Adaptive Rowing Machine

Final Report

BME 400

Lab Section: 307

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Abstract

Exercise is essential to maintain a healthy lifestyle. Fitness centers offer a wide variety of workout equipment to strengthen and exercise different muscle groups within the body. However, the majority of these exercise machines are not accessible to individuals with disabilities or injuries that require a wheelchair. For example, standard rowers require external modifications to accommodate individuals in wheelchairs. To address this problem, the Spring 2022 Johnson Health Tech Adaptive Rower design utilized an additional pulley on the adaptive side, held in place by mirroring support plates, as well as a wooden stabilization frame to secure the user. This semester, the wooden stabilization frame was replaced with an adjustable lap pad support mechanism that prevents the user from tipping backwards and sliding out of their wheelchair while rowing. The Matrix neck was removed and replaced by two antlers extending from the pulley plates that hold the handlebar directly above the pulleys. As a result, the console was relocated to a slightly off-center position beside one of the pulley plates. The console automatically rotates between the standard and adaptive sides via a stepper motor and feedback from three limit switches. Final testing of the design revealed that the pulley support plates and support mechanism withstood excessive loads experienced during rowing, and the stabilization frame limited the movement of the user during exercise. This unique and convertible design accommodates both wheelchair and non-wheelchair users and improves their quality of life through exercise.

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I. Introduction

A. Problem Statement

Individuals with injuries or disabilities have difficulty utilizing typical workout machines due to a lack of accessibility to exercise equipment. Among these affected individuals are wheelchair users. 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. To solve this issue, modifications must be made to current manufactured machines. A standard Matrix rowing machine will be adapted to accommodate wheelchair users while retaining its original functionality for non-wheelchair users [1]. 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 the rowing machine, ensure the proper rowing form is maintained, and ultimately help to improve the overall well-being of wheelchair users through exercise.

B. Motivation

Wheelchair users make up a significant proportion of the world’s population. In the United States alone, 5.5 million people require a wheelchair to perform daily tasks [2]. Currently, there is a lack of wheelchair accessible workout equipment in fitness centers, and a reported 81% of physically disabled individuals stated that they felt uncomfortable in gym settings due to this lack of accommodating exercise equipment [3]. In 2021, Planet Fitness, a major fitness center company, announced its goal to create a more inclusive gym environment by adding adaptive equipment to its new and existing locations; however, very few adaptive machines were added, and several other major gym companies have yet to add inclusive equipment to their gym space [4]. This proves the gap in the market for adaptive gym equipment.

Additionally, all current adaptations to fitness equipment are fabricated by the consumer or third-party services. Most fitness equipment manufacturers do not offer machines intended for users with physical disabilities. Common complaints among the wheelchair community include a lack of space between equipment for wheelchair access and an overall lack of adaptive equipment at fitness centers. In addition, wheelchair users reported a concern about needing or requesting assistance [5]. Even if all of these criteria are met, there is still a need for external assistance. Requests for additional stability measures that are not present at fitness centers include velcro to improve grip, straps for securement to the wheelchair, and elimination of the need to continuously leave the wheelchair for particular exercises [5]. These requests are not unreasonable and should be provided at every fitness center. Proper exercise leads to a healthier life; therefore, wheelchair users should not be denied this right due to a lack of equipment. To combat this, more adaptable equipment that satisfies the aforementioned criteria needs to be made. The creation of an adaptive rowing machine will allow wheelchair users to remain stable throughout their workout and offer gyms a solution to increase the accessibility of their facilities.

C. Existing Devices and Competition

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

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

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

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

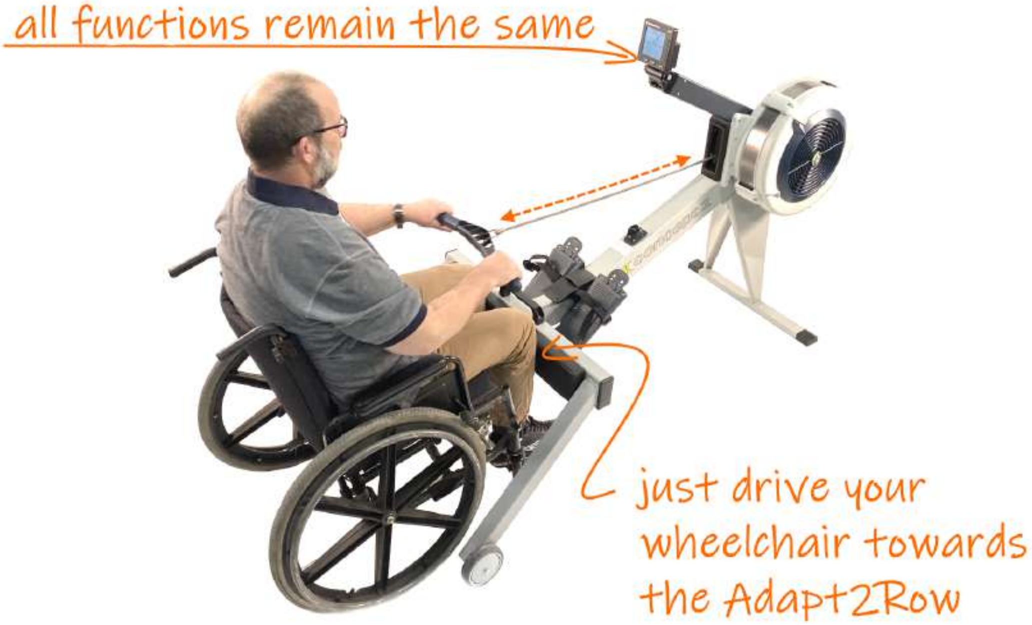


Figure 2. Adapt2Row on a Concept2 Rowing Machine. Adapt2Row allows for both standard and adaptive rowing on the Concept2 rowing machine but still requires outside assistance to transition between both states [9].

II. Background

A. Client

Ms. Staci Quam is a Biomedical and Mechanical Engineer, and lead of the biomechanics lab at Johnson Health Tech, in Cottage Grove, WI. She is interested in transforming standard workout equipment into adaptable machines accessible to individuals with different injuries and/or disabilities.

B. Physiological Research

Wheelchair users actively engage upper body muscle groups and their shoulder complex during the completion of everyday activities [10]. Such activities include pushing to propel themselves forward as well as pivoting between multiple positions. The need for well-developed muscles in the upper body is of utmost importance for wheelchair users. Without it, external loads lead to issues in the shoulder region. A common complaint from wheelchair users is shoulder pain [10]. It is important to note that shoulder pain could potentially be due to a lack of proper training and implementation of gradual increases in a workout regimen. Other factors that affect shoulder pain include age, weight, and BMI. In addition, increased intensity, frequency, and duration of a load may lead to shoulder pain. However, proper increases in resistance and form can reduce pain in this area [10].

For the common wheelchair user, small factors like improper posture while navigating in a wheelchair, can result in pain [10]. This further proves the importance of exercising. 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 [11]. The 4 phases of rowing engage these muscles as shown in **Figure 3**.

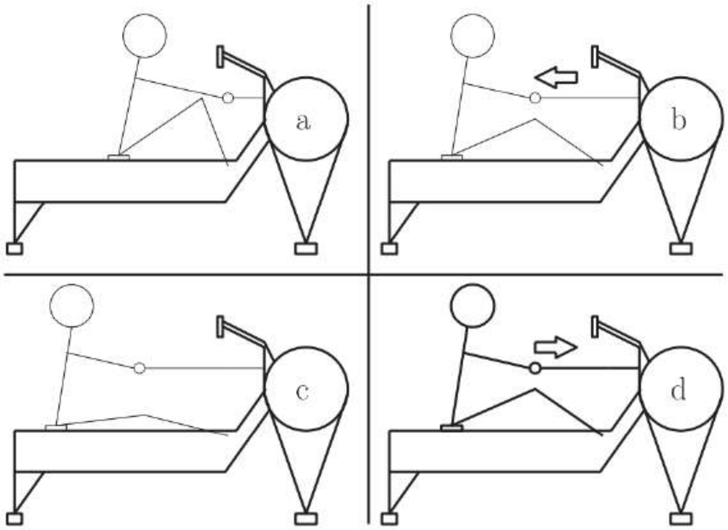


Figure 3. Visual Representation of the 4 Phases of Rowing. The figure labeled *a* corresponds to the Catch phase, *b* is the Drive phase, which is followed by the Finish phase in *c*, and finally the Recovery phase in *d* [12].

The first phase is the catch, and it primarily activates the triceps and the flexor muscles in the fingers. During this phase, the abdominal muscles are engaged and allow the user to flex the torso in a forward motion. The following phase is called the drive. In standard rowing, this phase includes the contraction of the hamstrings while the user propels themselves backwards. However, for an adaptive user, it will activate the biceps as they pull the handle towards their abdomen. The back muscles will also contract as the torso swings backwards. The drive's movement is completed by the finish phase. This phase is the final pull where the abdominals and lower back stabilize the body and the biceps engage to help keep the torso in place. The full rowing motion is completed during the recovery phase, which occurs when the individual returns to the catch phase. The triceps engage to push the arms away from the body while the abs flex the torso forward. The four phases, all together, allow for a complete workout that strengthens the shoulder complex and upper body muscles [11].

C. Design Specifications

The client provided a $500 research and development budget to create adaptations that will allow wheelchair individuals to use the Matrix Rower, as seen in **Figure 4**, with no outside assistance. Adaptations will first and foremost provide safety and stability to users, allow users to operate the rowing machine from their wheelchair, maintain the majority of aspects from the four phases of rowing and stimulate the same muscle groups, and allow a seamless transition between non-adaptive and adaptive use. Adaptations will withstand at least ten years of usage, which amounts to eight million meters, as well as stresses from tension up to 1050 N [13]. These benchmarks fall within the typical durability of a rower [14]. Additionally, the adaptations must be viable for fitness centers where space is often limited. Therefore, any adaptations will be removable and extend no more than 1.2 m from the rower frame.

Figure 4. Standard Matrix Rower. This figure illustrates the standard rower fabricated by Johnson Health Tech [1].

When loaded with a maximum force of 1050 N, materials chosen should deform no more than 2.0 mm. Additionally, components should not fracture under this benchmark. This deformation is minimal, so applying this criteria ensures the safety of the user and prevents failure of the adaptive side of the rower. Displacement in the lateral and vertical directions while rowing is an important consideration as well. A user's rowing mechanics may be hindered by external motion, which would lead to difficulties in performing proper technique during the workout. Consequently, the wheelchair and any stability mechanism should not move when the user is completing the rowing motion. The added components will be fabricated out of a durable metal to ensure strong performance and a professional aesthetic.

The design will also accommodate users of different sizes. The average reach from shoulder to fingertip is 70 cm; the design will accommodate variations up to ± 20 cm [15]. Additionally, the device must accommodate wheelchairs of different sizes. The device will fit average wheelchairs with the following dimensional specifications: width of frame of 60-70 cm, height of seat of 45-50 cm, and length of wheelchair of 90-125 cm [16]. Further product design specifications can be found in **Appendix A**.

D. Previous Design Work

In BME 301, the previous team made substantial progress on the current adaptive rower design. The adaptive rowing machine has four main components, which include (1) a slit cut in the rower neck, (2) pulley support plates and a second pulley, (3) a rotation bracket for the display console, and (4) a wooden stabilization frame (**Appendix B**).

The main competitive aspect of the adaptive rower design is the ability to convert between the traditional and adaptive state. The slit in the rower neck (**Figure 5**) allows the user to transition the rope from one side of the rower to the other. However, the wheelchair user requires external assistance to remove the tension in the rope to generate sufficient slack for transitioning the rope through the slit. Ideally, the wheelchair user should be able to use the rowing machine without external assistance. Therefore, this aspect of the design can be further improved.

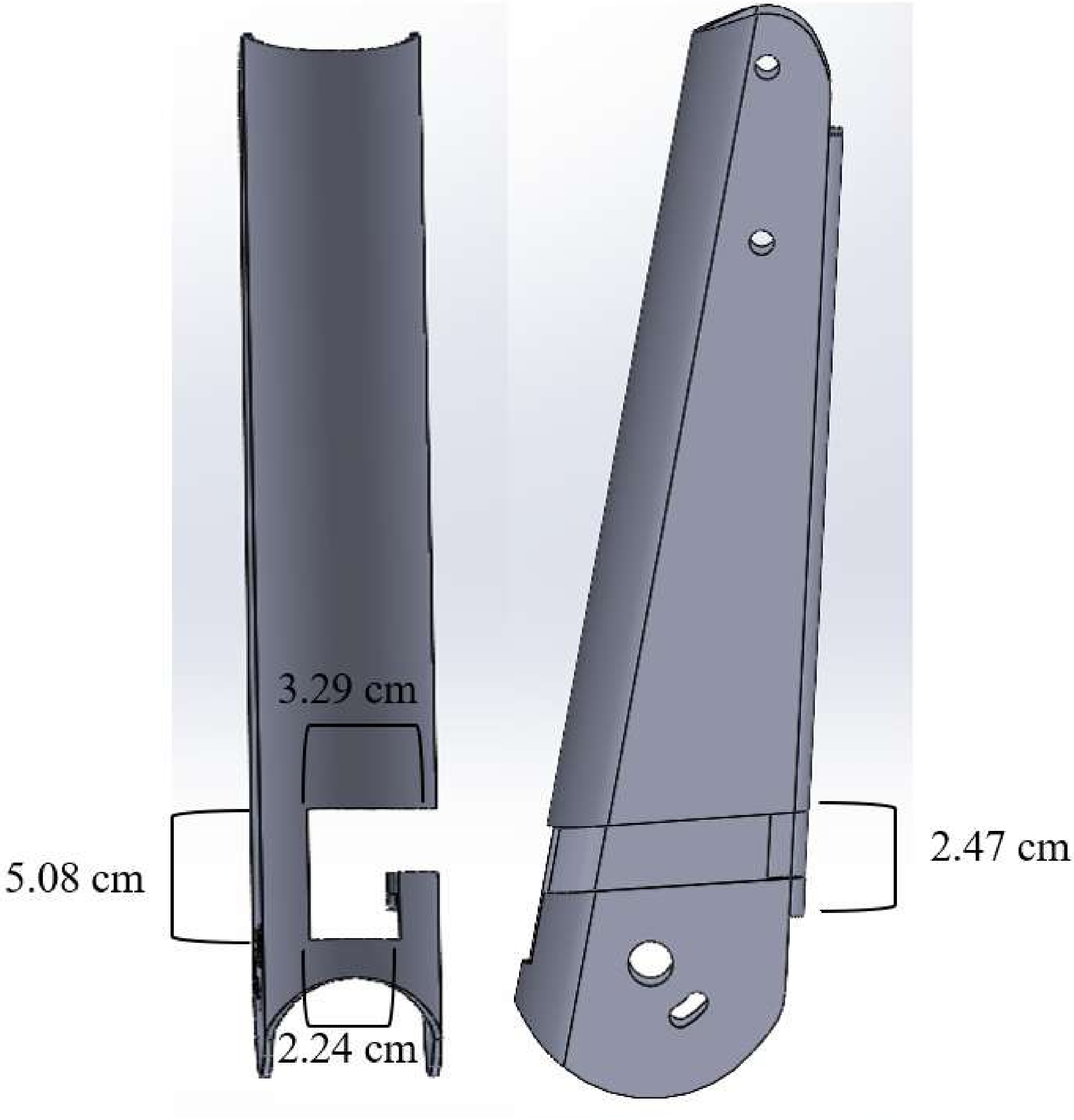


Figure 5. Rower Neck with Slit. The rower neck has a slit on the right side that allows for the rope to be transitioned from the standard to the adaptive side (see **Appendix B** for more details).

A second pulley was attached to the rower frame via two pulley support plates to allow rowing from the adaptive side (**Figure 6**). These plates were 3D printed out of tough PLA and rigidly attached to the rower. Using SolidWorks simulated stress tests, each plate was subjected to a 1050 N load applied downward at the location of the pulley. The maximum deflection for either of the two plates was 1.076 mm, which suggested the plates would be rigid and strong enough to endure any excessive loading that may occur while rowing. However, the plates did not fit on the rower as intended due to welds on the physical rower which vary by machine and were not modeled in the provided CAD of the rowing machine. Thus, the printed plates did not allocate space for the welds, and the geometry of the plates can be improved to account for the welds and create a more snug fit.

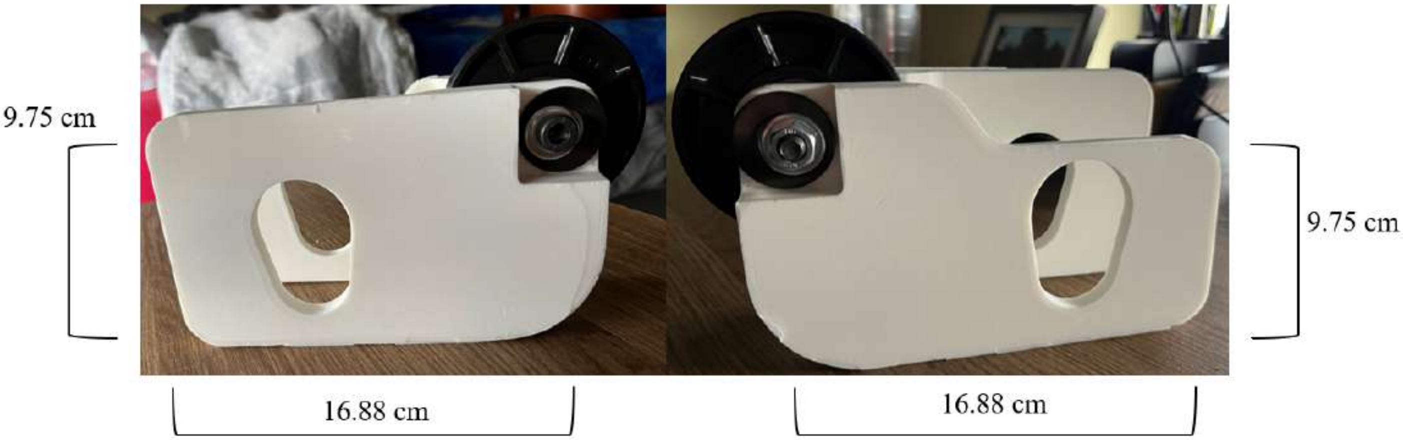


Figure 6. Left and Right Pulley Support Plates. The left (left) and right (right) pulley support plates fit tightly around the pulley bearing and have a hole that fits around the metal support arms for the rower neck. The right pulley support plate has material removed from the top surface to allow the rope to pass through the cut made on the right side of the rower neck.

One key design consideration was ensuring that the user could still view the output from the display console while rowing from the adaptive side of the machine. To accomplish this, a rotation bracket made of tough PLA was modeled to allow the console to rotate 180°. The user is able to lift the console out of the bracket, rotate it via a centering peg, and “lock” it into place with a guiding peg (**Figure 7**). Rotating the console display is a manual process, and users sometimes had difficulty rotating the display if the console was taken out of the bracket at an angle, rather than vertically upward. The usability of the rotation bracket can be further improved.

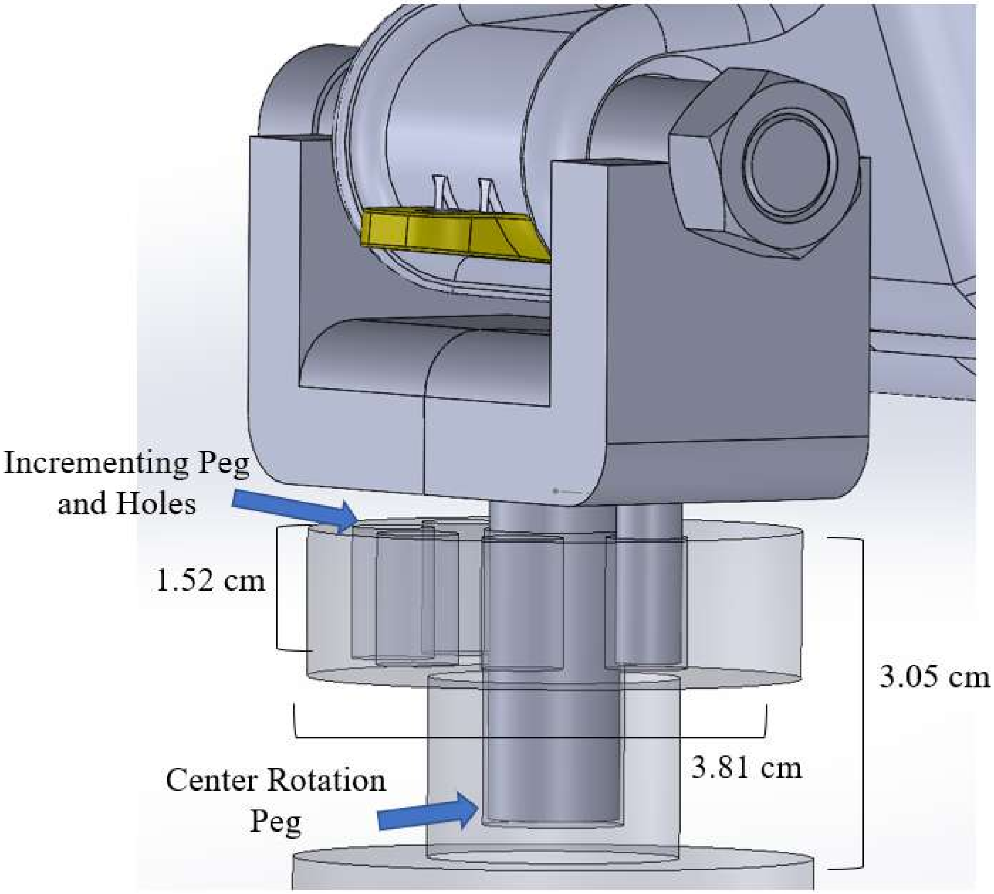


Figure 7. Rotation of Display Console. The large peg fits into the center rotating cavity of the receiving bracket, while the guiding peg fits into one of five smaller cavities to adjust the degree of rotation of the console.

Lastly, a wooden stabilization frame was built with the goal of holding the user securely in place during the rowing motion (**Figure 8**). The rowing machine sits on top of the frame to hold it rigidly in place. To secure themselves to the frame, users roll between the upright posts and wrap two buckle straps around the arm supports of the wheelchair. This design had several issues. First, the wooden stabilization frame was built to fit only one wheelchair, and thus is not accommodating for users who have larger wheelchairs. Additionally, the frame is not able to elongate, and thus does not accommodate users with varying reach lengths. Third, the wooden frame did not successfully hold the user in place while rowing. Kinovea Motion Capture was used to track the movement of both the user and the stabilization frame during rowing. Results showed that the user moved 4.09 cm forward and backward and the back of the frame lifted off the ground by 1.86 cm. Thus, the frame did not properly restrain the individual from moving during the workout. Additionally, the current wooden stabilization frame does not prevent the user from sliding forward out of the seat, which made users feel insecure within the stabilization frame. This stabilization design can be further improved to better hold the user securely in place while rowing and prevent motion of both the user and the frame.

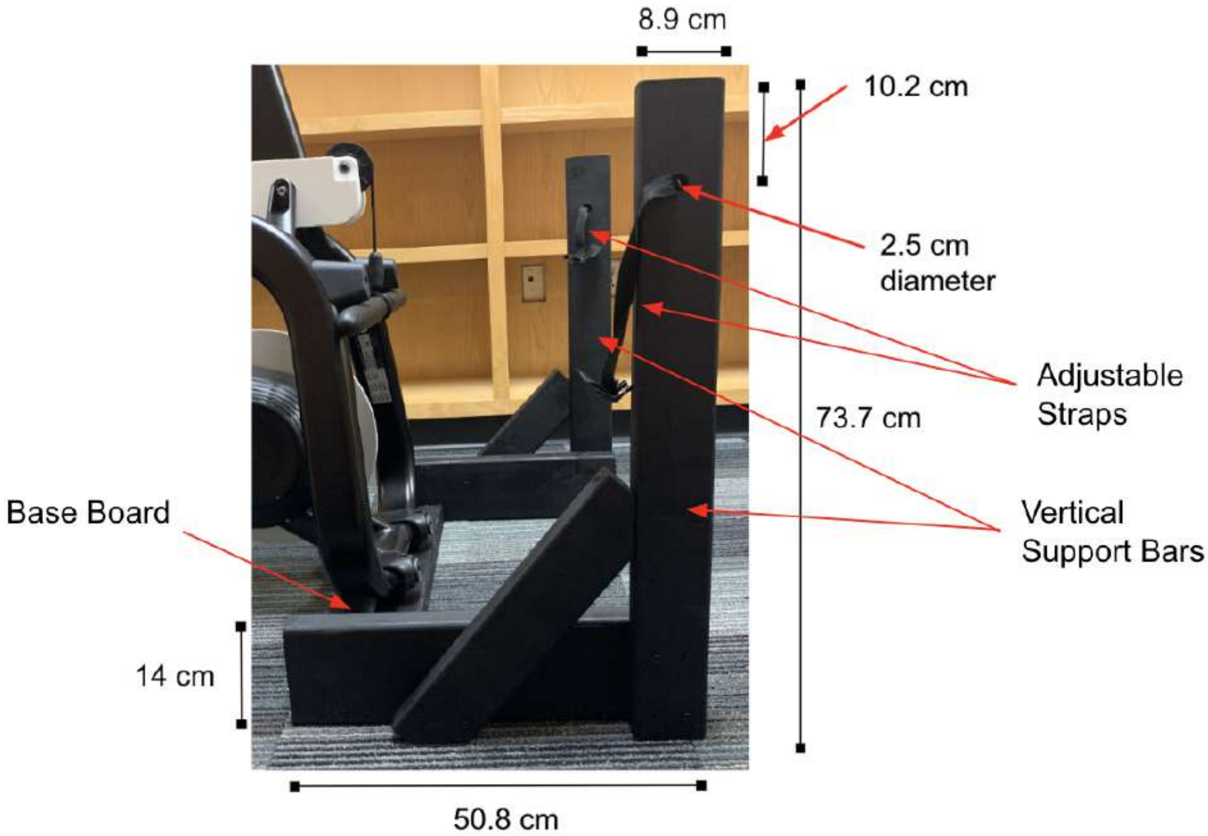


Figure 8. Side View of Base Stabilization Frame. The 50.8 cm boards that are attached to the baseboard create separation from the rowing machine to allow space for the user to complete the rowing motion comfortably. Additional diagonal supports were added to the base to further enhance the strength and stability of the wooden base. The 2.5 cm diameter holes in the vertical boards house the strap that attaches to the wheelchair.

