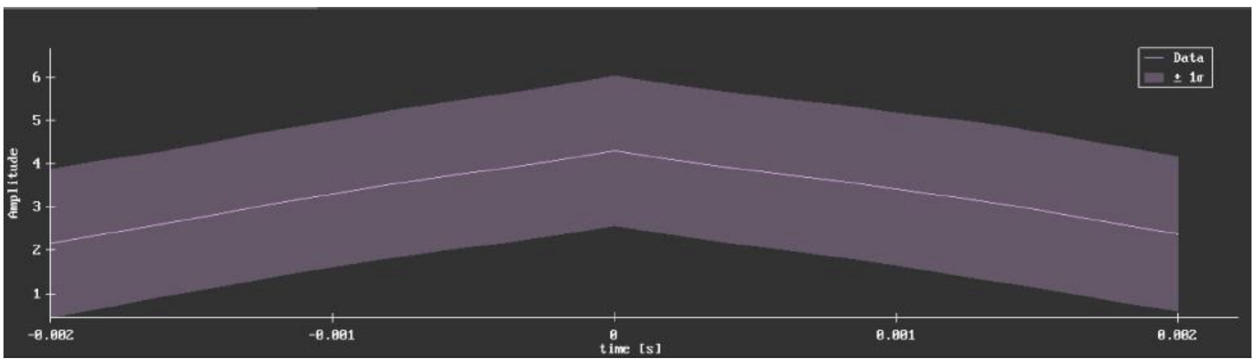

Figure 29. Adaptive Side Latissimus Dorsi Resistance 7 Average Waveform. The adaptive side latissimus dorsi waveform on resistance 7 had a maximum amplitude around 4.5.

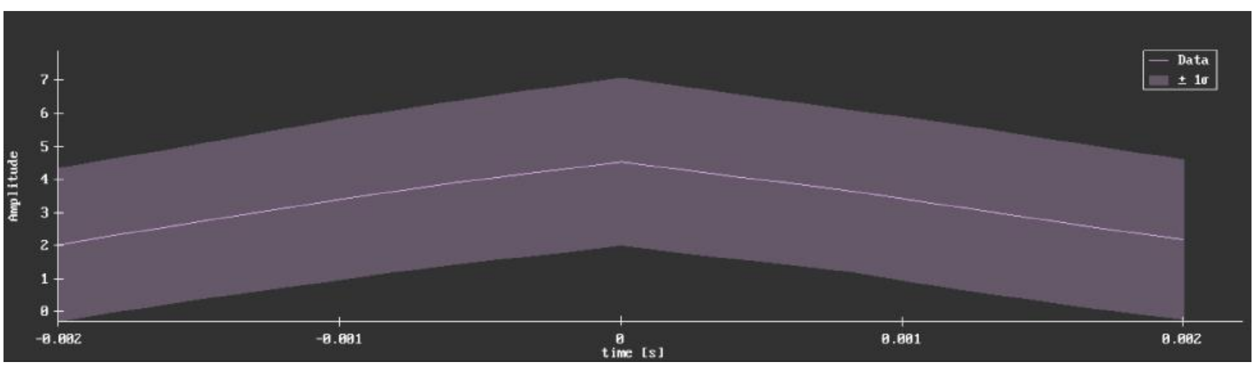

Figure 30. Adaptive Side Latissimus Dorsi Resistance 9 Average Waveform. The adaptive side latissimus dorsi waveform on resistance 9 had a maximum amplitude around 5.