The previous adaptive rower (**Figure 9**) is a proof of concept for a convertible rowing machine that is accessible to wheelchair users. However, the design has a lot of room for improvement before it is ready for wheelchair users to comfortably and successfully use the machine. The goal for this semester is to further improve upon the previous work of the adaptive rowing machine by creating a more competitive, accommodating, and user-friendly device for the wheelchair community. Further information about previous design work can be found in **Appendix B**.

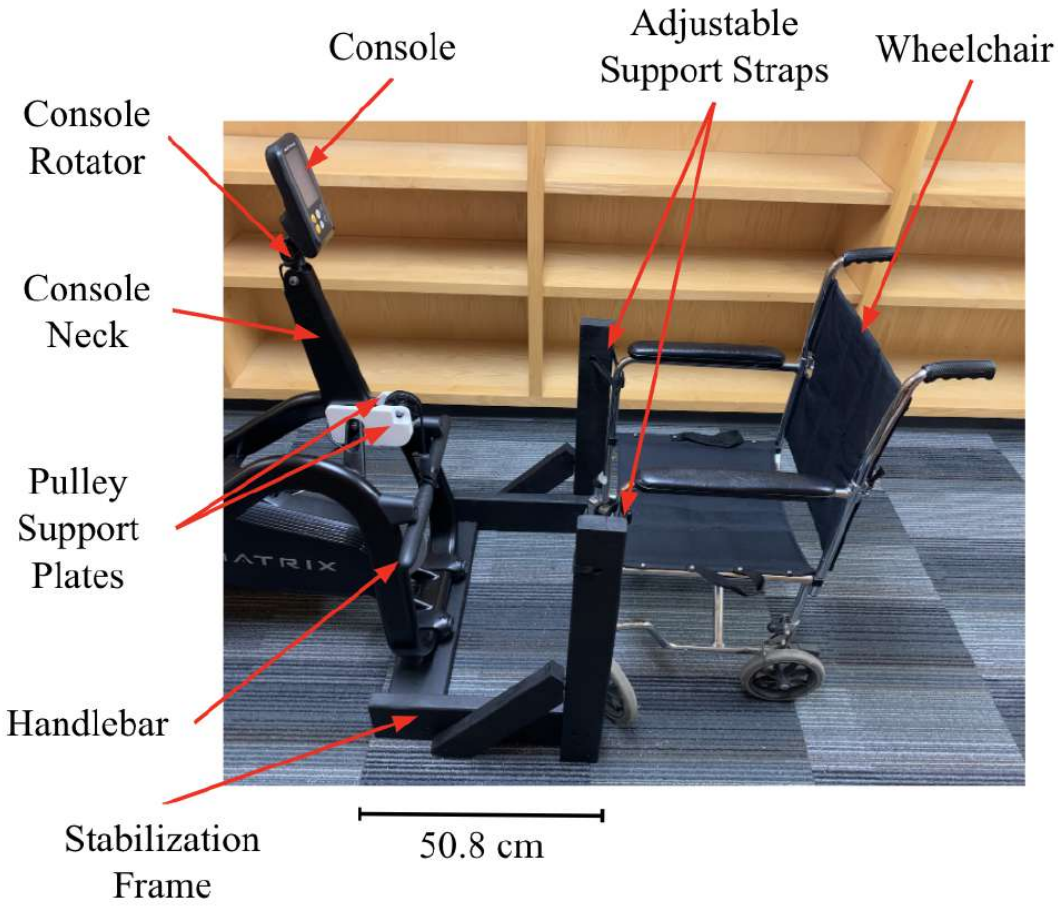


Figure 9. Previous Design Full Assembly. The full assembly includes the pulley support plates, the console rotation bracket, and the wooden support base. The wheelchair is locked into the support base with adjustable straps.

III. Preliminary Design and Evaluation

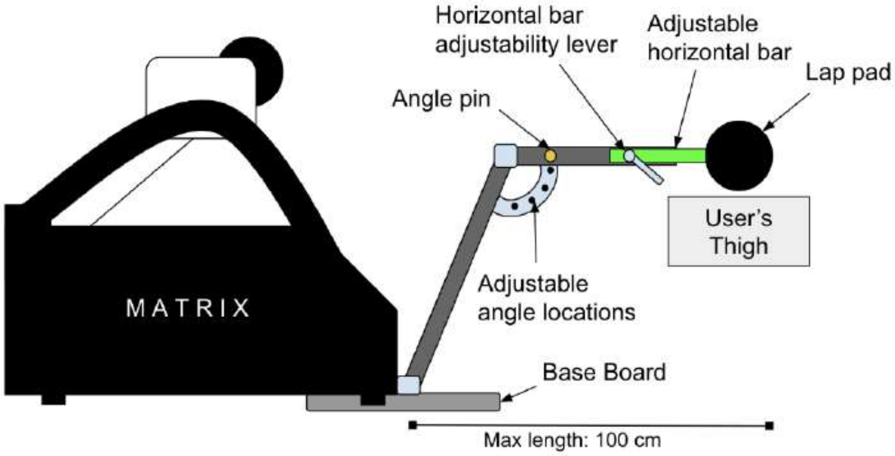
A. Stabilization Frame

a. Stabilization Frame Design 1: Base Stabilization Frame

The Base Stabilization Frame is the current support mechanism used to secure the wheelchair during the rowing motion (**Figure 8**). The design features a non-adjustable frame which can only accommodate a limited range of user/wheelchair sizes. To secure the wheelchair to the rower, the Base Stabilization Frame includes adjustable straps located on the vertical support bars. When attached to the front arm bars of the wheelchair (**Figure 9**), these straps provide a forward reaction force that prevents the wheelchair from both tipping and rolling backwards during the rowing exercise. The Base Stabilization Frame includes a base board that rests underneath the rowing machine. The rubber supports on the bottom of the rower rest within divots cut out from the base board. The weight of the rowing machine resting on the base board prevents the Base Stabilization Frame from moving during use.

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 10)**. 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 10. 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

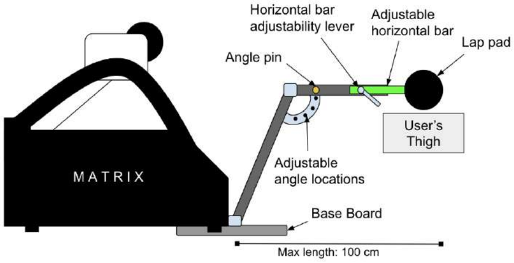
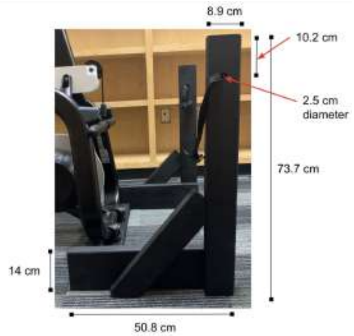
The stabilization frame design criteria include safety/security (30%), adjustability (25%), ease of fabrication (15%), ease of use (15%), cost (10%), and integration to environment (5%). Safety/security is the most important design criteria for the stabilization frame. The stabilization mechanism should 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**  *Note: Drawings not to scale		**Base Stabilization Frame**  	
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 (**Appendix B**) 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 11**) 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 12**). 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.

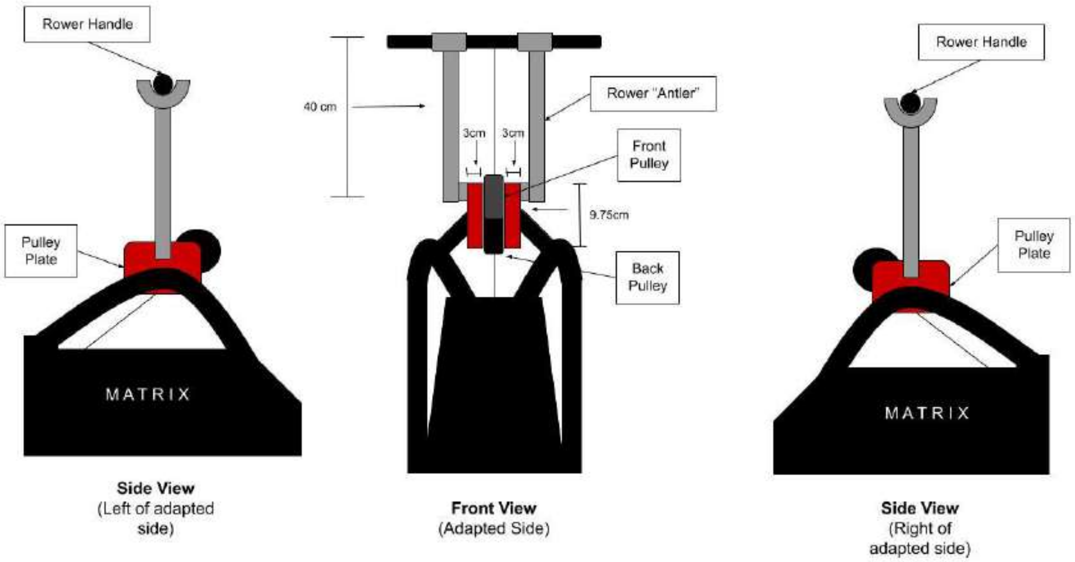


Figure 11. Antler Design. This design relocates the handle bar of the rower to a more central location and allows the user to row from the adaptive or standard side of the rower without needing to remove rope tension before transitioning the bar.

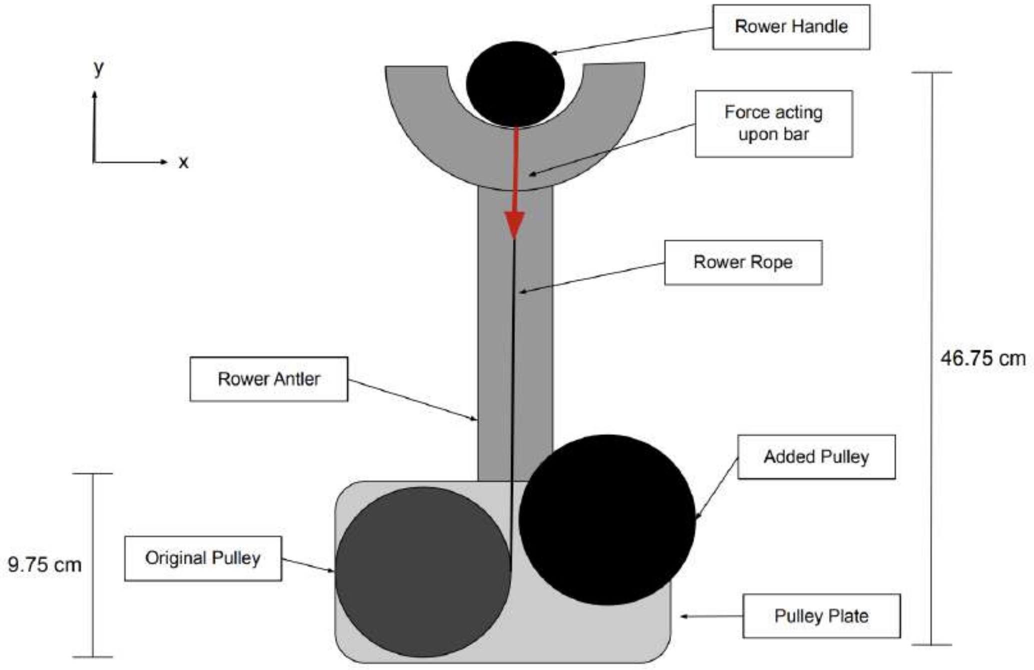


Figure 12. Tension on Handlebar of Antler Design. As part of the antler design, the handlebar is relocated such that it lies directly in between the two pulleys on the rower. Therefore, the net tension acting upon the bar is directly downward.

C. Console Rotation

a. Console Design 1: 1 Pivot Point

The 1 Pivot Point design (**Figure 13**) 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 last semester (**Appendix B**), the pivot point incorporates a locking peg to prevent unintended movement (**Figure 14**). 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.

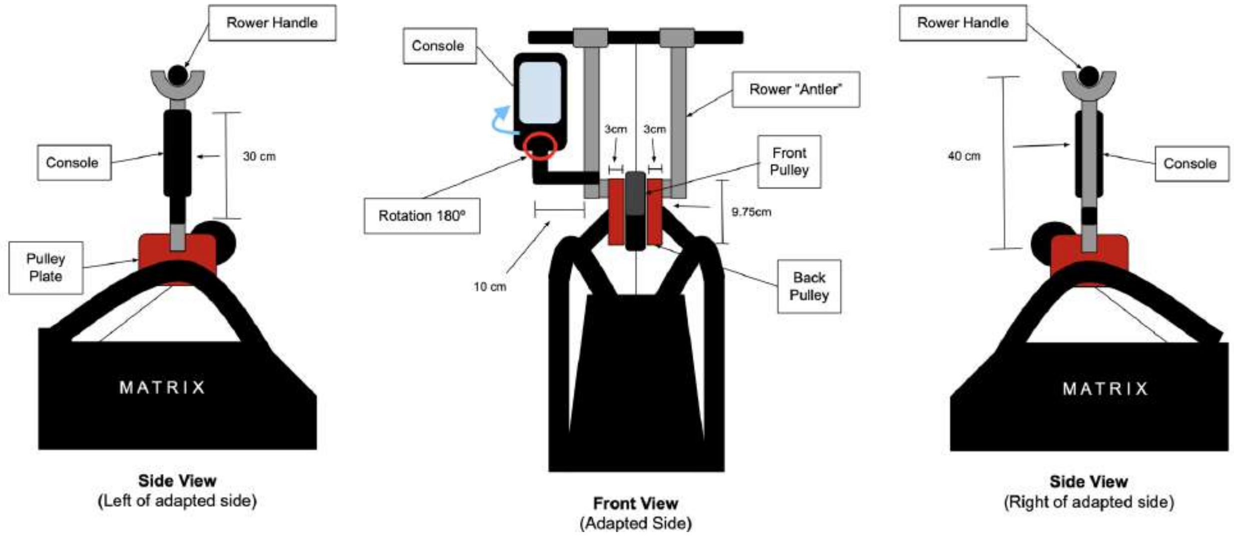


Figure 13. Console Design 1: 1 Pivot Point. This design secures the console to one of the antler structures. A pivot point directly below the console allows 180° manual rotation between the standard and adaptive sides of the machine.

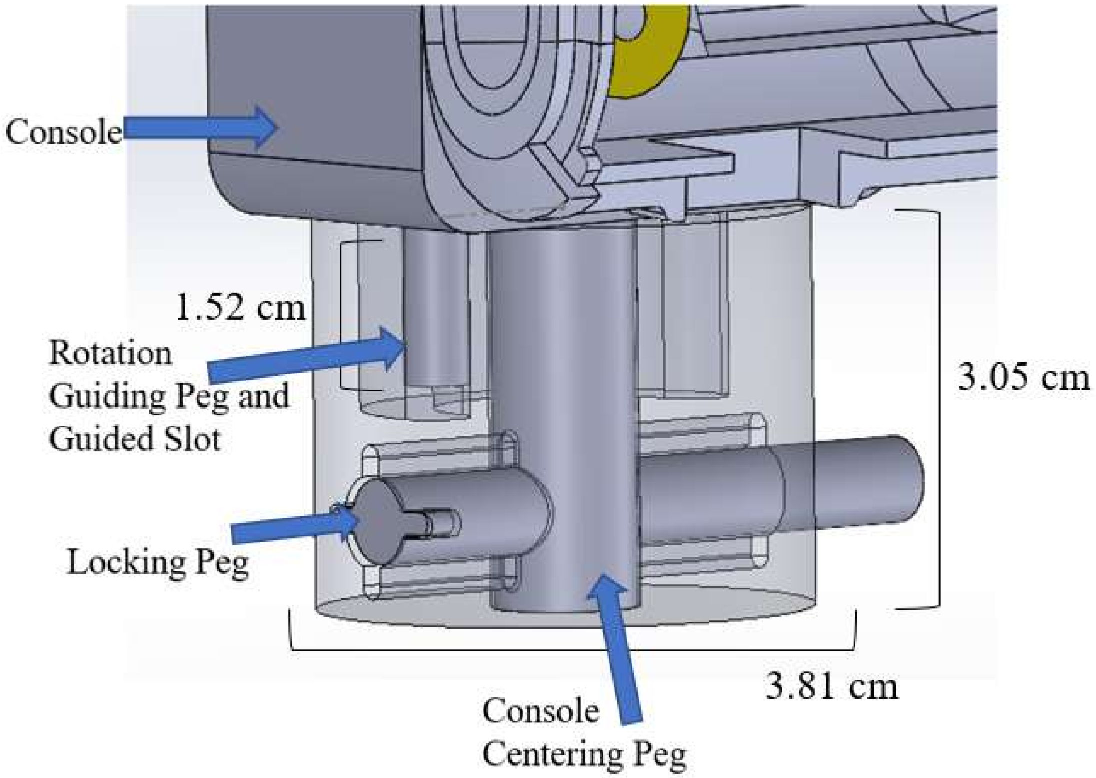
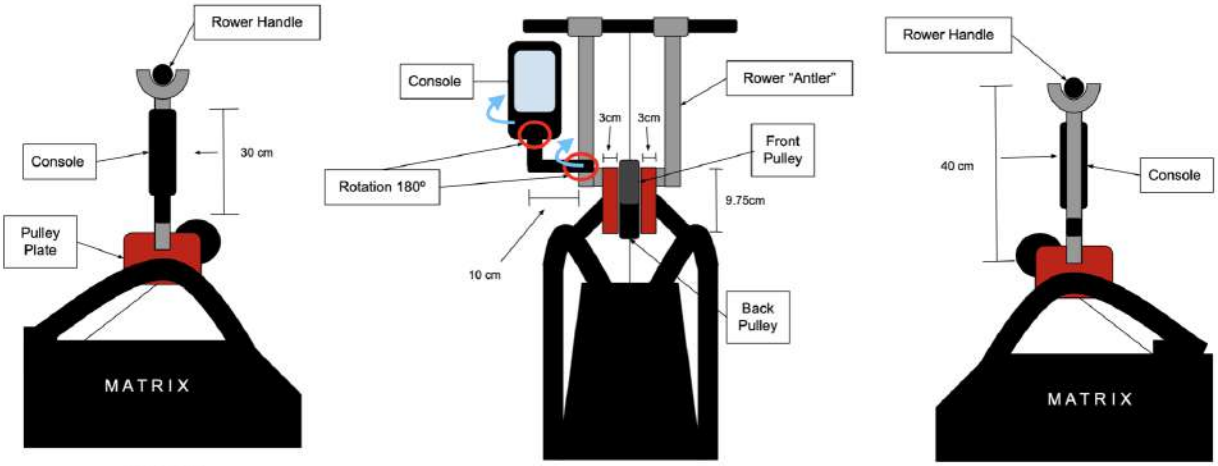


Figure 14. Updated Console Swivel Bracket with Locking Peg. The updated console swivel bracket contains a locking peg to prevent unwanted rotation of the display. When unlocked, the display can rotate 180º to face either the standard or adaptive sides of the machine. Locking only occurs in these two positions, and not at any other point along the guided slot.

b. Console Design 2: 2 Pivot Points

The 2 Pivot Points design (**Figure 15**) 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 14**) previously described for the 1 Pivot Point design (See **Section III.C.a**).



Side View
(Left of adapted side)

Front View
(Adapted Side)

Side View
(Right of adapted side)

Figure 15. 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 16**) 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 17**). 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 18** 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.

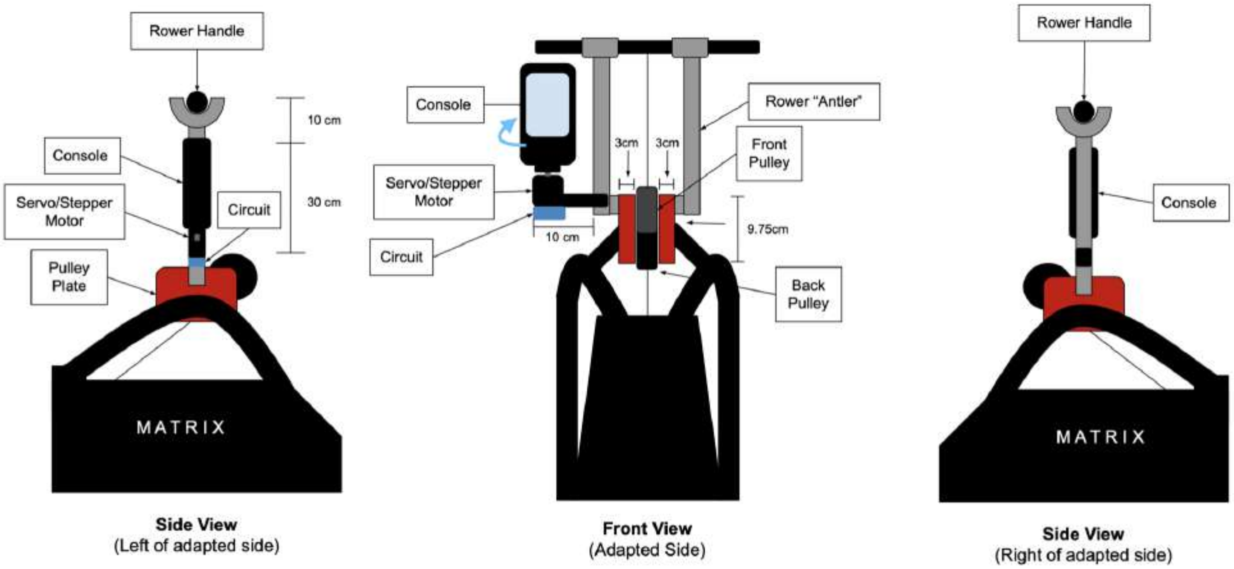


Figure 16. Console Design 3: Motor. This design utilizes a servo/stepper motor to electronically turn the console 180°. All circuit components, except the limit switch (not depicted), motor, and their associated wires will be stowed in a compartment (shown in blue) below the console support for safety and aesthetic purposes.

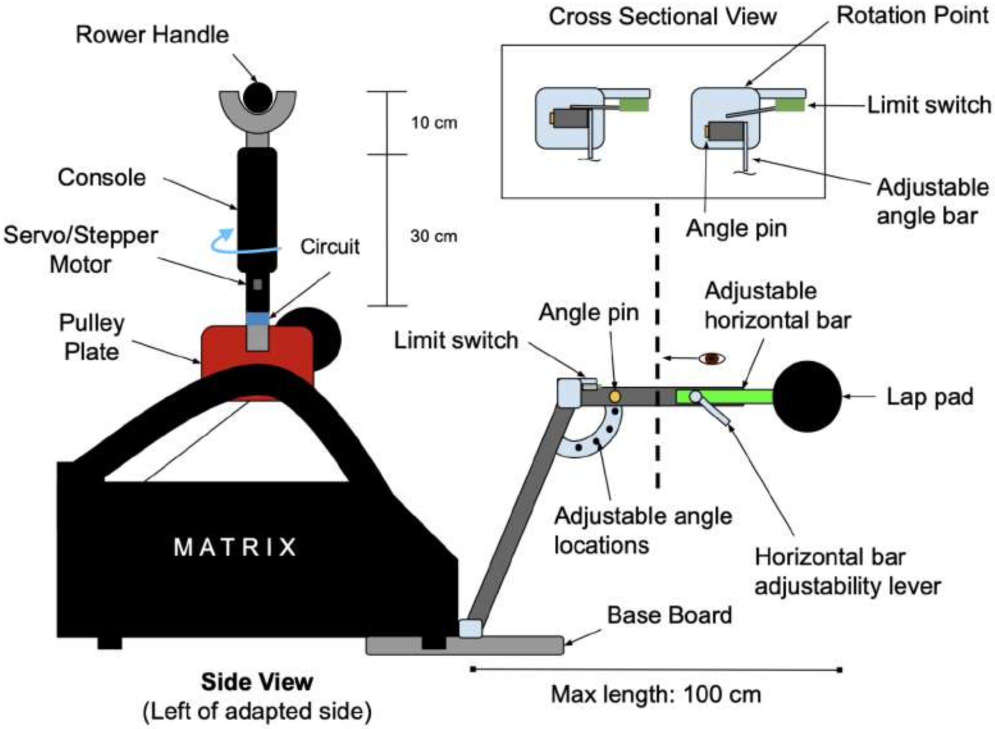


Figure 17. Limit Switch Placement. A limit switch placed above the lap bar near its pivot point provides feedback to the Arduino program about whether the adaptive side is in use or not. Wires (not depicted) run along the stabilization frame and Matrix rower to the electronics box near the console (shown in blue).

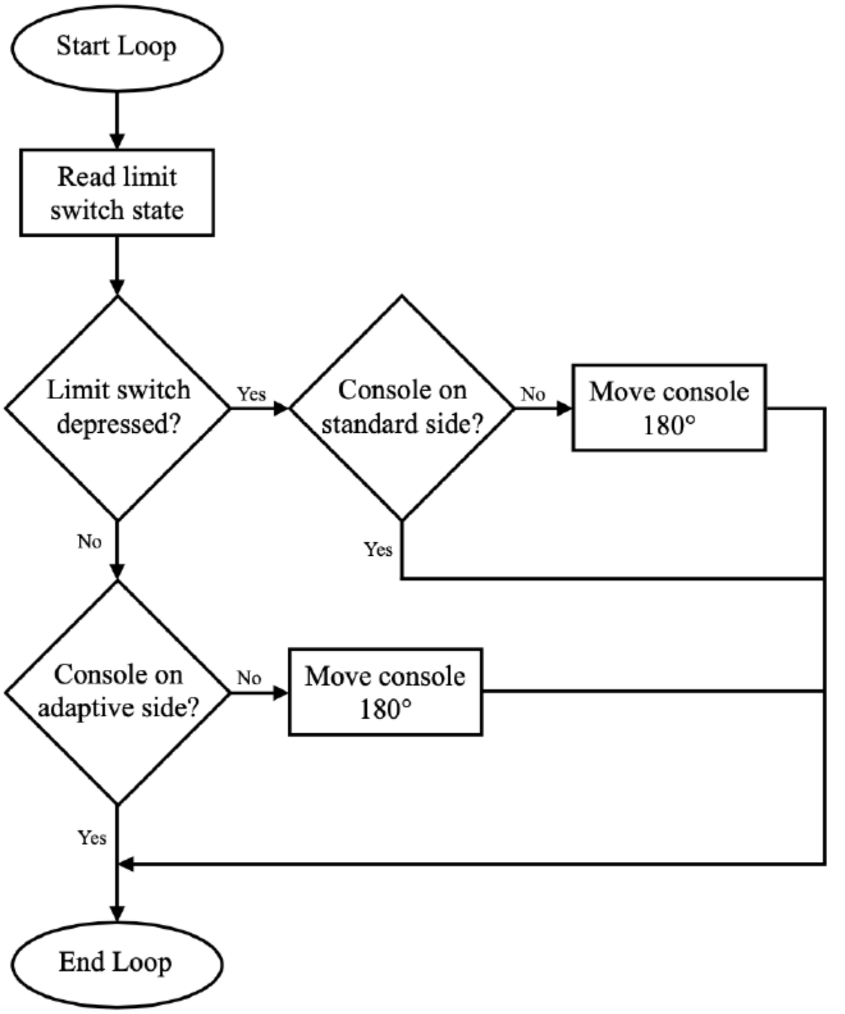


Figure 18. Coding Flowchart. The position of the console is determined by feedback from the limit switch. The console will face the standard side of the machine by default and automatically rotate to the adaptive side when a wheelchair user is secured by the stabilization frame.

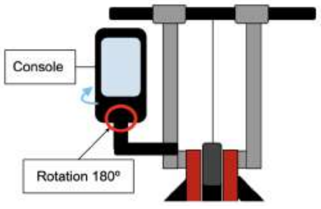
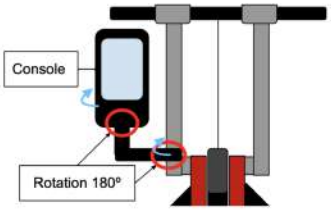
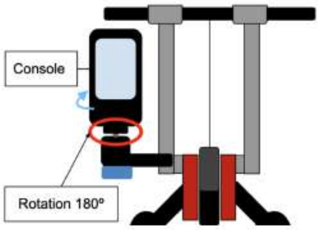
d. Console Rotation Design Criteria

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.

IV. 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 19**). 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 20** illustrates this logic in a coding flowchart.

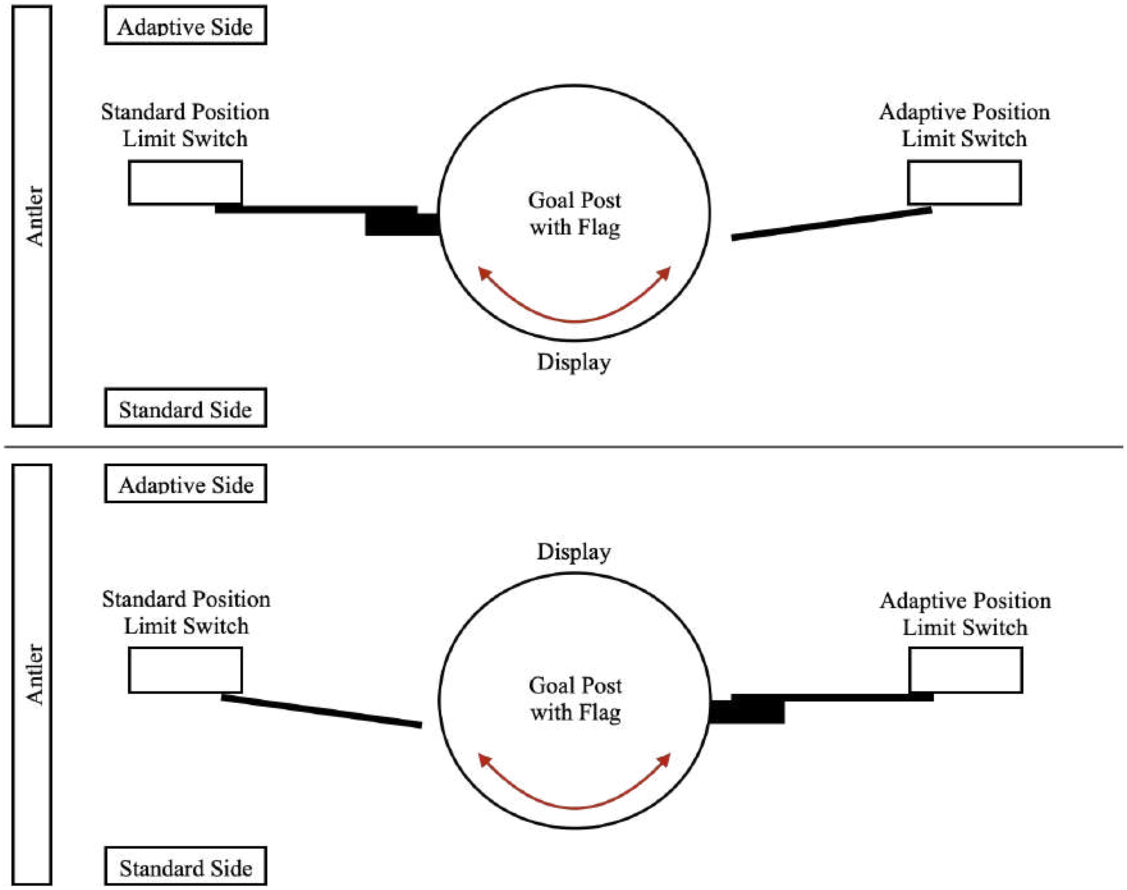


Figure 19. Standard and Adaptive Position Limit Switch Placement. Two limit switches are placed at 180 degrees from each other such that they create stop blocks for rotation between the standard and adaptive sides of the machine. In the top image, the flag on the goal post depresses the standard position 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.

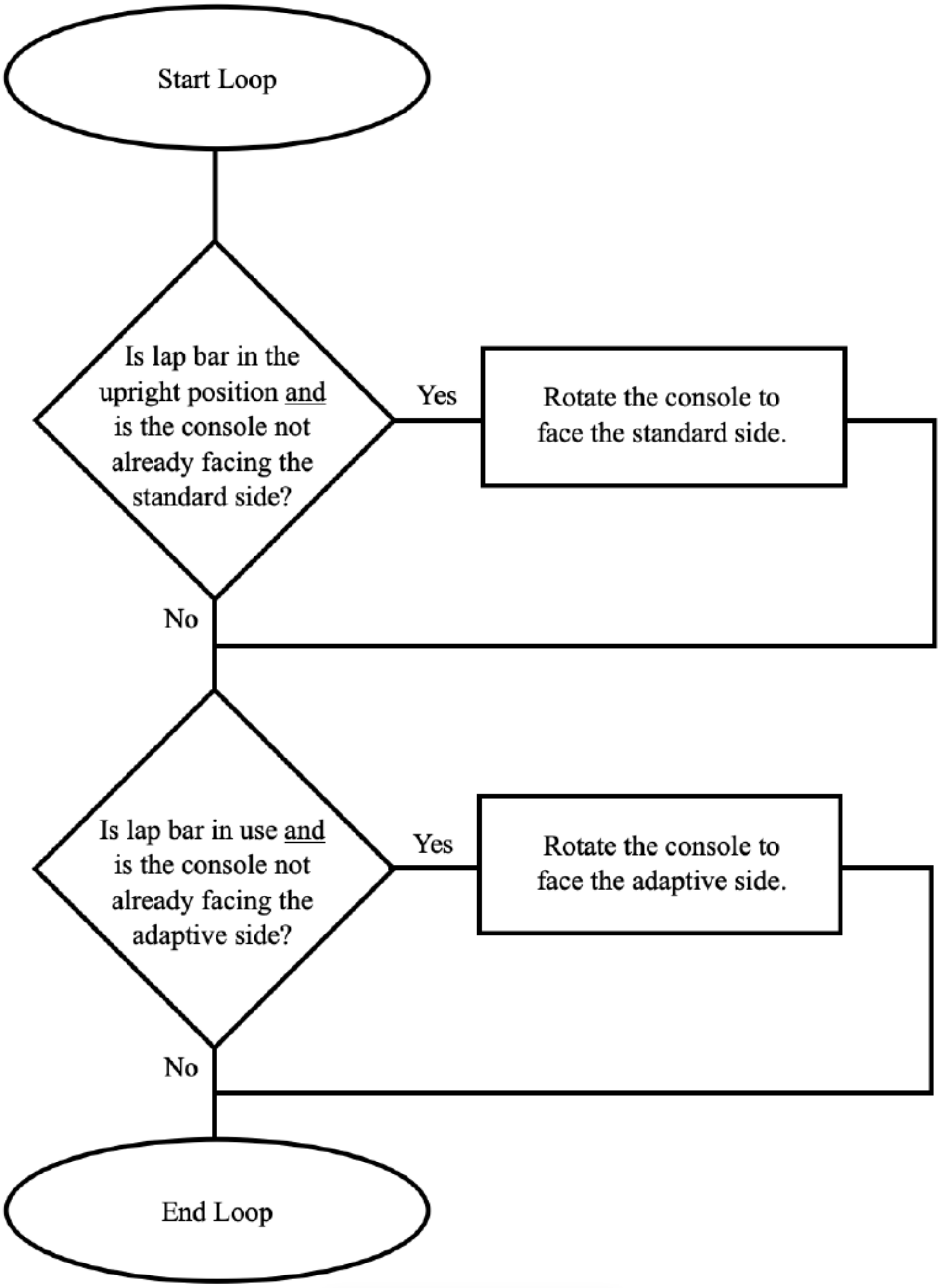


Figure 20. Final Coding Flowchart. Each loop iteration, the code checks the position of the console and compares it to its expected location according to the state of the transition limit switch placed near the pivot point of the lap bar. If the lap bar is upright and the console is not already facing 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 21**) 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].

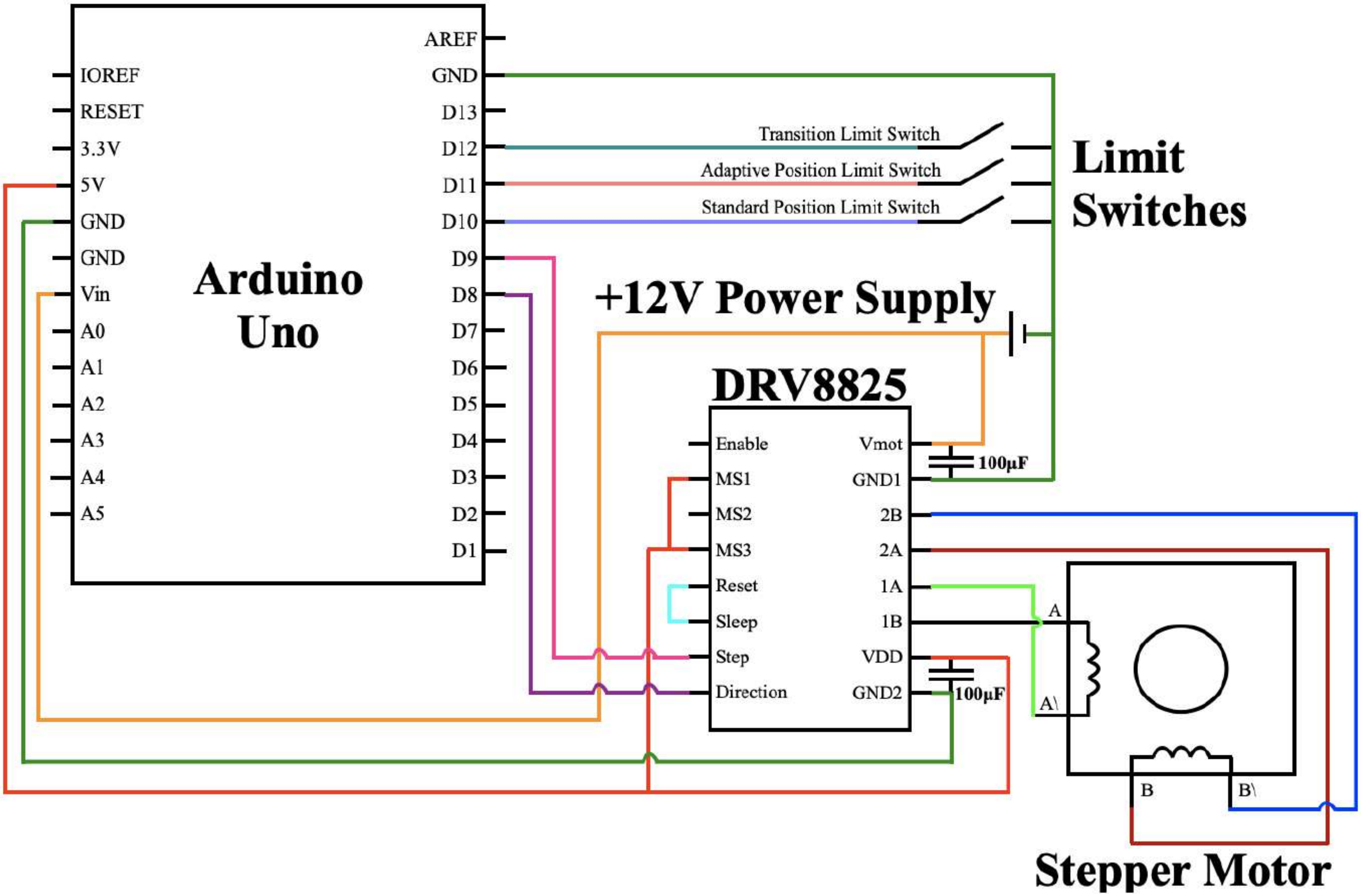


Figure 21. Final Circuit Schematic. The final circuit consists of an Arduino Uno, DRV8825, NEMA17 stepper motor, +12V power supply, two 100 µF capacitors, and three NO limit switches. The colored lines represent the wire connections present between each physical component.

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 22**). The new dimensions allowed the solder board to fit within the electronics box.

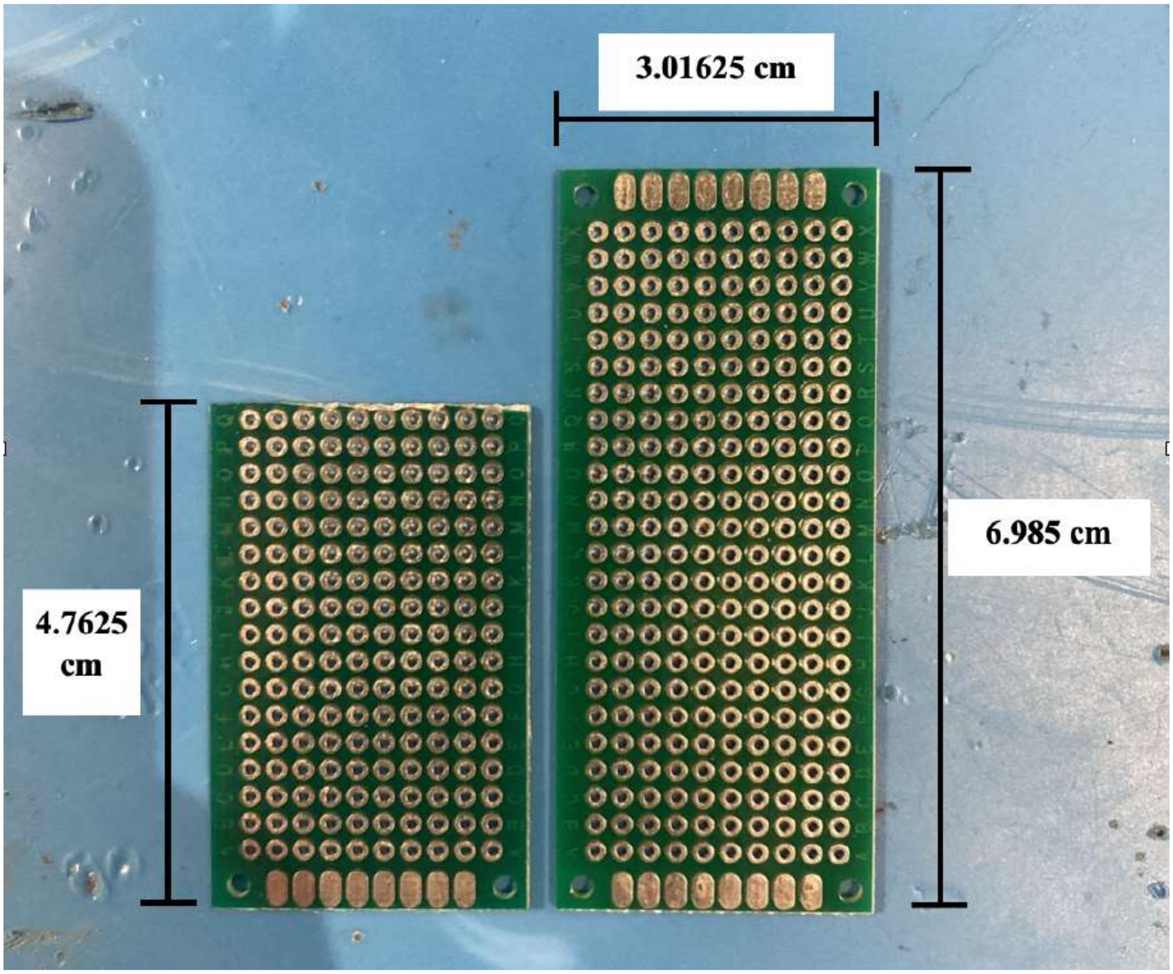


Figure 22. Solder Board. The solder board was sourced from the BME 400 storage closet. To fit within the electronics box, its length was cut down to 4.7625 cm from 6.985 cm.

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 23** 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.

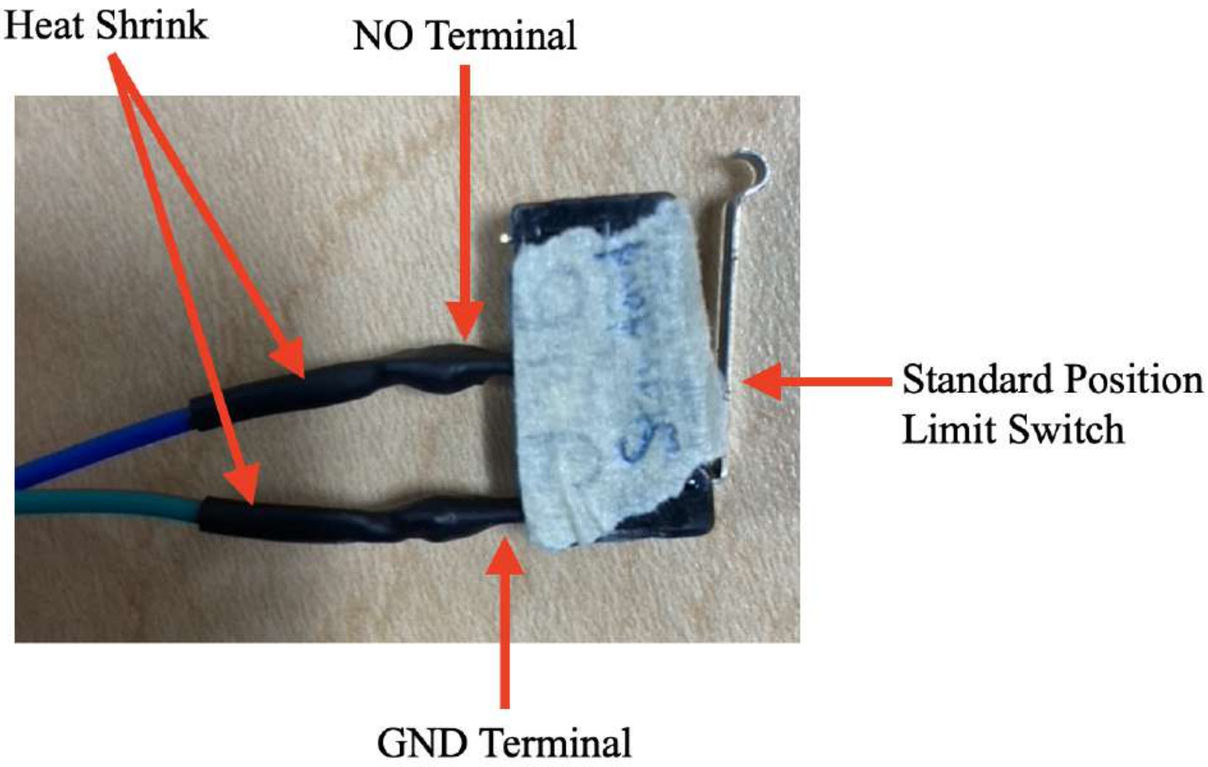


Figure 23. Standard Position Limit Switch Connections. Two wires of approximately 20.32 cm in length are soldered to the standard position limit switch. The green wire (GND) is connected to the terminal labeled with “C” while the blue wire (D10) is connected to the terminal labeled with “NO”. These connections 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 21**). 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 21**). **Figure 24** shows the top and bottom face of the solder board.

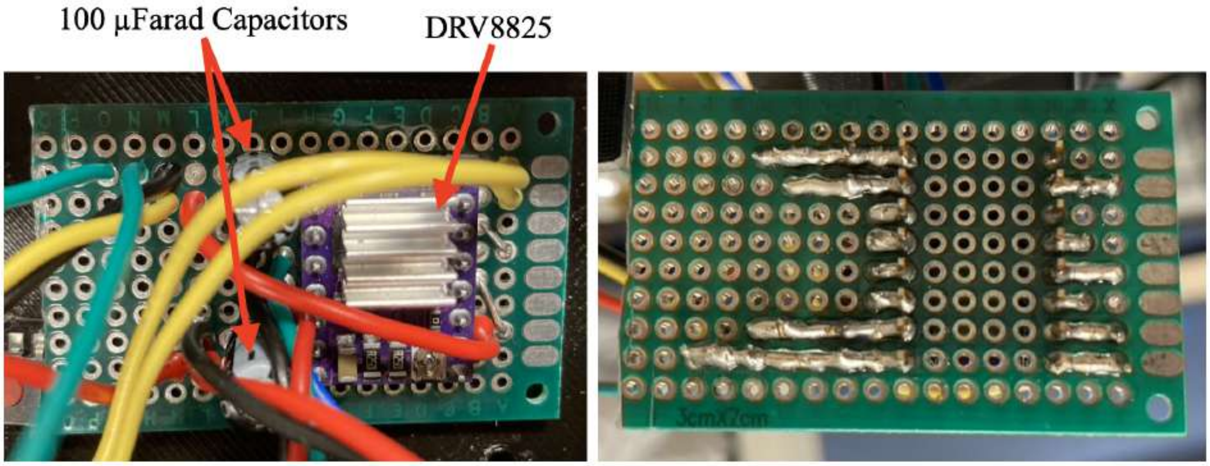


Figure 24. Solder board. The image on the left shows the top face of the solder board populated with the DRV8825, two 100 µFarad capacitors, and wire connections. The image on the right shows the bottom face of the solder board with the ties for each row of connections.

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 25** illustrates these connections according to the final circuit schematic (**Figure 21**).

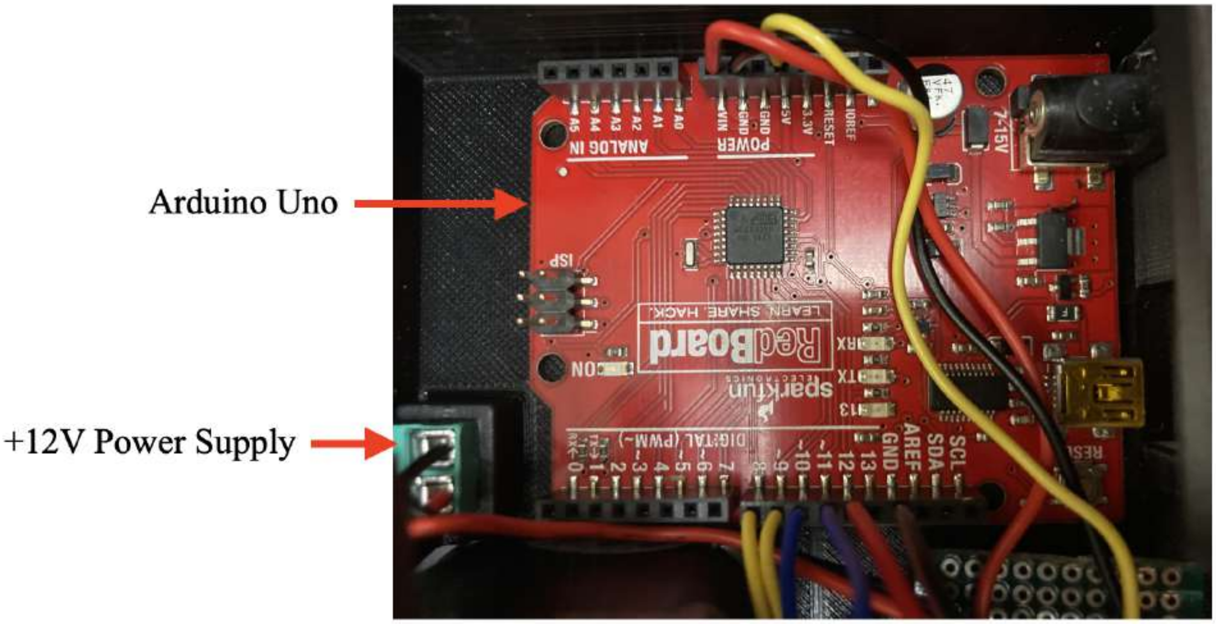


Figure 25. Arduino Uno and +12V Power Supply Connections. This image shows the wires connecting to the Arduino Uno and +12V power supply.

At this point, the final code (**Appendix C**) 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 26**) 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 27**).

The new pulley plate design also includes an antler on each plate (**Figure 26**). 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 (see **Section V.B.**). 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.

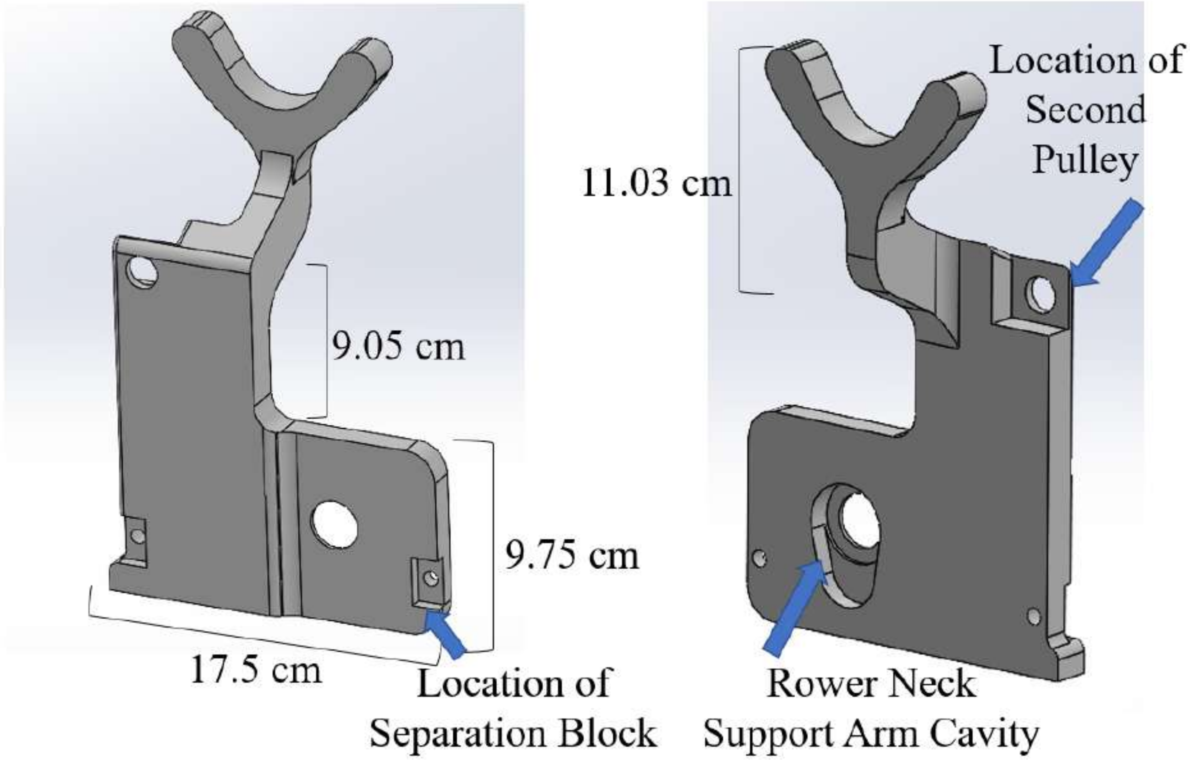


Figure 26. Pulley Support Plates with Antlers. The left and right pulley support plates are mirror images and fit tightly around the pulley bearing with a cavity that fits around the metal support arms for the rower neck. The antler extending upward on each plate holds the handlebar in a neutral location which allows it to be easily reachable from both the standard and adaptive sides of the rower.

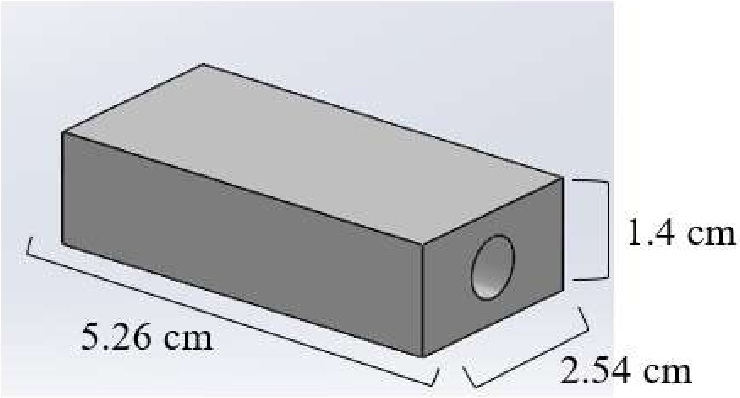


Figure 27. Pulley Support Plates Back Separation Block. The back separation block is inserted between the two pulley plates on the standard side of the rower to offer an outward reaction force that prevents the plates from slipping off the rower neck support arms inward.

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 28**). 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 29**). 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 29**. 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 (see **Section V.B.**). 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.

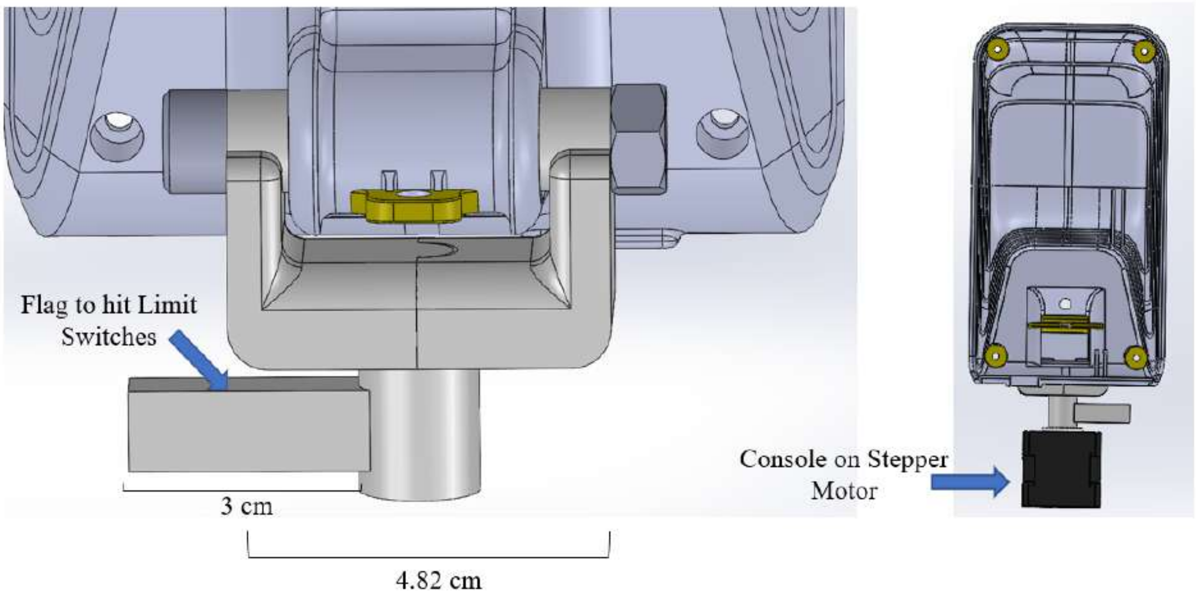


Figure 28. Field Goal Posts Allow Console Angle Adjustment. The field goal posts have cylindrical components that insert into the back of the display console to permit rotation about its original axis (left). This allows the user to adjust the angle at which the console is bent. The full console-field goal post assembly is shown attached to the stepper motor (right).

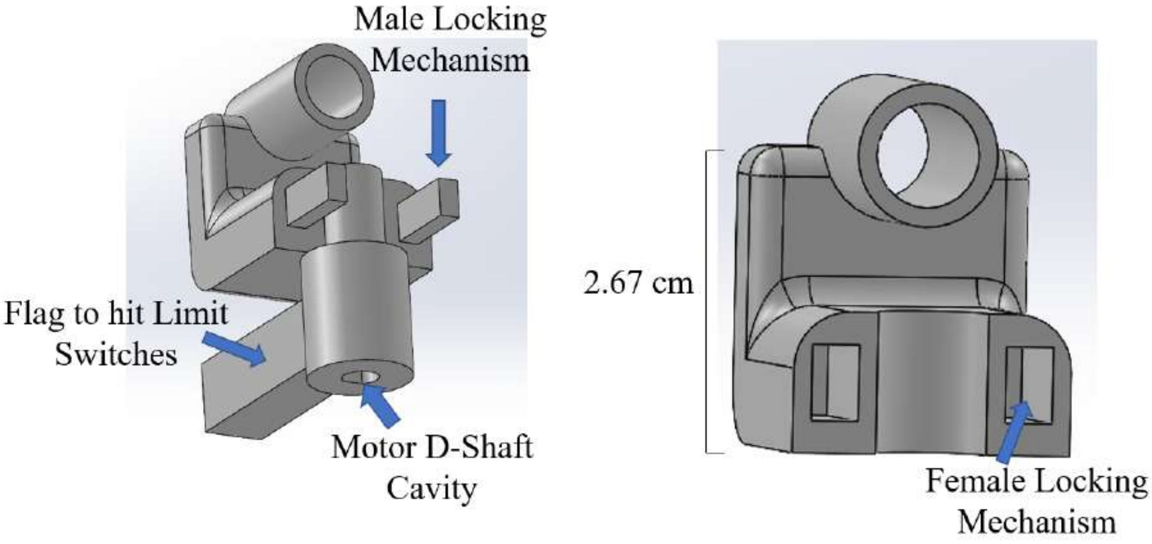


Figure 29. Female and Male Field Goal Posts. The male (left) and female (right) field goal posts fit together via extending inserts on the male piece that fit into corresponding cavities on the female piece. The male piece has a large central peg which press-fits onto the stepper motor's D-shaft and 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 30**). The box has compartments for each electrical component. First, as viewed in **Figure 30**, 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 31**) 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 (see **Section V.B.**). 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.

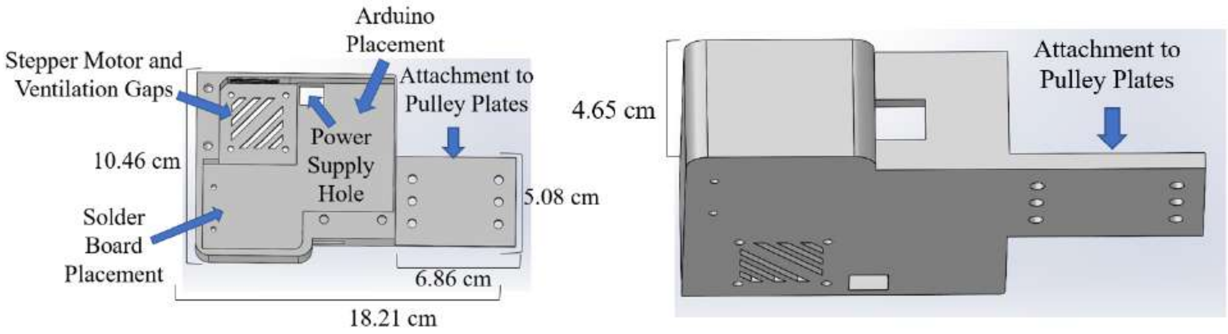


Figure 30. Electronics Box. The top view (left) and bottom view (right) of the electronics box shows sections for each electrical component, including the stepper motor, Arduino, and solder board.

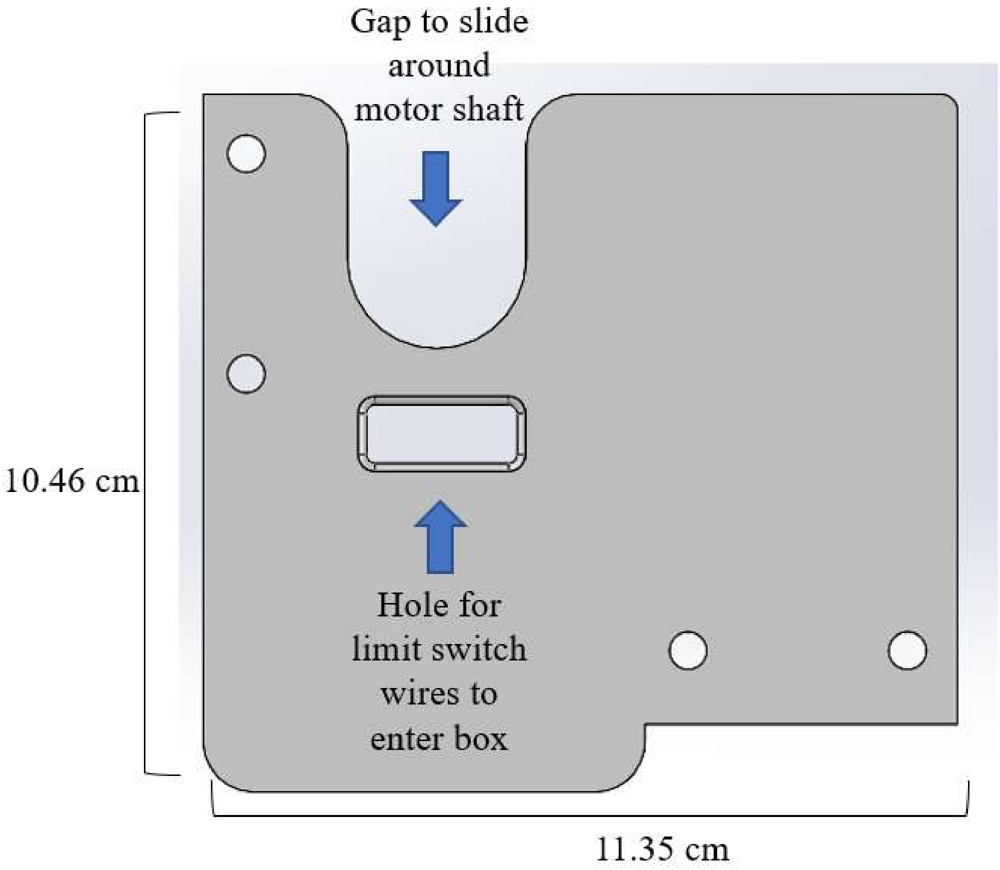


Figure 31. Electronics Box Lid. The electronics box lid fits over the electronics box to cover all electrical components. It includes a gap to allow the lid to be slid around the stepper motor shaft, and a hole to guide all limit switch wires into the box.

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 32** and in top and bottom views in **Figure 33**. 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 34**.

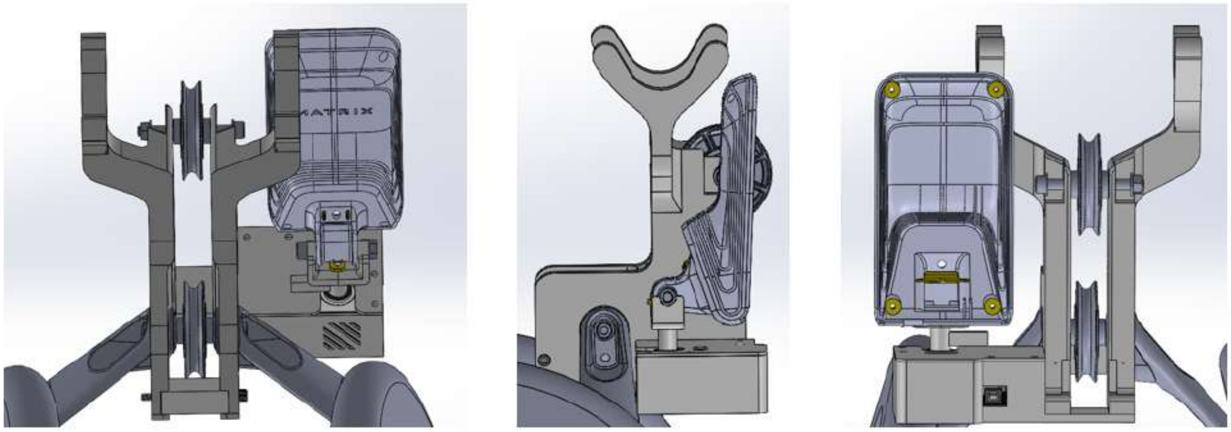


Figure 32. SolidWorks Assembly Back, Side, & Front View. The back (left), side (middle), and front (right) views of the rower assembly are shown. The adaptations made to the original rower include adding a second pulley stabilized by mirroring support plates, antlers to hold the handlebar in a central location, and an electronics box to hold all the electrical equipment that rotates the console between the standard and adaptive sides.

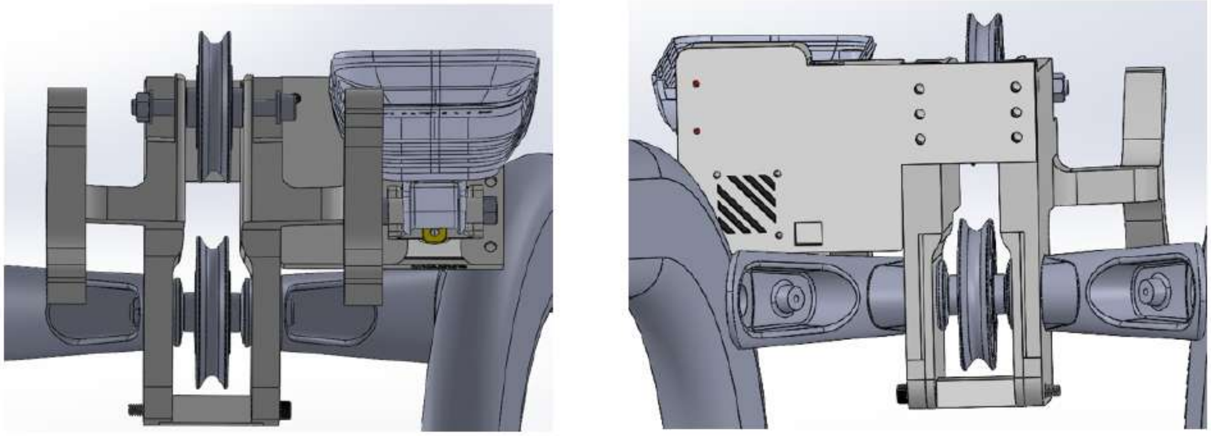


Figure 33. SolidWorks Assembly Top & Bottom View. The top (left) and bottom (right) views of the rower assembly are shown. The adaptations made to the original rower include adding another pulley stabilized by mirroring support plates, antlers to hold the handlebar in a central location, and an electronics box to hold all the electrical equipment that rotates the console between the standard and adaptive sides.

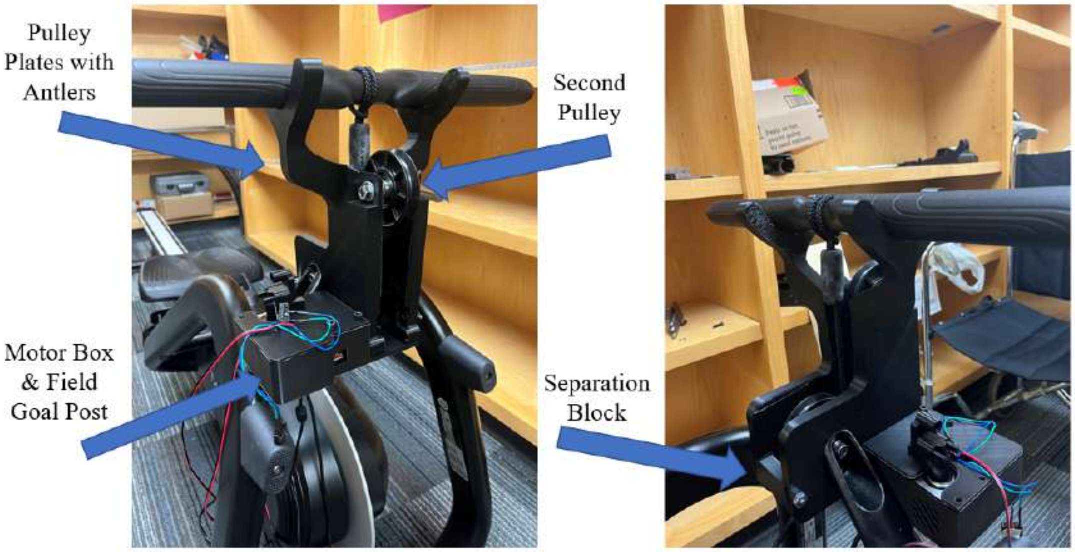


Figure 34. 3D Printed Components on Physical Assembly. The pulley plates with antlers, console rotation field goal posts, and electronics box of the full rower assembly are shown in a front (left) and back (right) view.

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 from **Section III.A.b** was modeled in SolidWorks to determine the correct dimensions of each of the bars (**Figure 35**). 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.

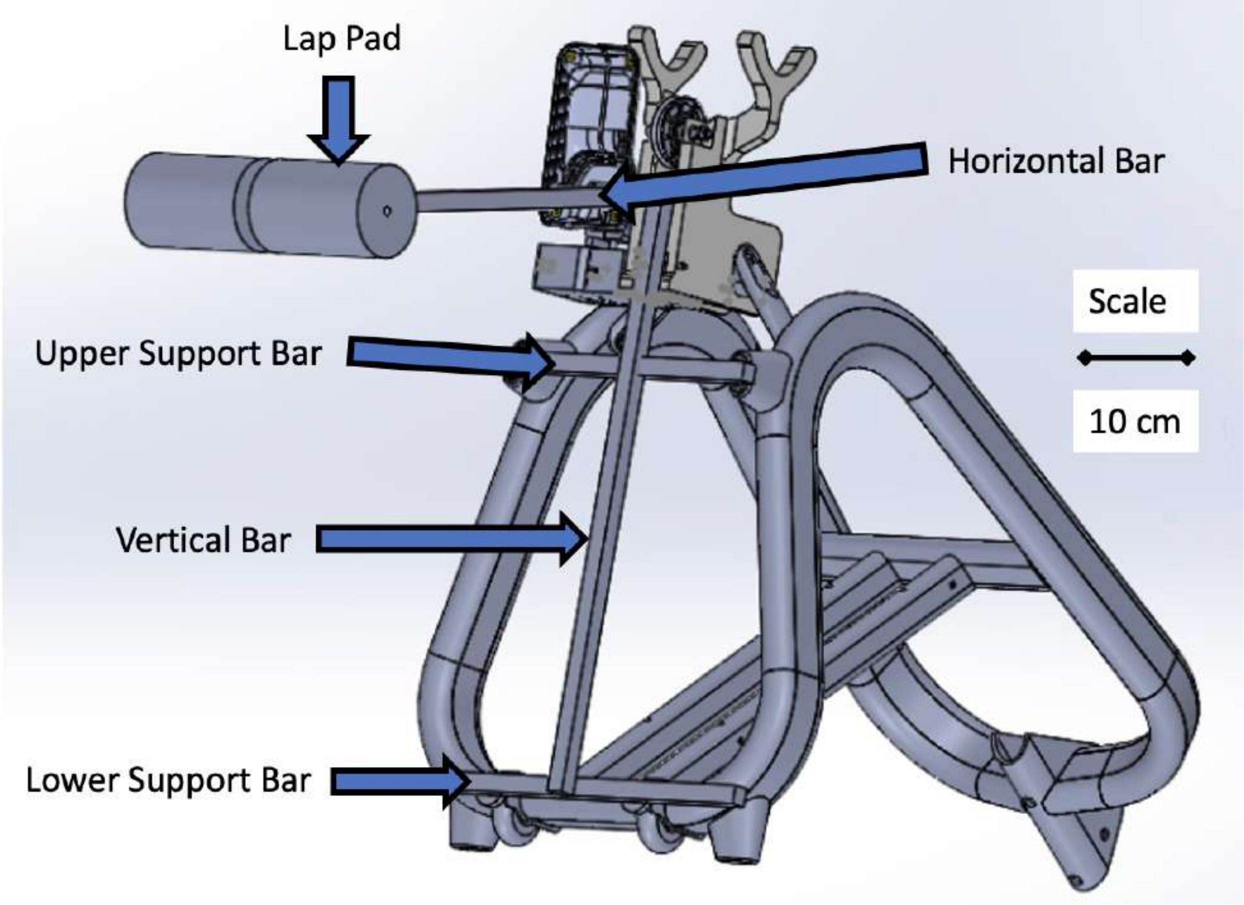


Figure 35. SolidWorks Model of Stabilization Frame. Before sourcing the steel bars from Johnson Health Tech, the stabilization frame was modeled in SolidWorks to determine each bar's dimensions.

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 36)**. 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.

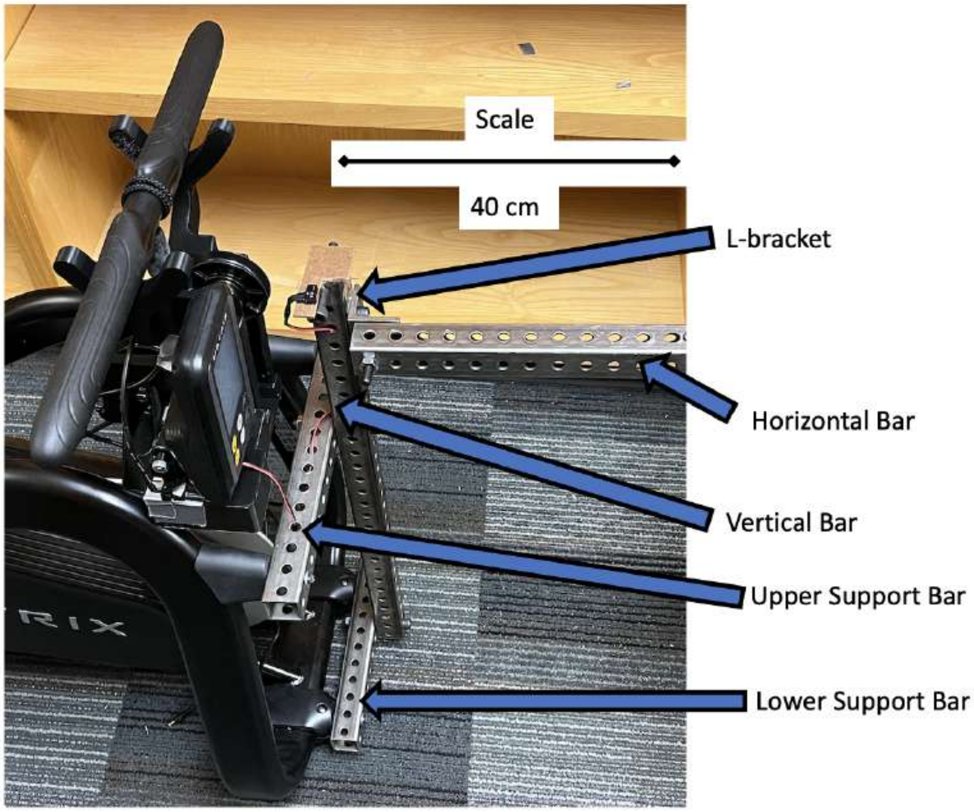


Figure 36. Stabilization Frame Components. The stabilization frame is attached to the backside of the rowing machine. It is made up of two support bars, a vertical bar, and a horizontal bar. The horizontal bar pivots at the top of the vertical bar via an L-bracket and bolt.

The lap pad was secured to the open end of the horizontal bar using two smaller perforated bars and two triangular braces (**Figure 37**). 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).

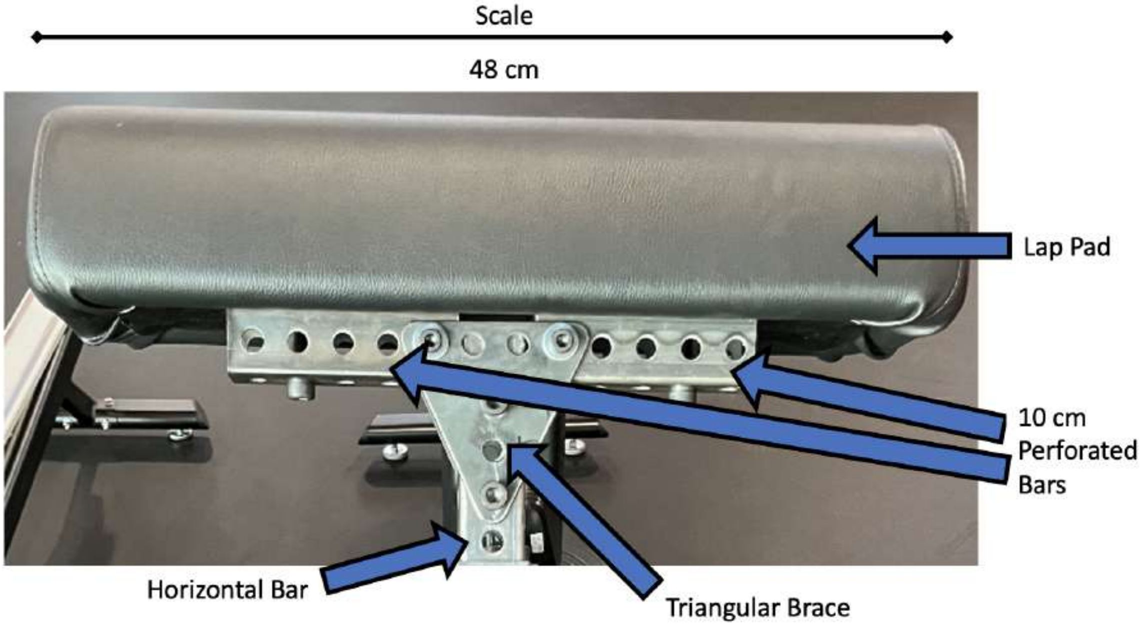


Figure 37. Pad Attachment to Horizontal Bar. The pad was attached to the horizontal bar using two smaller perforated bars, two triangular braces, and M-10 nuts and bolts.

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 38**). 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. A full list of all components purchased to create the final assembly can be seen in **Appendix D**.

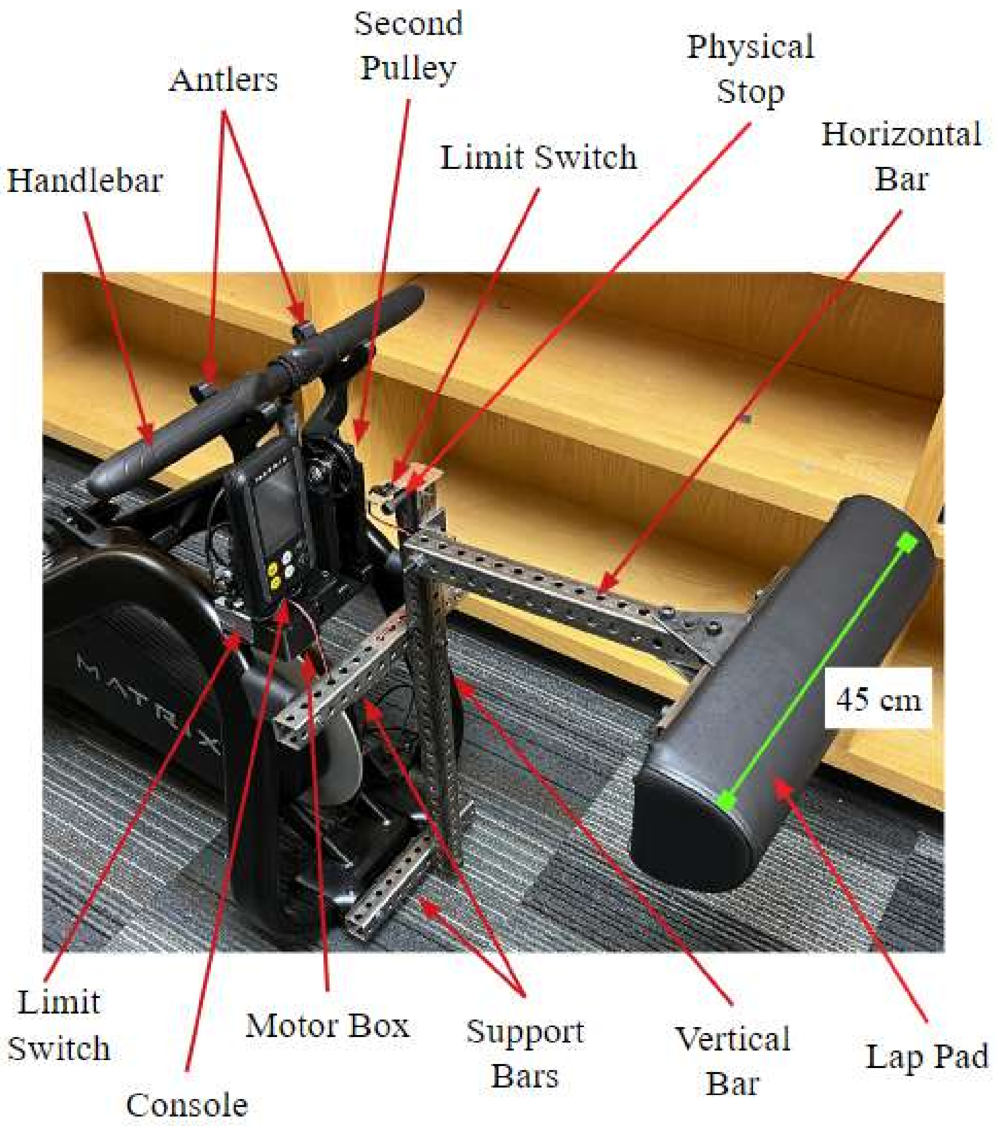


Figure 38. Full Assembly. The full assembly includes the pulley support plates with antlers, the console rotation mechanism and electronics box, and the metal adjustable stabilization frame.

V. 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 3** 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 3. 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.

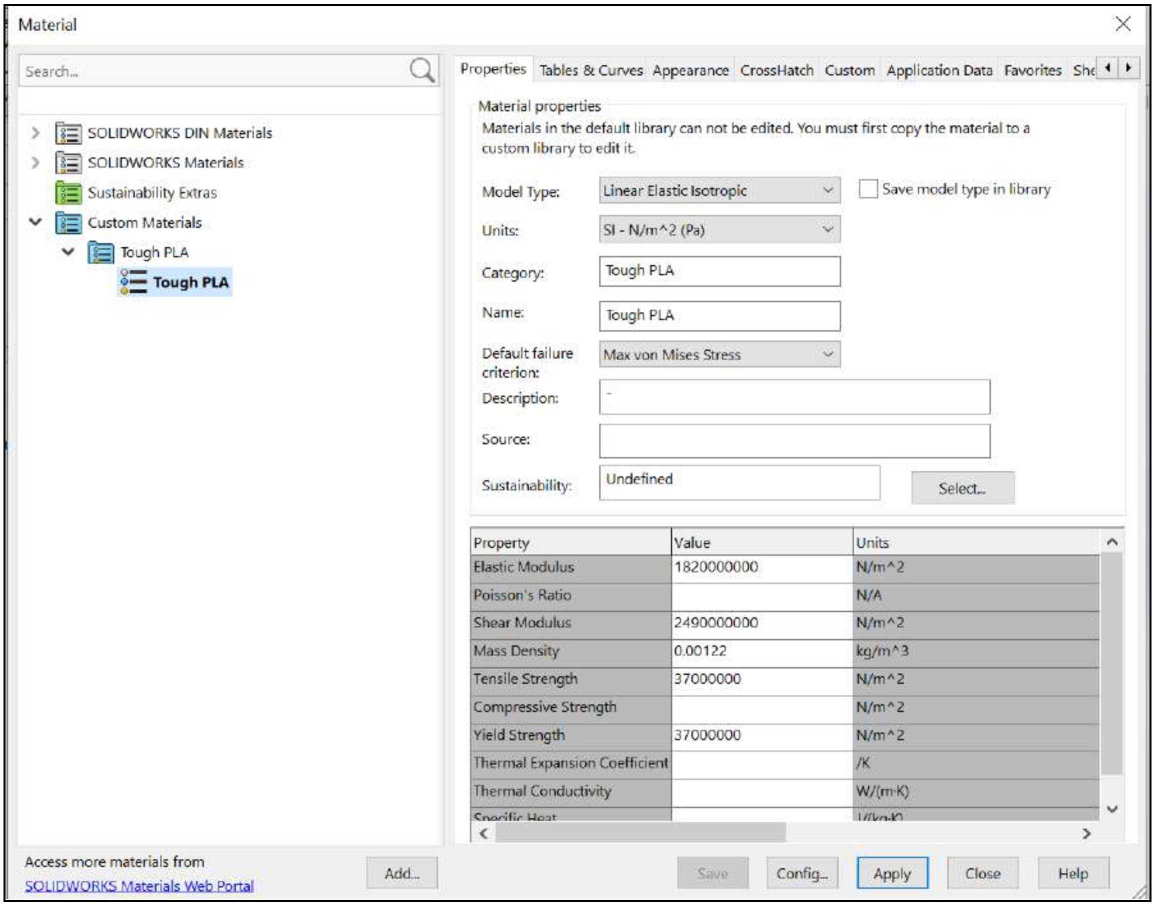
Edge Case	Testing Setup and Implementation Instructions	Expected Outcome
1	● Before power application: Position the console in no-man's land (not facing the standard or adaptive sides). Lower the lap bar such that the transition limit switch is not pressed. ● Apply power.	The console rotates to the adaptive 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 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.
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 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.	After the console finishes rotating to the position to which it was originally traveling, the console either stays there or rotates to the opposite side in accordance with the state of the transition limit switch.

B. SolidWorks Simulation

A SolidWorks simulation was conducted to analyze the stresses and displacements acquired due to a maximum, worst case load. In order to properly test the strength and geometry of the pulley support plates, the plates were modeled as Tough PLA in SolidWorks [24]. This was done by creating a new material and altering the mechanical properties as shown in **Figure 39**. 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 in **Appendix A**, this would be the maximum load applied to the additional pulley under maximum rowing effort. Ideally, this load would be transmitted equally to each pulley plate. Thus, by applying the full 1050 N load to each plate individually, this load has a safety factor of two, and represents the maximum loading of the plates [13].

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



Material properties

Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic

Units: SI - N/m^2 (Pa)

Category: Tough PLA

Name: Tough PLA

Default failure criterion: Max von Mises Stress

Description: -

Source:

Sustainability: Undefined

Property	Value	Units
Elastic Modulus	1820000000	N/m^2
Poisson's Ratio		N/A
Shear Modulus	2490000000	N/m^2
Mass Density	0.00122	kg/m^3
Tensile Strength	37000000	N/m^2
Compressive Strength		N/m^2
Yield Strength	37000000	N/m^2
Thermal Expansion Coefficient		/K
Thermal Conductivity		W/(m·K)
Specific Heat		J/(kg·K)

Figure 39. 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 40**. 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.

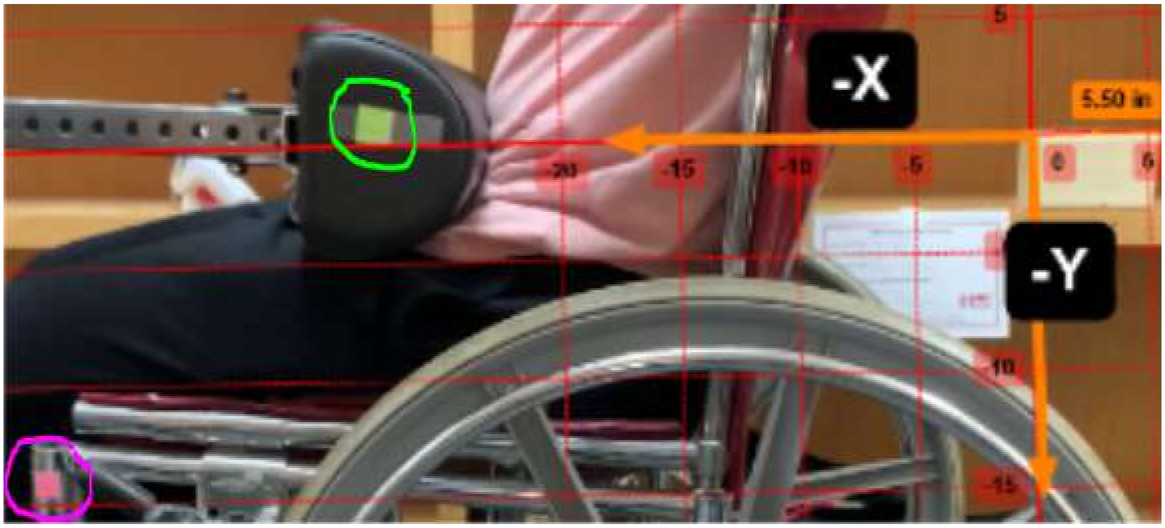


Figure 40. Motion Testing Experimental Setup. Markers (green and pink) placed on lap pad and wheelchair, respectively. Kinovea defaults the coordinate system to originate from the calibration line.

VI. Results

A. Circuit and Code Functionality

The circuit and code passed all eight edge cases implemented three times each (**Table 4**). 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 4. 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 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.	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.	3	Pass

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

*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 41**). 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 42**). This is much less than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed along the inner surface of the bearing cavity where the load was directly applied. This was expected because when the load is applied, the cavity would want to fold in on itself. Loading with a safety factor of two shows that both pulley support plates will withstand loads experienced during typical rowing.

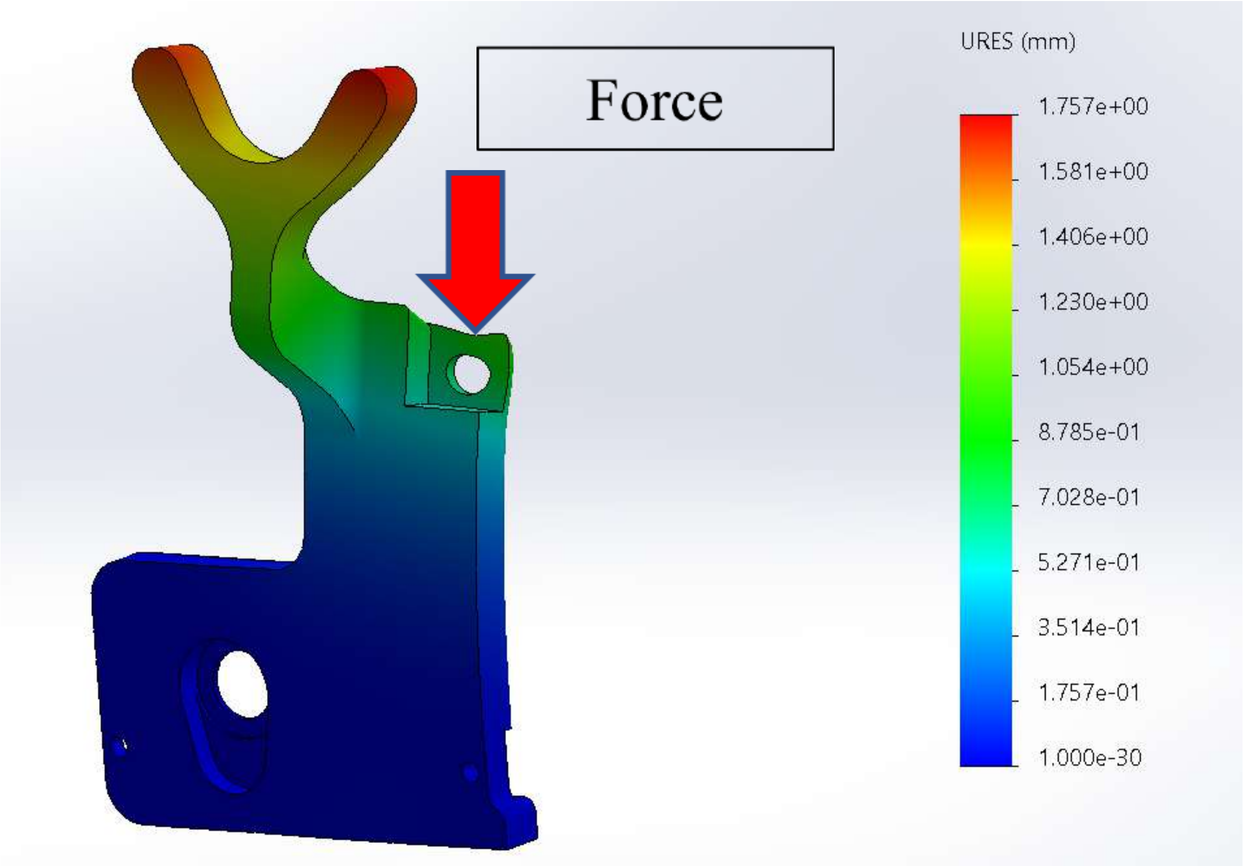


Figure 41. Pulley Plate Deformation. The pulley plate deformed the most at the tips of the antler handlebar cavity due to having the least amount of structural integrity.

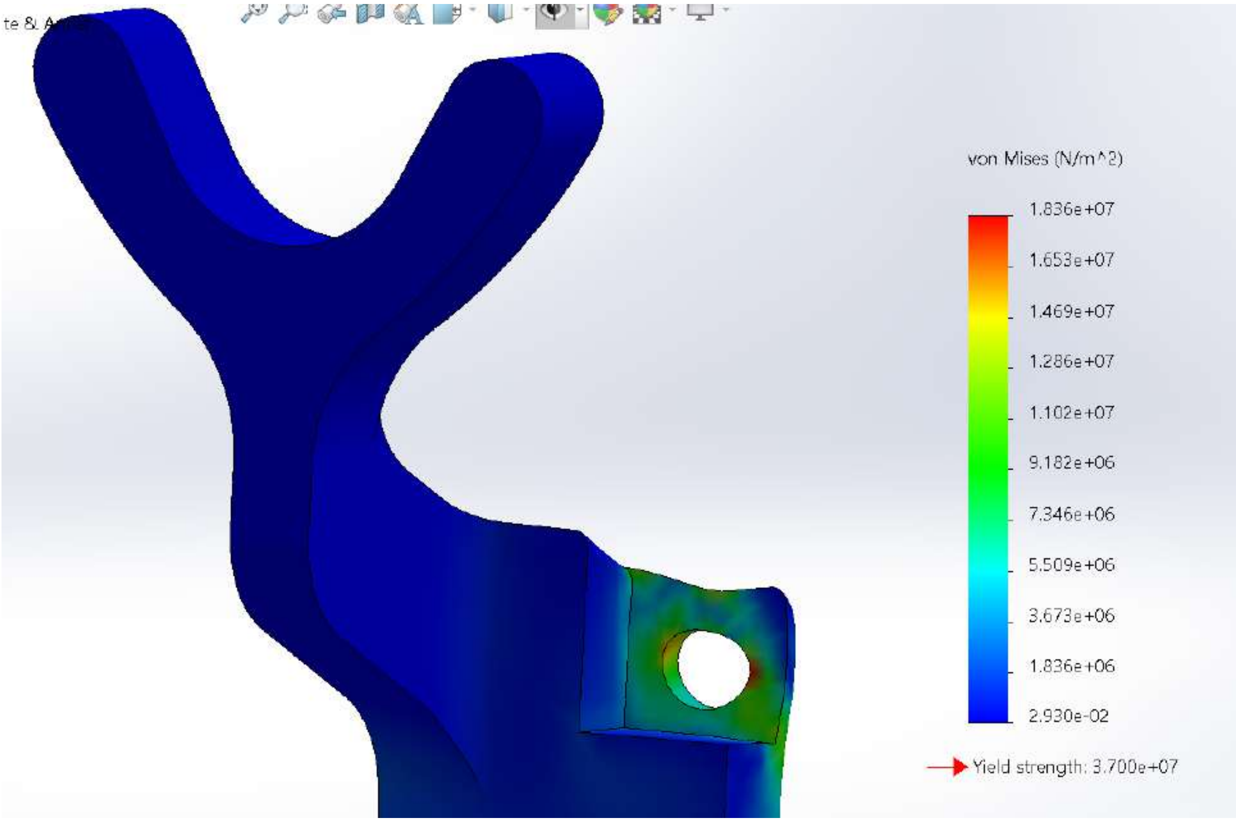


Figure 42. Pulley Plate Stress. The pulley plate developed the largest stress concentration at the outer edge of the center of the cavity in which the load was applied due to the cavity wanting to collapse.

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 43**). 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 44**). This is much greater than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed along the slanted surface of the antler which supports the handlebar cavity. This was expected because when the load is applied, the antler arm would want to bend away from the plate and fracture.

After applying a 1050 N load to the slanted edge of the inner surface of the handlebar cavity on the adaptive side of the rower directed towards the adaptive side of the rower, a maximum displacement of 29.57 mm occurred at the top of the antler handlebar cavity (**Figure 45**). 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 46**). This is much greater than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed in the same place as the previous test and was expected because the antler arm would want to bend away from the plate and fracture during loading.

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

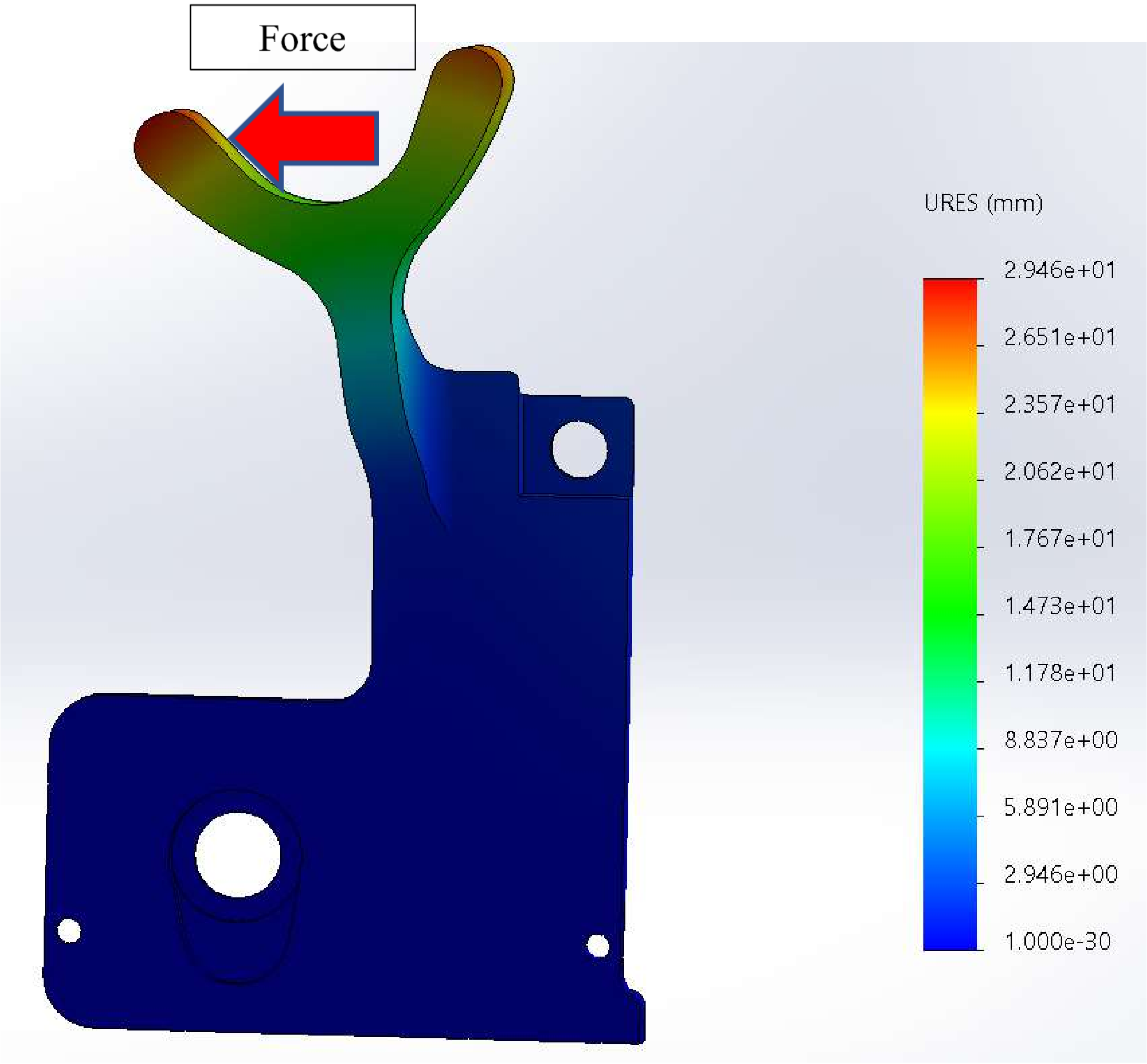


Figure 43. Antler Standard Side Deformation. The antler deflects almost 30 mm towards the standard side of the rower when subject to a very high and extreme load.

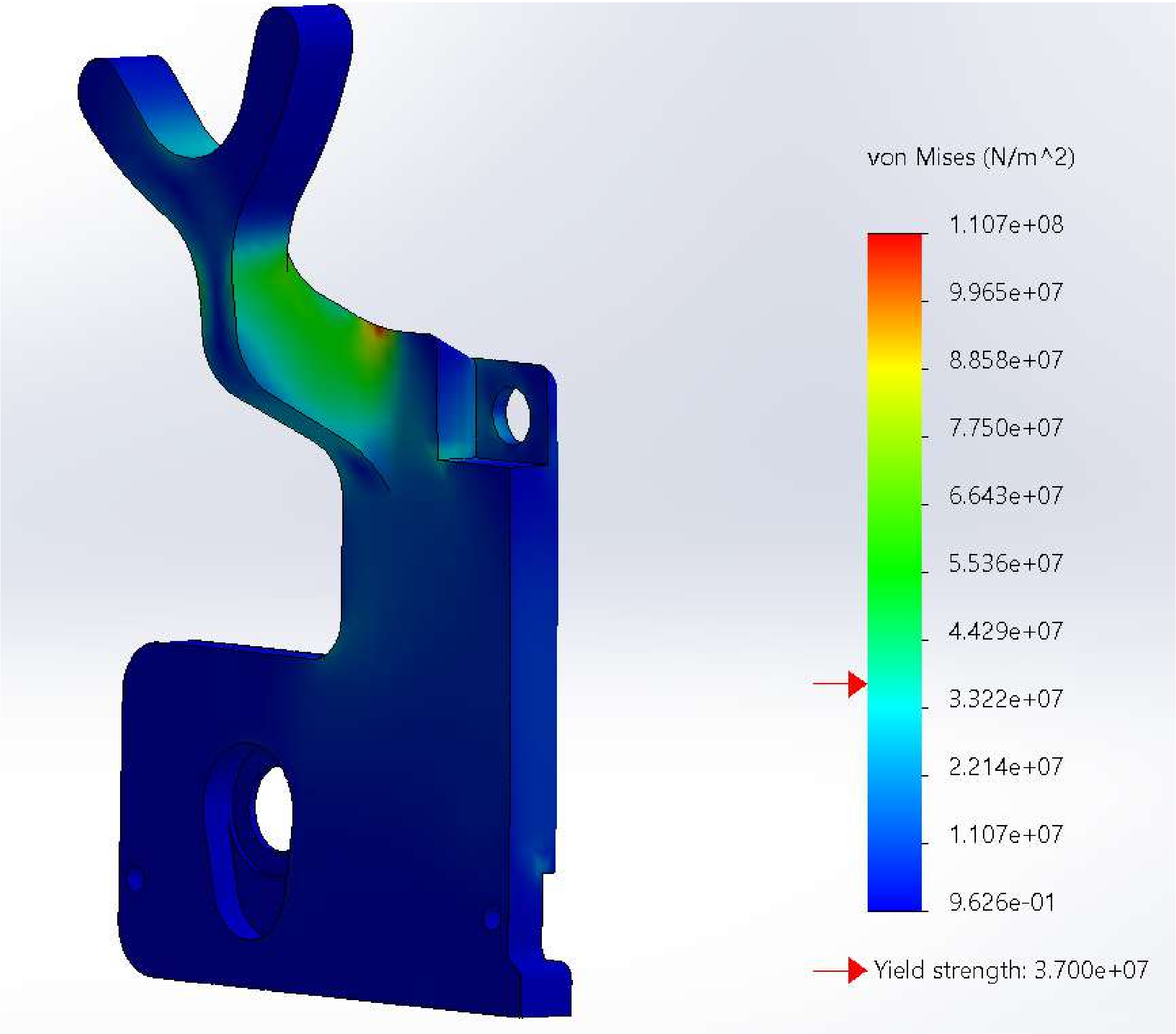


Figure 44. Antler Standard Side Max Stress. The antler develops significant stress in the arm of the antler support under extremely high and excessive loading, causing the structure to fail under this given loading scenario.

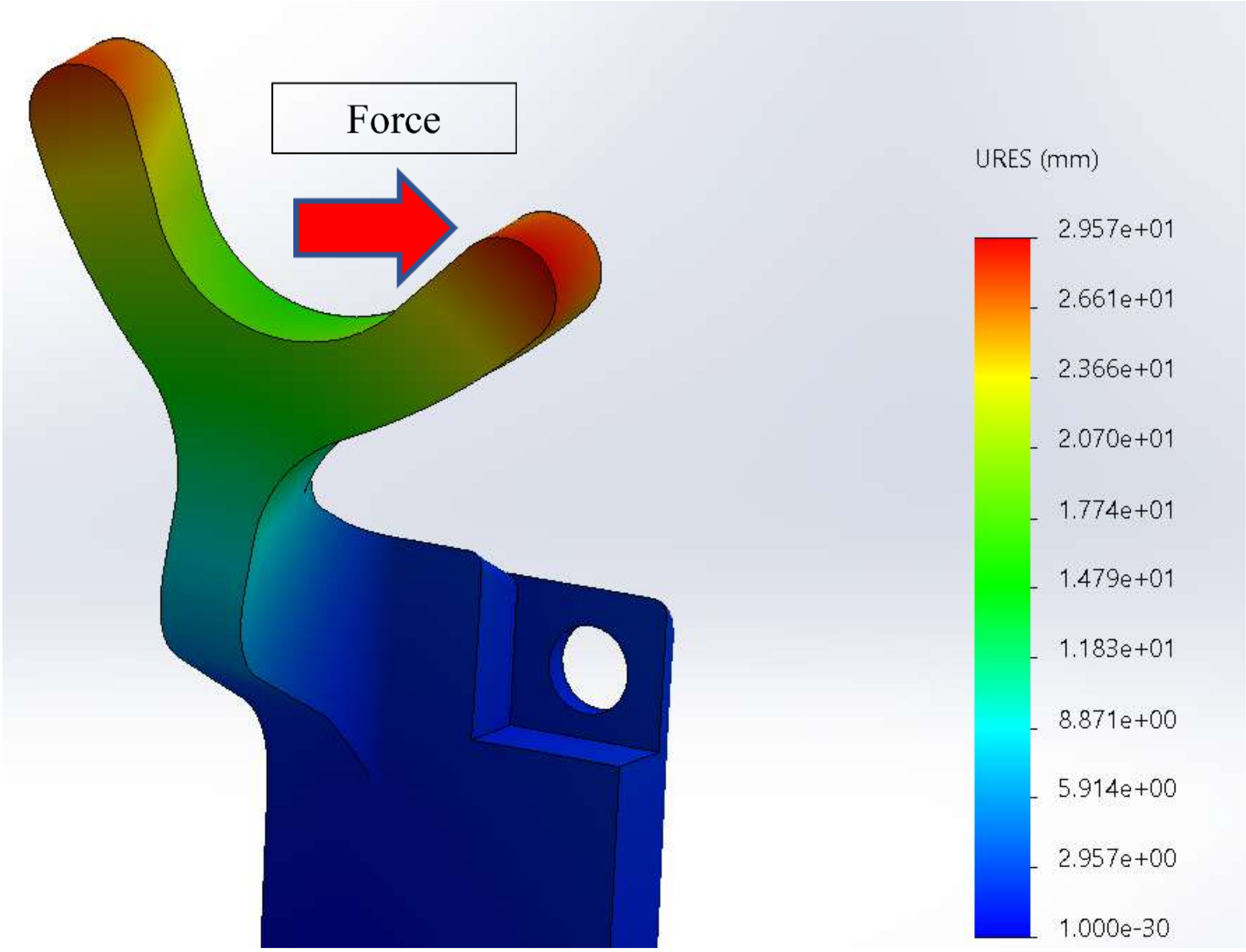


Figure 45. Antler Adaptive Side Deformation. The antler deflects almost 30 mm towards the adaptive side of the rower when subject to a very high and extreme load.

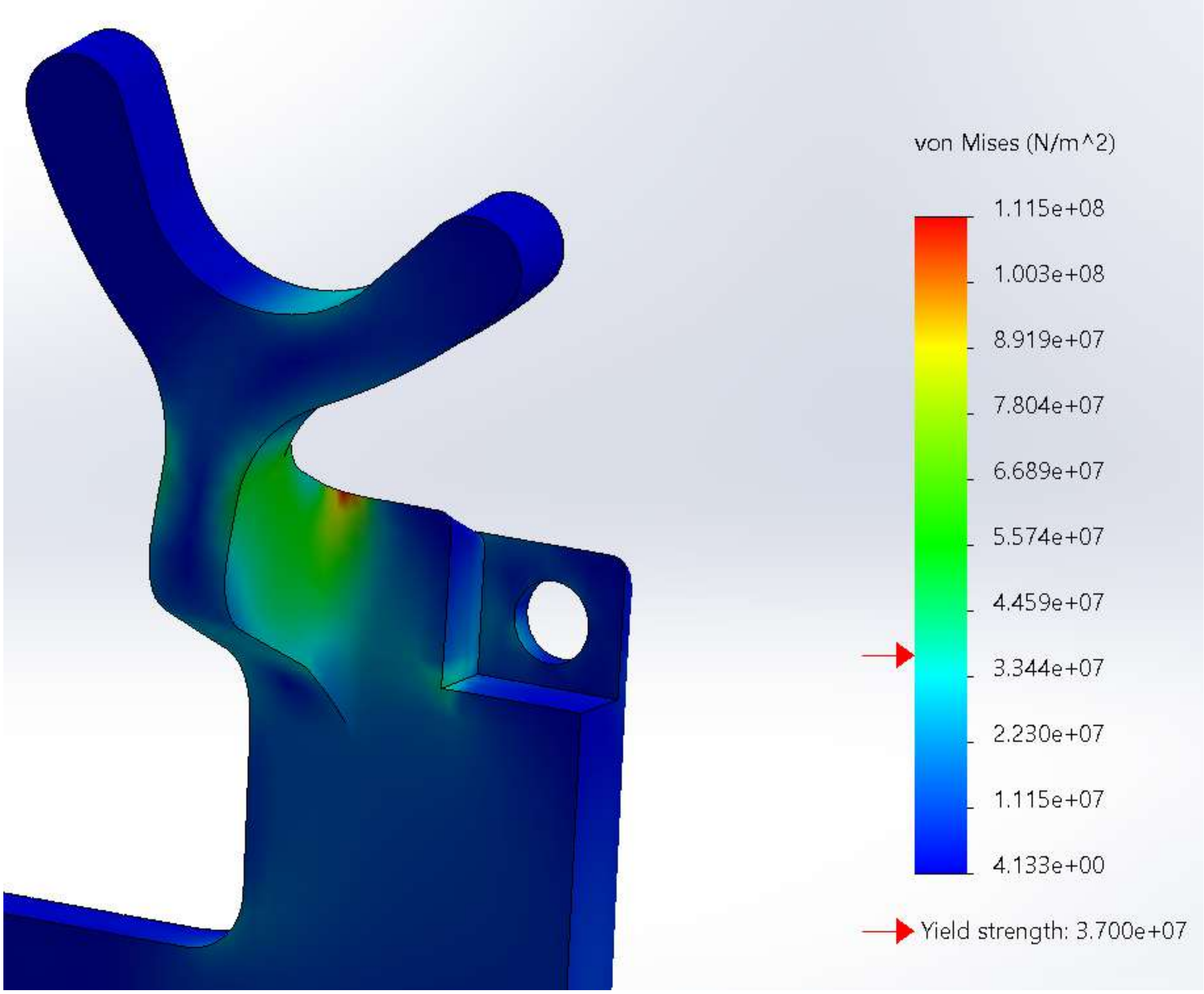


Figure 46. Antler Adaptive Side Max Stress. The antler develops significant stress in the arm of the antler support under extremely high and excessive loading, causing the structure to fail under this given loading scenario.

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 47**). 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 48**), which is much less than the yield strength of Tough PLA of 37 MPa [24]. This maximum stress developed along the edge where the box is no longer rigidly connected to the underside of the pulley plates. This was expected because when the load is applied, the box will begin to kink at this location. Loading with a safety factor of 2.25 shows that the electronics box will be able to withstand loads of the console, electronics, and extra downward directed forces, such as from the user pressing down slightly on the console when pressing a button, without fracturing or deforming excessively.

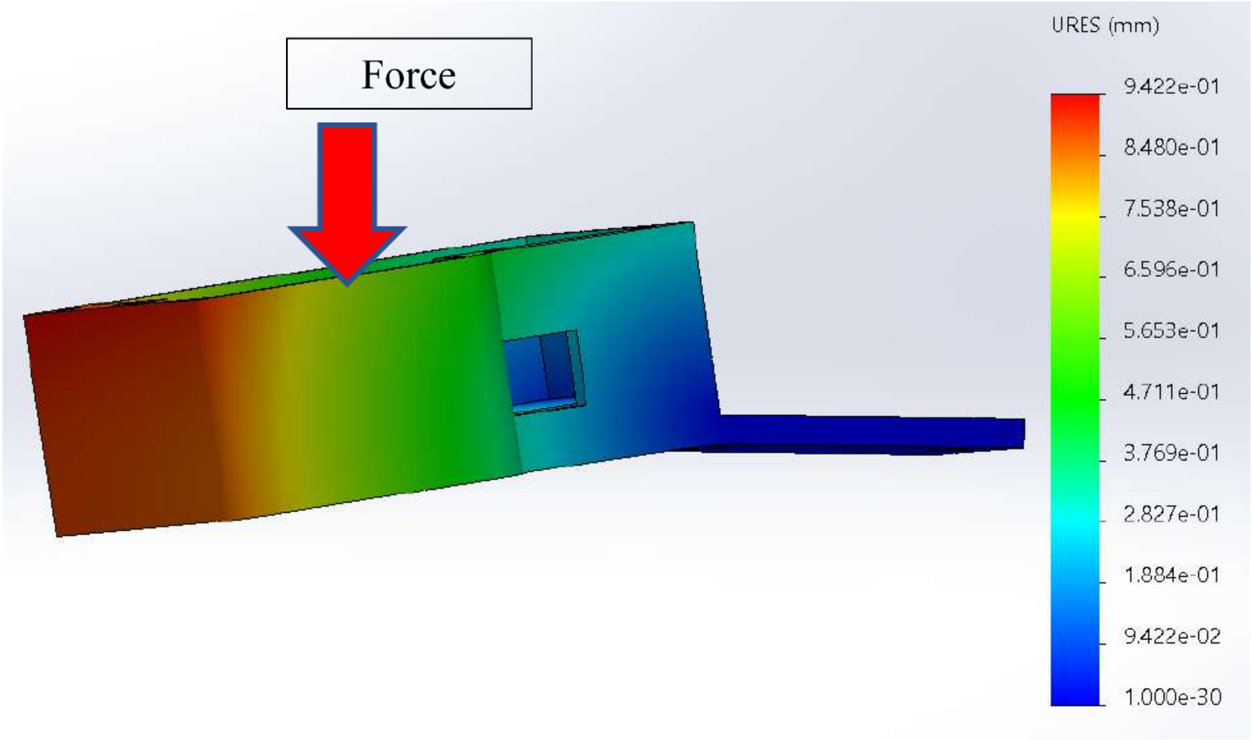


Figure 47. Electronics Box Deformation. The electronics box deflects less than 1 mm under a worst case loading, proving it is likely to succeed in holding the weight of the designed circuit.

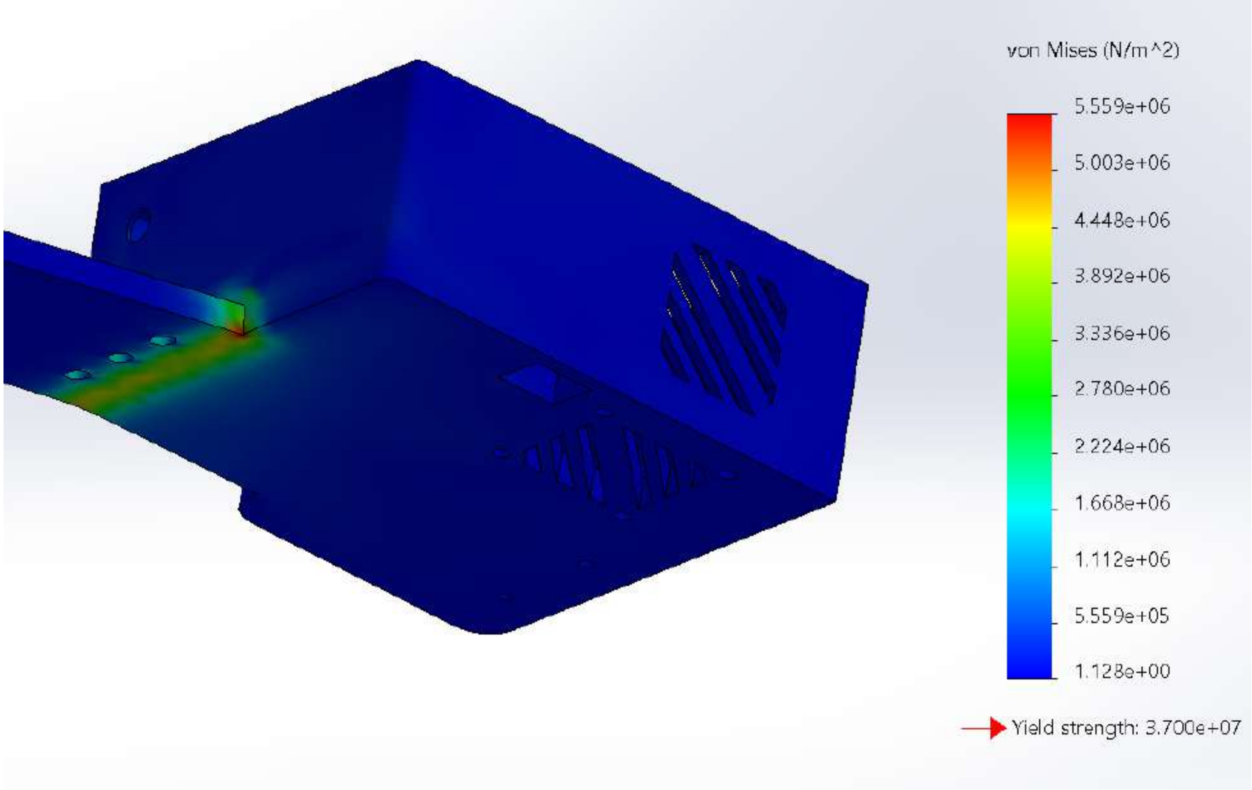


Figure 48. Electronics Box Max Stress. The electronics box has a higher likelihood to fail right at the location where it begins to bend and is no longer rigidly connected to the underside of the pulleys. However, these developed stresses are much less than the yield stress of Tough PLA, so the box is 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 49**. The complete breakdown of the lap pad and wheelchair displacements can be found in **Table 5**. 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.

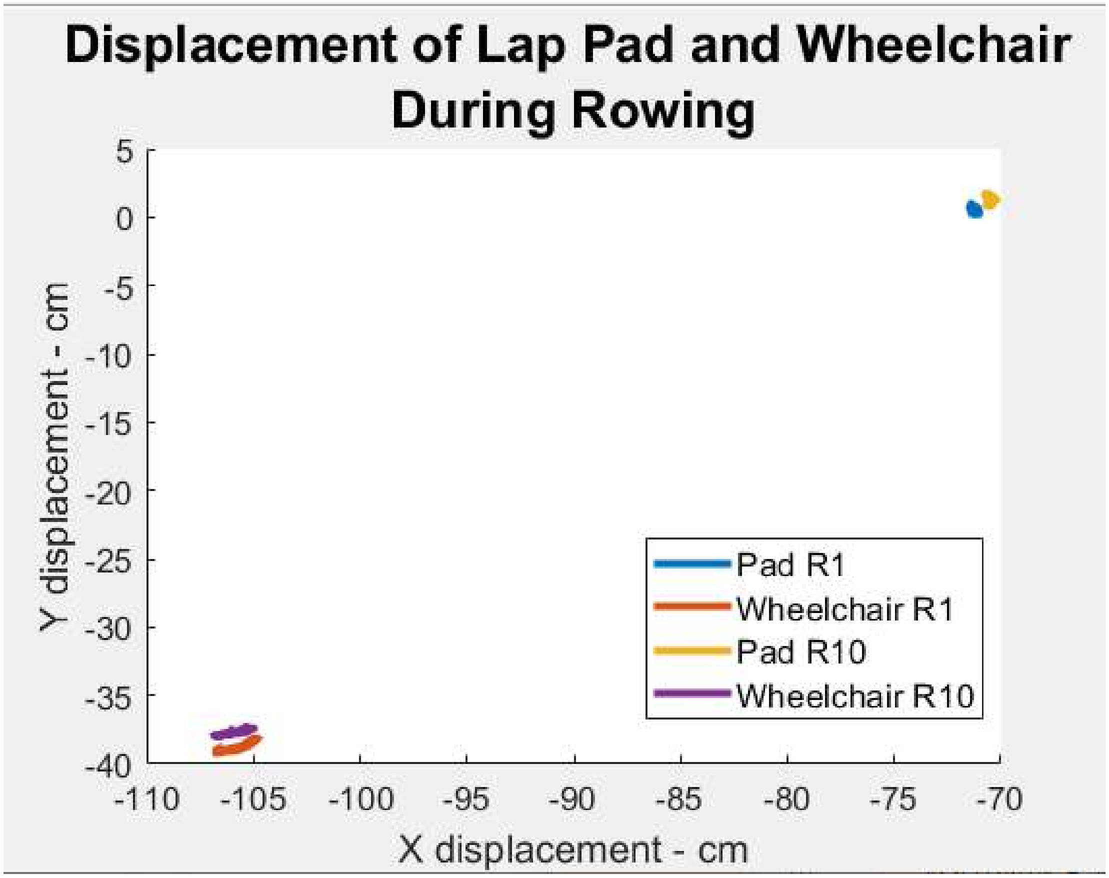
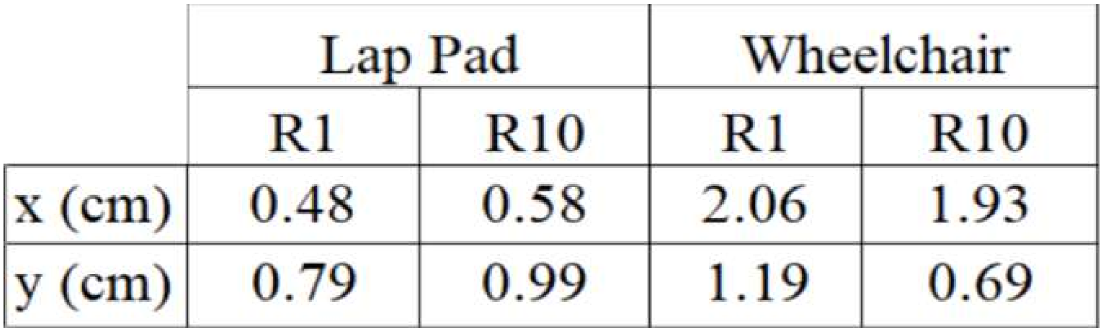


Figure 49. Diagram of Lap Pad and Wheelchair Motion. Motion of the wheelchair and lap pad during the rowing trials are represented with the four different lines. The axes are not centered at 0, due to the coordinate system originating from the calibration line.

Table 5. 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

VII. Discussion

This semester, substantial progress was made on the adaptive rower design. Successful integration of the antler and pulley plate, console, and stabilization frame designs was completed to constitute a working prototype. Entering the Fall 2022 semester, three main goals were established. First, the ease of transition of the handlebar between the standard and adaptive sides should be improved. Second, a more durable and effective stabilization frame should be incorporated into the adaptive rowing machine to secure the user and their wheelchair on the adaptive side. This frame should be adjustable to accommodate more individuals and their varying wheelchair dimensions. Lastly, a mechanism to allow the swivel of the console between both sides of the rower should be designed.

Fortunately, all of these goals were accomplished. First, the antler and pulley plate design gives the handlebar a neutral resting location which can be easily accessed from both sides of the rower and eliminates the rope tension issue from the Spring 2022 design (**Appendix B)**. Second, a durable metal stabilization frame with a lap pad was fabricated using materials supplied by Johnson Health Tech. Additionally, this semester's design was able to target a larger audience because the frame allows for height adjustment, fitting more users and wheelchairs. Finally, through the use of electronics and strategically-placed limit switches, the console automatically rotates between the standard and adaptive sides based on the position of the lap bar. This means that the user can view their workout information while rowing without having to worry about manually swiveling the console before getting set in the rowing position, improving the ease of use of the rower. The console rotation passed all of its functionality tests, as it rotated to the correct side of the rower when placed in several different edge cases.

Load and displacement testing revealed successful functionality of the pulley support plates and the electronics box but predicted failure for the antler feature on the pulley plates. SolidWorks simulations used for extreme loading cases on the 3D-printed pulley plates and electronics box indicated no signs of failure because the maximum displacements for each component were lower than the tolerance specified in the PDS, and the maximum stresses that developed were less than the yield strength of the Tough PLA material. This proved that the pulley plates and electronics box are able to withstand loads with at least a safety factor of two. The antlers were predicted to develop stresses beyond the yield strength of the Tough PLA material and develop displacements larger than specified in the PDS under extreme loading. To address this failure, the geometry will be improved, and the material will be upgraded to metal (see **Section IX.A.**). Although the antlers are likely to never experience these worst case loads, it is important for this feature to withstand worst case loading.

The stabilization frame also proved its design durability during user testing because the motion capture recorded minimal displacement of the lap bar and the wheelchair on the highest and lowest resistance settings. The wheelchair experienced greater displacement during the lower resistance trial, and the lap pad sustained greater displacement during the higher resistance trial. These results can be explained by the differing tensions developed in the rope while rowing. For the lower resistance trial, less tension develops in the rope, which allows the user to reach a higher backward velocity during the pulling phase. This faster recoil of the body impacts the wheelchair backrest and causes the wheelchair to tip and translate backwards slightly. For the higher resistance trial, a greater tensile force develops in the rope when compared with the lower resistance trial. This larger force pulls the users forward out of the wheelchair. To counteract this, the user braces themselves against the lap pad with a larger force, which ultimately moves the lap pad a greater distance. For the lower resistance trial, the user does not have to brace against the lap pad with as large of a force. This results in the lap pad not moving as much during the lower resistance trial. The updated stability frame yielded improved displacement values compared to the previous wooden stabilization frame. Wheelchair displacement was reduced from 4.09 cm in the x direction down to 2.06 cm, and the stabilization frame's displacement was reduced from 1.86 cm in the x direction to 0.58. In comparison with the previous wooden stabilization frame, this was a major improvement. During the testing of the stabilization frame, it was important to ensure the safety of the test subject.

Potential sources of error during testing could have skewed the results. During motion capture testing, potential error sources include inaccurate dimension calibration in Kinovea and movement of the recording device (phone) between takes such that it did not rest in the same spot for both resistance trials. Inaccurate placement of the calibration line in the Kinovea analysis could have also led to an unreliable displacement reading created during either rowing intensity trial. Furthermore, although users were instructed not to use their legs while rowing on the adaptive side, there was no way to completely ensure this standard was followed. Any lower extremity muscular effort by the test participant during rowing could have skewed the results of the Kinovea tests. However, since the previous Kinovea test was conducted with the same procedures, the improvements seen in the updated stabilization frame indicate a true improvement of the stabilization frame’s ability to limit movement while rowing as compared to the previously built wooden structure from Spring 2022.

Additionally, although the Fall 2022 adaptive rower design can accommodate a wider variety of wheelchair dimensions as compared to the Spring 2022 design, the stabilization frame still does not allow access to wheelchairs with narrower widths. Since the stabilization pad is too wide to fit in between the armrests of the average wheelchair, only users with wider wheelchairs can use the rower. Furthermore, users with shorter arm lengths may experience difficulty reaching the handlebar as the stabilization pad is not able to retract. These considerations must be accounted for to improve the inclusivity of the device. By catering to a larger demographic of wheelchair users, the final design will offer a more welcoming and accessible experience to the wheelchair community in comparison to the products that are currently offered.

VIII. Conclusion

Currently, there is a lack of wheelchair-accessible exercise machines, which creates a market for adaptive fitness equipment. One such machine in need of adaptation is the standard rowing machine. As requested by the client, the adaptive rowing design was enhanced to improve the exercise experience for wheelchair users and provide them with a means to actively engage their upper body and core muscles. The updated Fall 2022 adaptive rower design replaced the previous semester's wooden stabilization frame with an adjustable lap pad design which accommodates users and wheelchairs of varying sizes. The rower neck was removed, and the antler design was implemented to reposition the rower handlebar between the two pulleys for improved reachability and to resolve the previous cable tension issue. Additionally, an automated console rotation mechanism was added to improve upon the previous manual rotation bracket.

The final design was evaluated using multiple methods. An initial SolidWorks simulation was run to test the durability of the pulley plates and electronics box, which resulted in minimal deformation. The SolidWorks simulation for the antlers resulted in failure due to excessive deformation and material yielding. Displacement measurements of both the wheelchair and stabilization frame were tracked using Kinovea and analyzed in MATLAB. Excess motion of both the wheelchair and the metal stabilization frame were reduced as compared to the previous semester's design. Lastly, the functionality of the circuit and code passed edge case testing conducted to assess the system's ability to operate as intended.

The analysis of the existing adaptive rower design reveals clear successes and areas for improvement. This semester's design was successful in allowing the conversion between a standard and adaptive rowing machine and significantly improved ease of use relative to the previous semester's design. Additionally, the steel stabilization frame proved to be more effective at securing the user while rowing from the adaptive side. Finally, the automation of the console rotational mechanism between the standard and adaptive sides enhanced the ease of use of the adaptive rower design. Overall, an increased access to workout equipment allows wheelchair users to pursue a more active lifestyle and contributes to an improved quality of life.

IX. Future Work

A. Design Iterations

For future design iterations, modifications will be made to the stabilization frame. First, an angle adjustment mechanism will be incorporated between the pivot point of the vertical and horizontal bars (see **Figure 38** for visualization). This mechanism will allow for the locking of the lap pad in discrete positions to secure the user and wheelchair in place during the rowing exercise. An adjustable strap will also be included to connect the stabilization frame to the wheelchair. This strap will prevent the wheelchair from moving backward while the user is rowing. Additionally, the lap pad will be cut to a smaller width such that it fits between the armrests of wheelchairs whose armrests are 40 cm wide. This will increase the number of users who are able to access the adaptive rowing machine. As part of the stabilization frame, a mechanism that allows for the adjustment of the resistance will be incorporated. This will allow wheelchair users to alter the resistance of the rowing machine from the adaptive side rather than having to wheel over to the standard side. After all the necessary modifications are made to the stabilization frame, the bars of the stabilization frame will be welded together in the TEAMLab to strengthen the connections between the bars.

In addition to the stabilization frame, a few adjustments will be made to the 3D-printed materials and electronics. The height of the antlers will be increased to ensure that the console does not bump into the handlebars when it is rotating from one side to the other. Since the MakerSpace does not have a 3D printer large enough to print these modified antlers in one piece, the antler design will be divided into two smaller pieces that can be attached to one another via screws. This updated pulley plate and antler design will be 3D printed for initial proof of concept testing. Additionally, the dimensions of the electronics box and lid will be adjusted such that accessing the electronic components will be easier if any modifications need to be made. Ultimately, both the pulley plates with antlers and electronics box with lid will be fabricated at Johnson Health Tech out of steel to increase their strength and durability. Screws will be used to permanently attach the limit switches to the adaptive rower. Lastly, sleep mode and interrupt functions will be incorporated in the console rotation code to reduce the power consumption of the electronics.

B. Testing

For future testing, a strength test of the antler design will be conducted using an MTS machine. Although SolidWorks simulations have already been conducted to determine the durability of the antlers, completing the strength test will deliver more accurate results. In addition to an MTS test, another test will be conducted to simulate a more extreme scenario for the antler design. Sometimes, rowing machine users release the handlebar before returning it to its resting position. In order to test the durability of the antler design, the handlebar will be pulled back from the resting position and let go to crash into the antlers. Lastly, both wheelchair and non-wheelchair users will be invited to use the adaptive rowing machine from the adaptive and traditional sides, respectively, after receiving permission from the Institutional Review Board (IRB). Data will be collected to determine the experience and ease of use of the participants. One ethical consideration involves determining how to quantify ease of use and effectiveness of the adaptations for individuals with disabilities when receiving feedback because the severity of disability varies between individuals.

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XI. Appendices

Appendix A: PDS

Johnson Health Tech: Adaptive Indoor Rower for Wheelchair Users

Product Design Specifications
Dec 14th, 2022

Client: Mrs. Staci Quam (staci.quam@johnsonfit.com)
Advisor: Dr. Tracy Jane Puccinelli (tracy.puccinelli@wisc.edu)
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Communicator: Josh Andreatta (jandreatta@wisc.edu)
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BPAG: Roxi Reuter (rmreuter@wisc.edu))
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 up to 1050 N [2].
            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 100-350 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 1050 N with a safety factor of two [2]. 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 [3]
      2. At least 8 million meters [3]

    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 [4].
- 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 [5].
    - 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.
    - iv. After application of 1050 N [2] (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 [6].
        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 [7].
    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 [8].

ii. Adapted rowing machines such as the AROW (Adapted Rowing Machine) by BCIT REDLab [9] 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 [10]. 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

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

[3] "How Long Will A Concept 2 Rowing Machine Last? - Rowing Machine 101." http://rowingmachine101.com/concept-2-rowing-machine-lifespan/ (accessed Feb. 09, 2022).

[4] J. Looker, "Reaching for Holograms: Assessing the Ergonomics of the Microsoft™ Hololens™ 3D Gesture Known as the 'Air Tap," Oct. 2015.

[5] "Stainless steel in sports and Leisure Equipment." [Online]. Available: https://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_in_Sports_and_Leisure_Equipment.pdf. [Accessed: 15-Sep-2022].

[6] "ISO 20957-7:2020 | Techstreet Enterprise." https://subscriptions-techstreet-com.ezproxy.library.wisc.edu/products/878217# (accessed Sep. 20, 2022). https://www.iso.org/standard/39908.html (accessed Feb. 09, 2022).

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[8] "Wheelchair Rowing Equipment," *The Accessible Planet*. https://www.theaccessibleplanet.com/fitness/wheelchair-rowing-equipment/ (accessed Feb.

09, 2022).
[9] “Rowing Solutions – Adapted Rowing Machine (AROW).” https://adaptederg.commons.bcit.ca/rowing-solutions/ (accessed Feb. 09, 2022).
[10] 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 Materials

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.

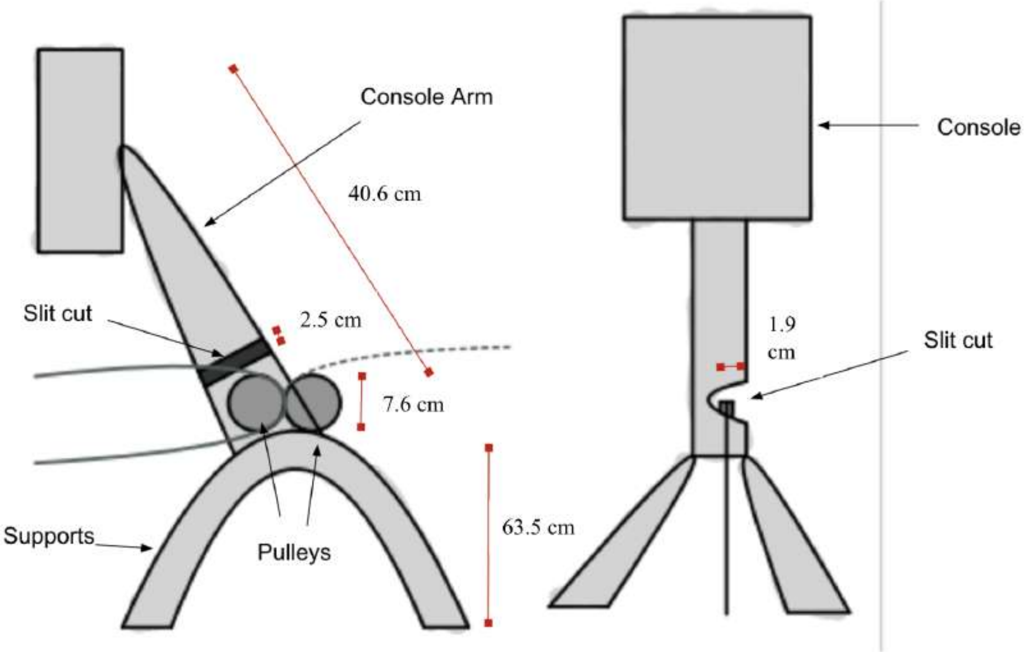


Figure 1. Visual Representation of 2 Pulleys with Slit Design. The 2 Pulleys with Slit design consists of two pulleys that are at the same height. The rope can be transferred from one pulley to the other to switch from standard to adaptive rowing. A slit cut will be made in the console arm to allow for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

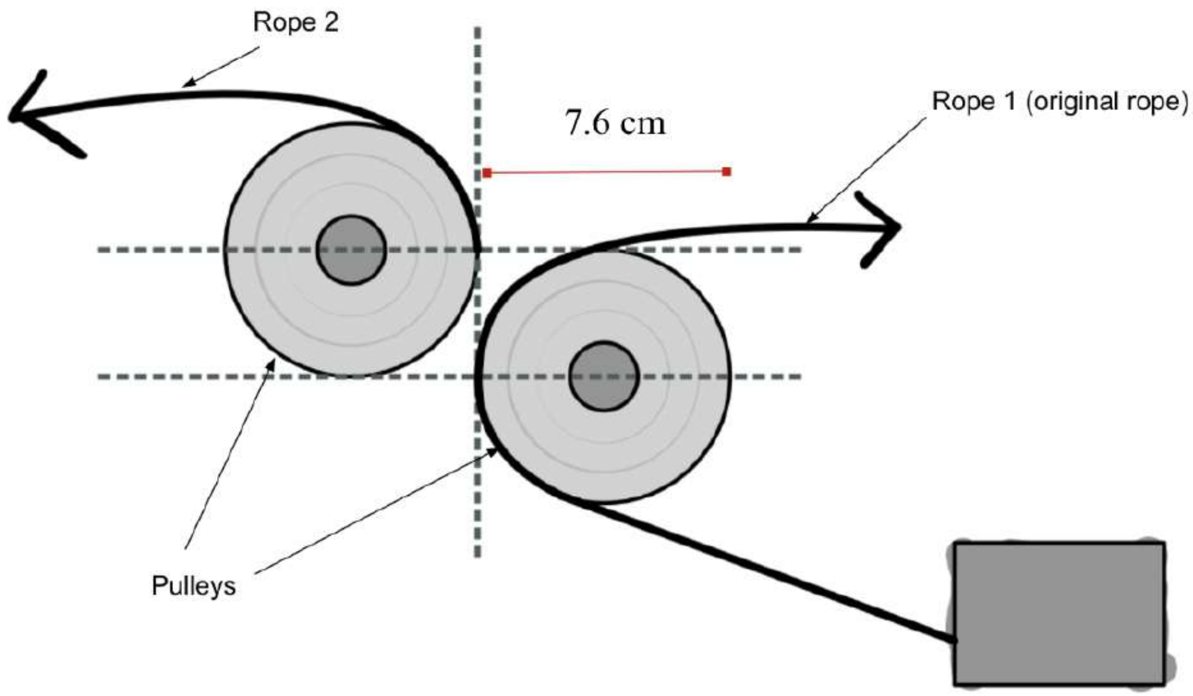


Figure 2. Visual Representation of 2 Pulleys with 2 Ropes. The 2 Pulleys with 2 Ropes design involves adding an additional pulley, handle, and rope to the existing rowing machine. The transitioning of the handle and rope from the standard side to the adaptive side would not be required since there would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

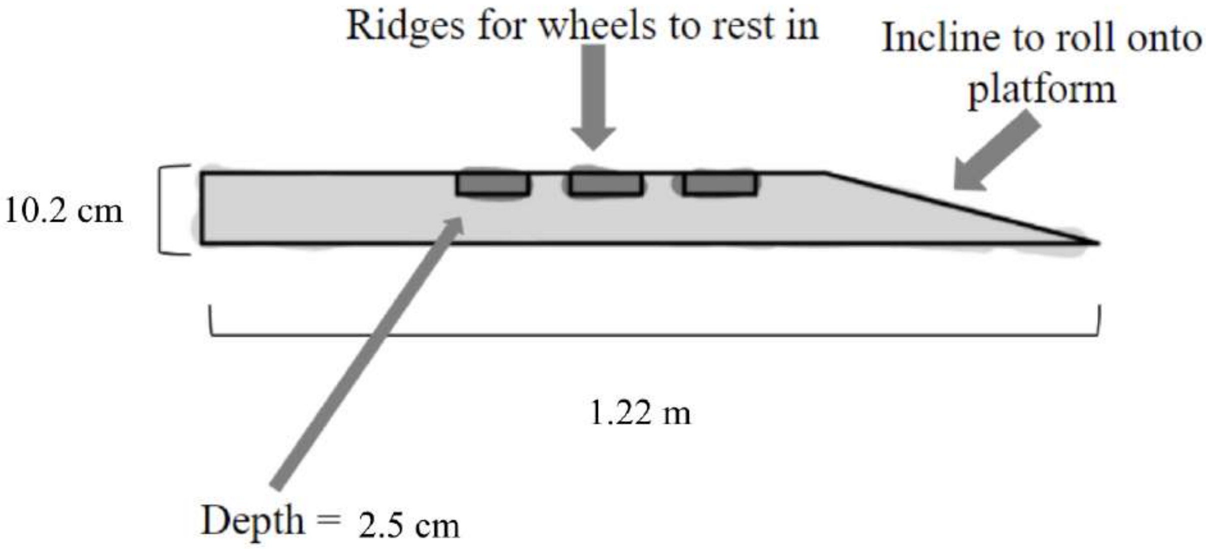


Figure 3. Visual Representation of the Highway Ridges Design. The platform has an incline down to the floor so that the user can roll up and into place on top of the platform. The base will have ridges cut into it for the wheels to rest in during the action of rowing to stabilize the wheelchair.

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.

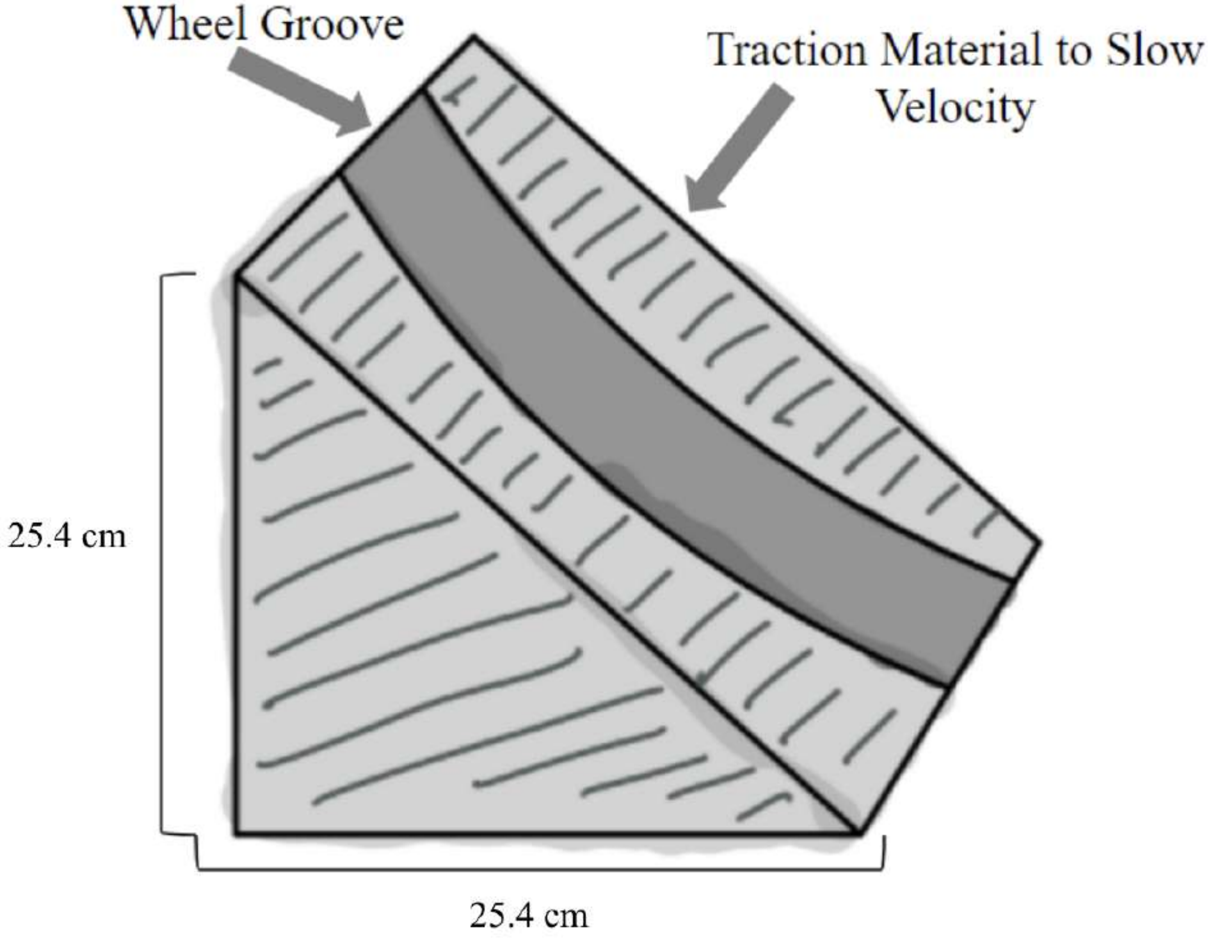


Figure 4. Visual Representation of the Traction Blocks Design. The block has a semicircle groove down the middle which allows for the user to experience slight recoil during the action of rowing. The user will roll up and into the block, which is covered in a traction-like material to reduce velocity,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

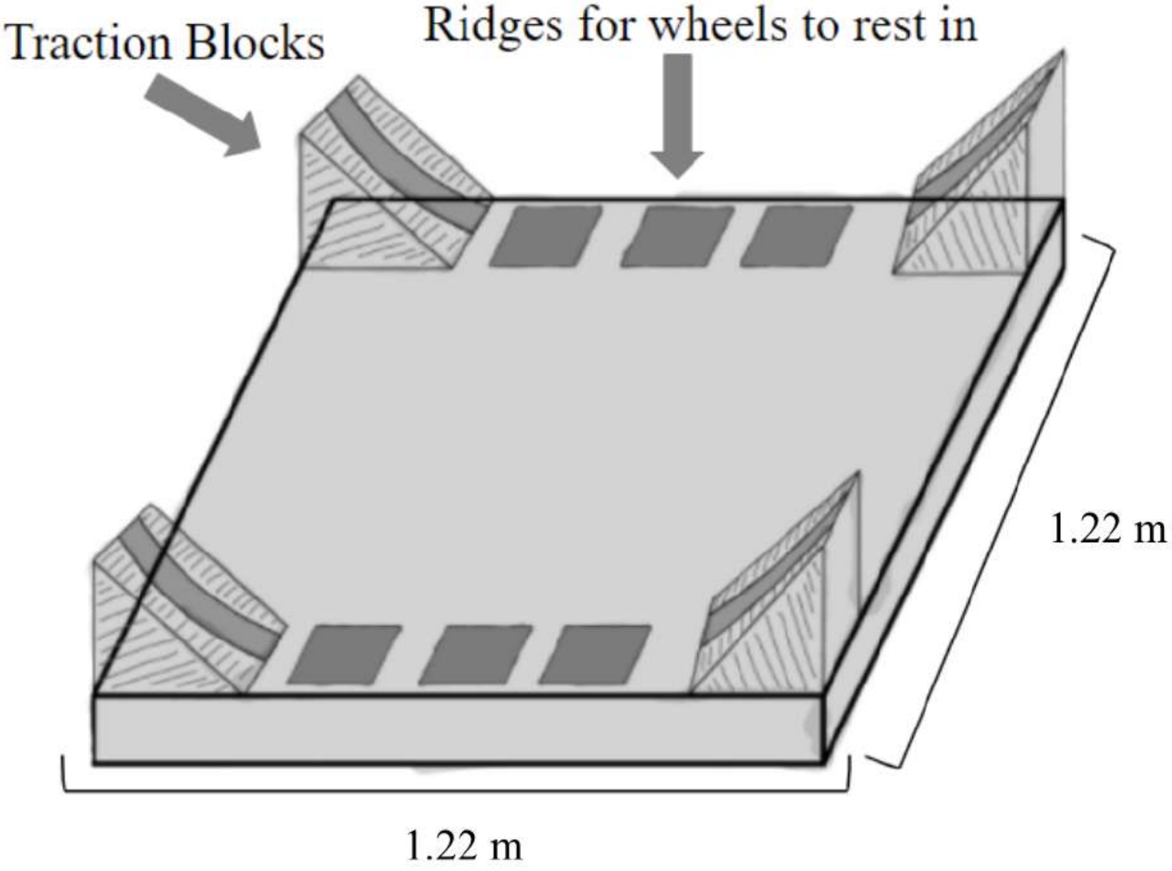


Figure 5. Visual Representation of the Combined Design. The inclined platform with ridges is combined with 4 traction blocks to prevent translation / rotation of the wheelchair during the action of rowing.

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.

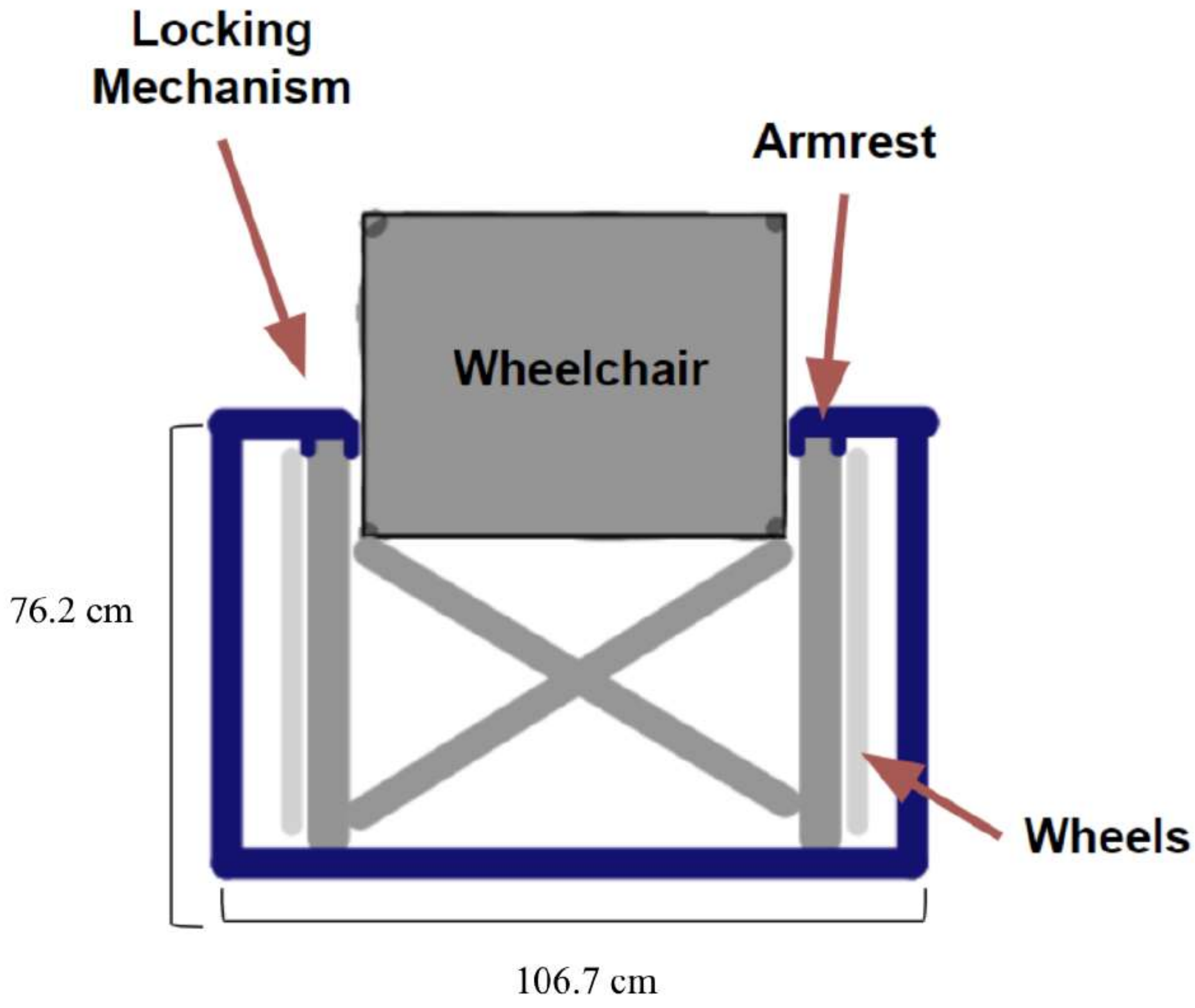


Figure 6. Visual Representation of the Armrest Hooks Design. The base platform will have two sideboards connected via a hinge that can swing up to be parallel with the wheels. Extendable hooks will reach out and grasp the armrests of the wheelchair to prevent side-to-side rotation during the action of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

II. Preliminary Design Evaluation

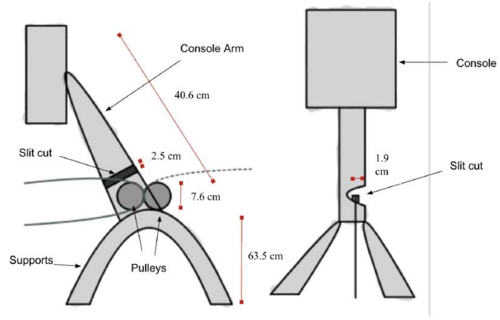
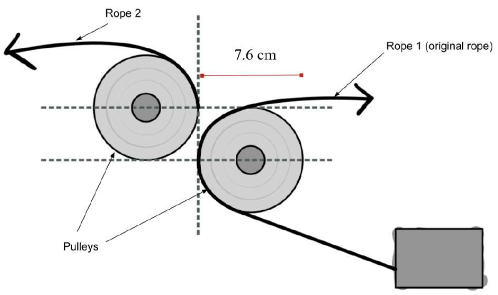
A. Pulley and Stability Design Matrices Criteria

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.

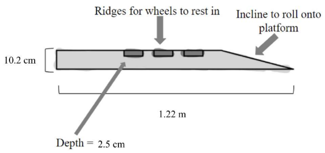
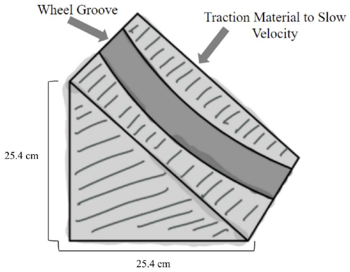
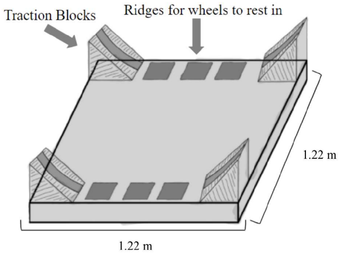
C. Pulley Design Matrix

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><td>Design</td><td colspan="2">2 Pulleys with Slit
 </td><td colspan="2">2 Pulleys with 2 Ropes
 </td></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>

D. 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**	

E. 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.

F. 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.

III. 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 7**). 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. This diagram (see **Appendix B**) was used to determine the force that would be applied in these straps with maximum rowing effort. For a full list of materials refer to **Appendix C**.

Figure 7. 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 8**) 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.

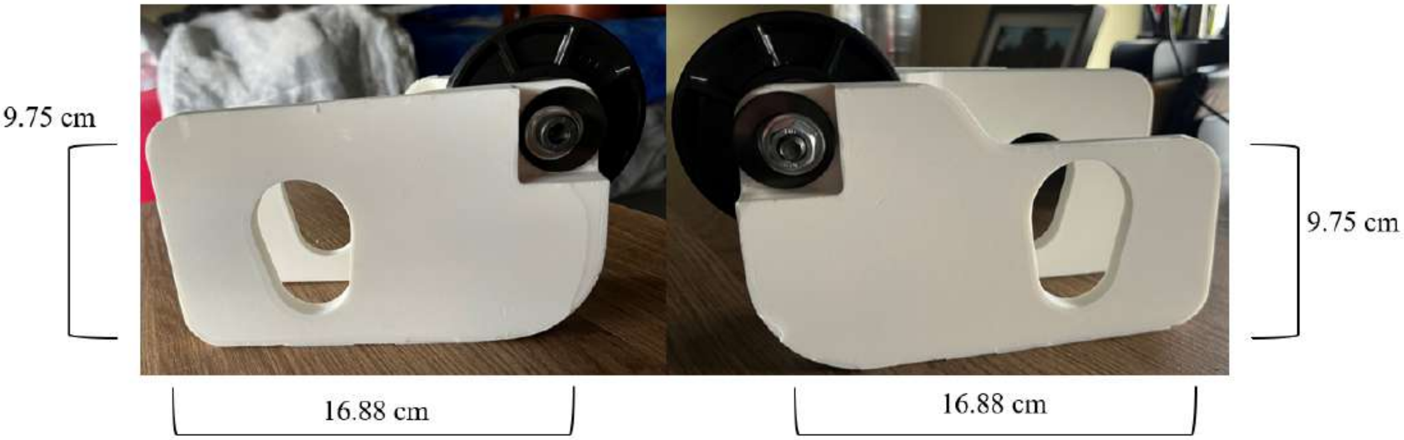


Figure 8. Left and Right Pulley Support Plates. The left (left) and right (right) pulley support plates fit tightly around the pulley bearing and have a cavity that fits around the metal support arms for the rower neck. The right pulley support plate has material taken off of the top surface to allow 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 9**). 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 10**. 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 11**). 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 12**). 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.

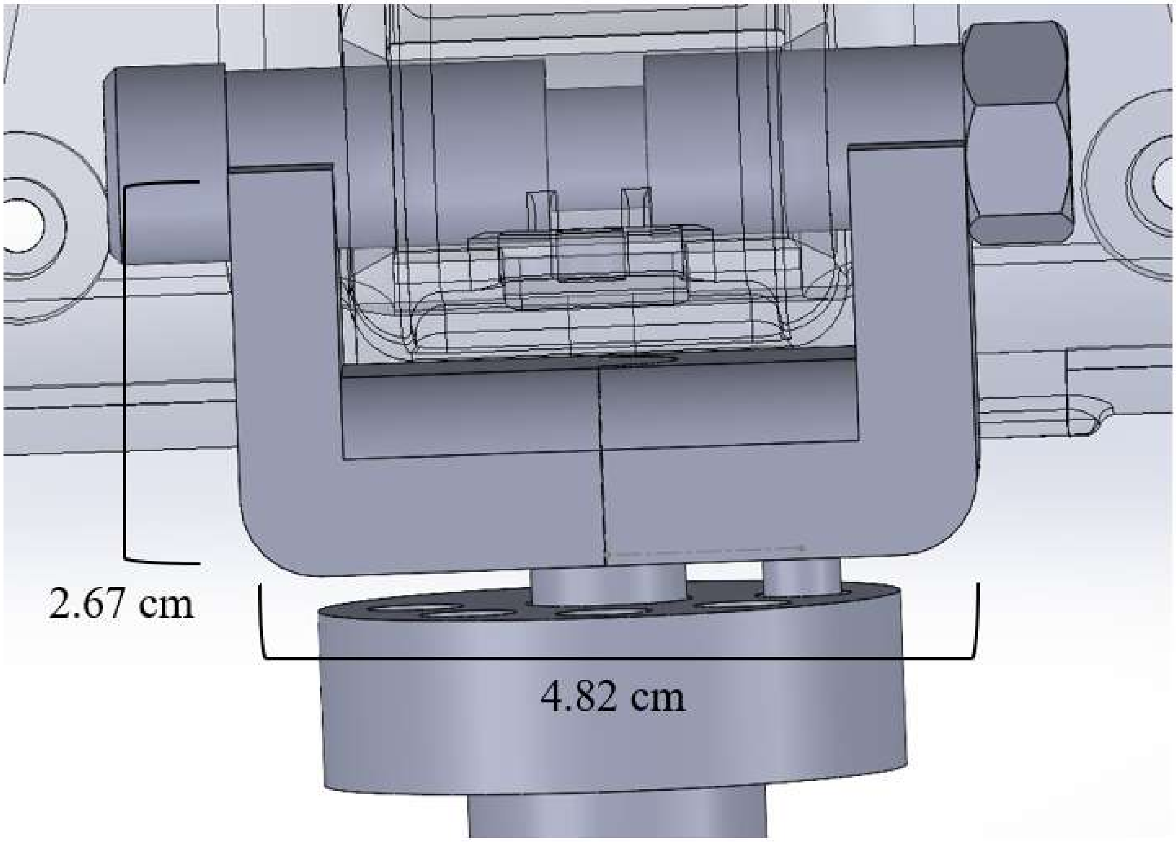


Figure 9. Field Goal Posts Allow Original Console Rotation. The field goal posts have cylindrical components that insert into the back of the display console to allow it to rotate about its original axis. This allows the user to adjust the angle at which the console is bent.

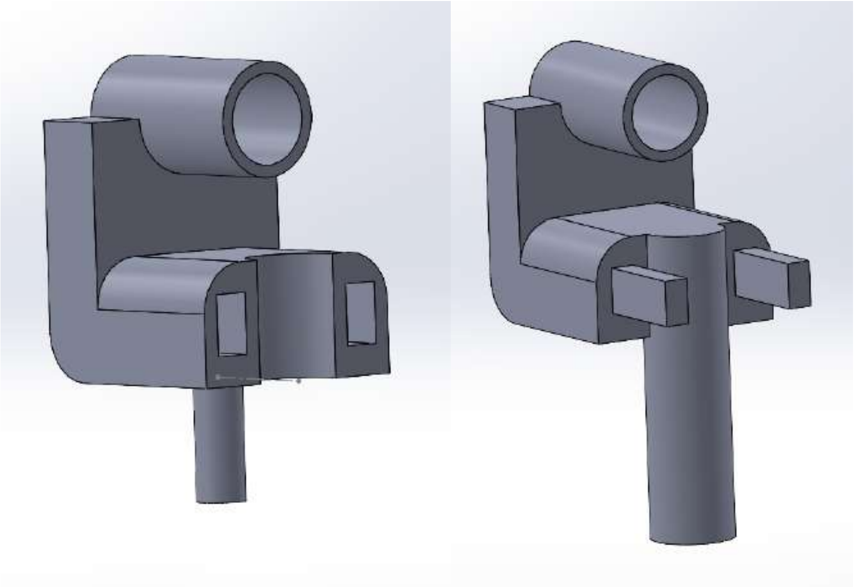


Figure 10. Female and Male Field Goal Posts. The female (left) and male (right) field goal posts fit together via extending inserts on the male piece and a circular peg on the male piece that fit into corresponding cavities on the female piece. The male piece has a large and longer peg to rotate around 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.

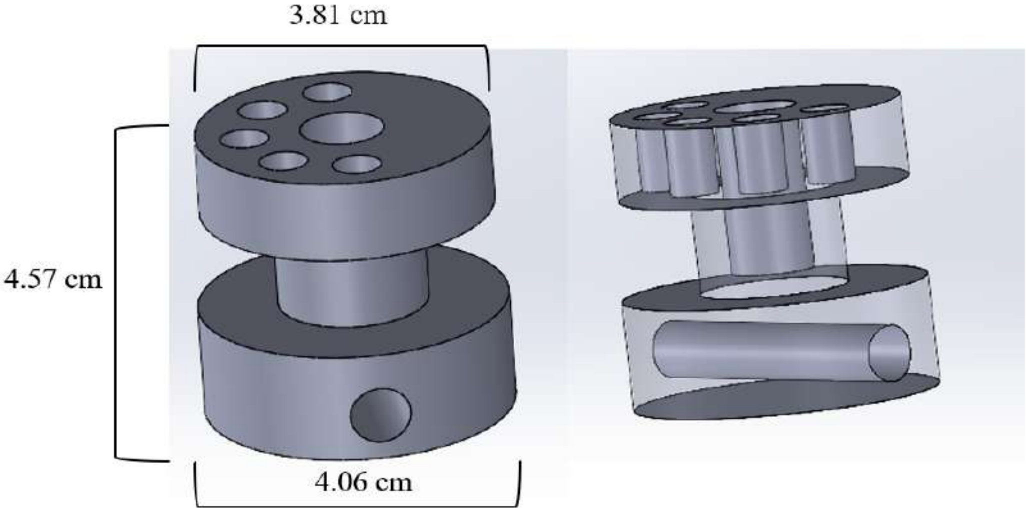


Figure 11. Swivel Receiving Bracket. The swivel receiving bracket has a center cavity to allow the large peg on the male field goal post to rotate. It also has five smaller cavities for the guiding peg to insert into to adjust the degree of rotation of the console. A through hole in the bottom allows for a screw to be inserted through the bracket and the rower neck and tightened.

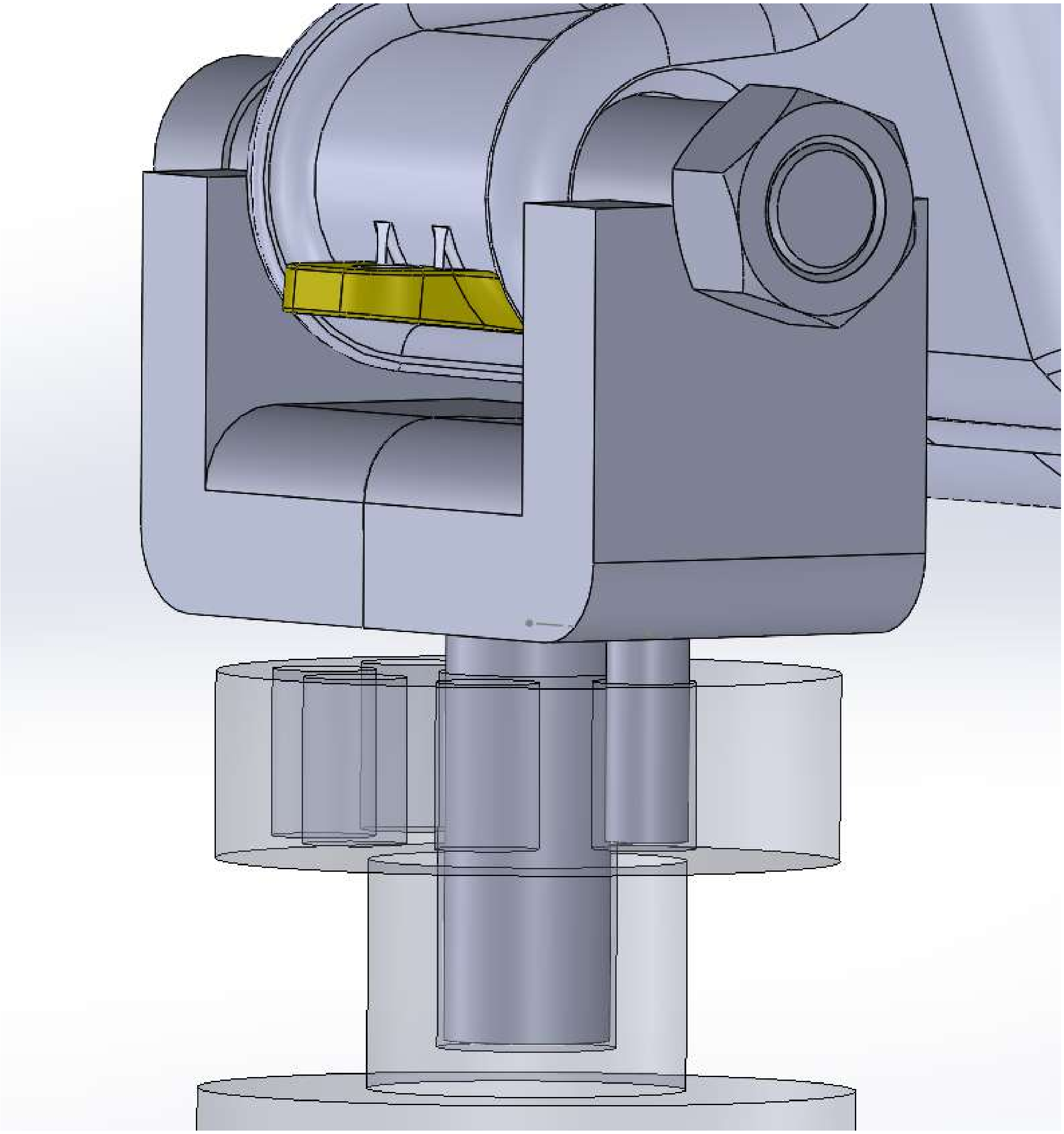


Figure 12. Rotation of Display Console. The large peg fits into the center rotating cavity of the receiving bracket, while the guiding peg fits into one of five smaller cavities to adjust the degree of rotation of the console.

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 13**) 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 14**.

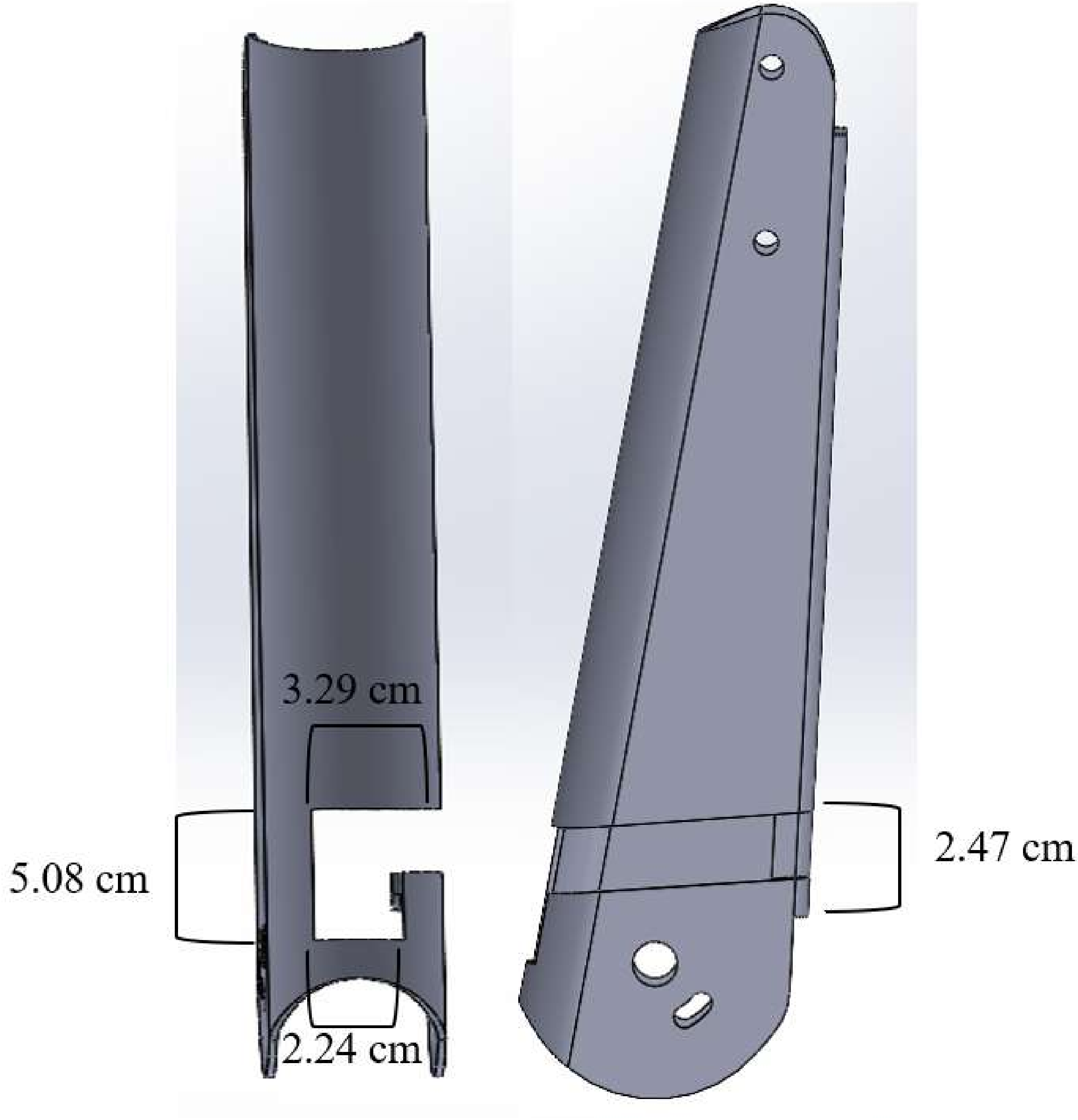


Figure 13. Rower Neck with Slit. The rower neck has a slit in the right side that allows for the rope to be transitioned from the standard to the adaptive side.

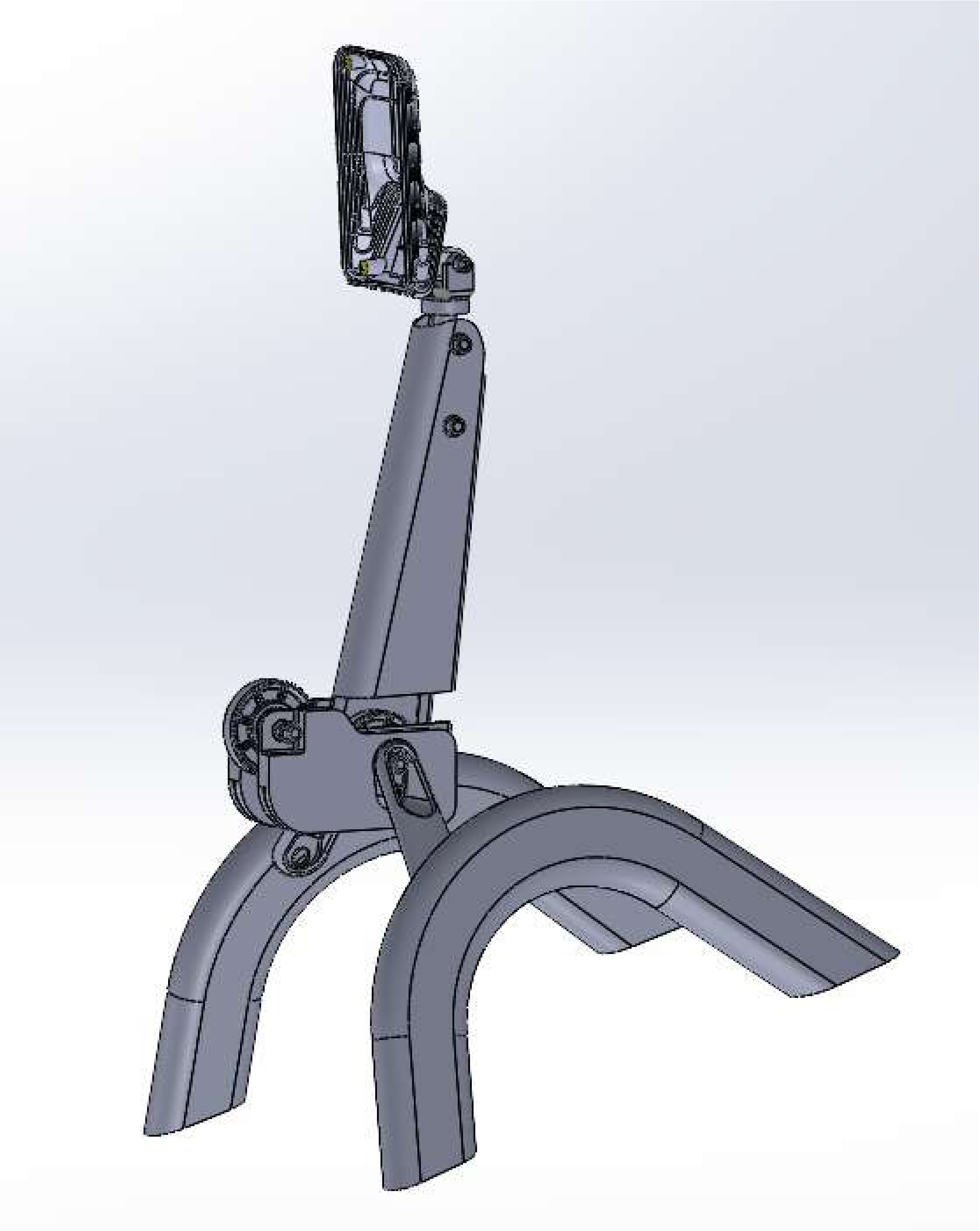


Figure 14. Full SolidWorks Assembly. The adaptations made to the original rower include adding an additional pulley stabilized by mirroring support plates, cutting a slit into the rower neck to transition the rope and handlebar from one side to the other, and a swivel bracket that allows the user to 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 15**. 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 16**). 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 17)**. 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.

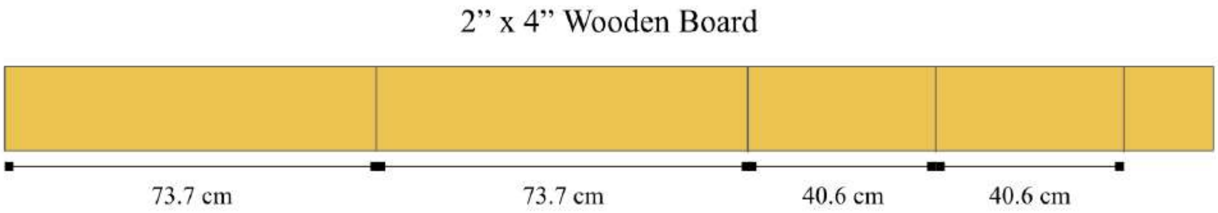


Figure 15. Measurements on 2” x 4” Board. Two 73.7 cm markings were made on the 2” x 4” board along with two 40.6 cm markings.

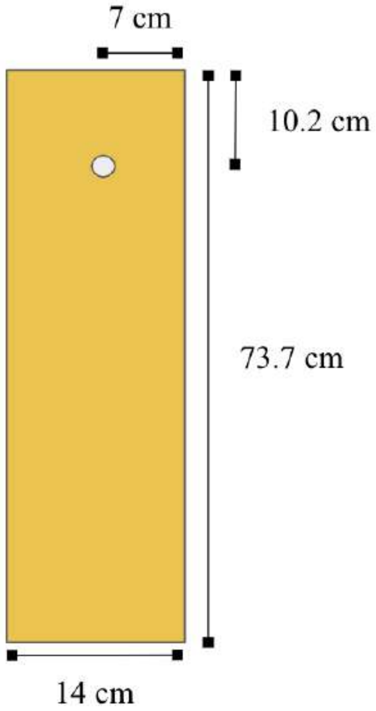


Figure 16. Hole Marking for Vertical Support Board. Markings were made 7 cm across the width and 10.2 cm down the length of the 73.7 cm vertical support boards. The holes that were drilled at these markings held the support straps that attach to the wheelchair.

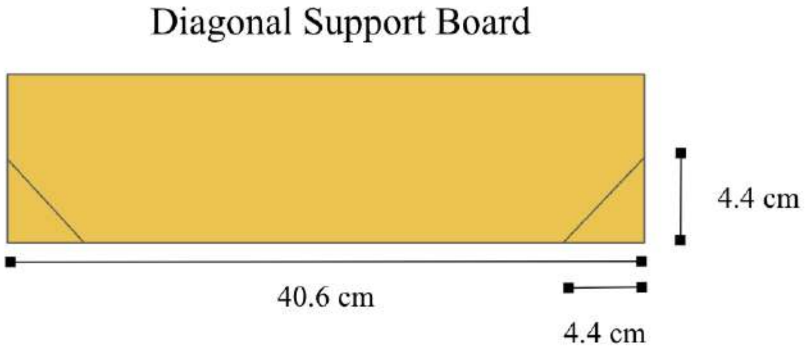


Figure 17. Diagonal Support Board Measurements. On the 40.6 cm diagonal support boards, 4.4 cm markings were made along the width and the length of the board. These markings were then connected with a diagonal line.

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 18**). 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 18**).

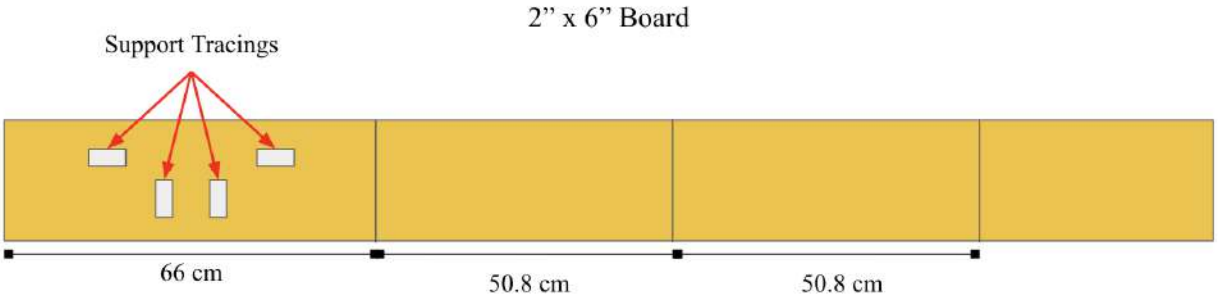


Figure 18. Markings on 2” x 6” Wooden Board. The 66 cm baseboard marking and two 50.8 cm horizontal support markings were made on the 2” x 6” wooden board. The tracings of the rowing machine’s front supports were also made on the baseboard portion of the 2” x 6” board.

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 19** for the locations and side of the divots on the baseboard.

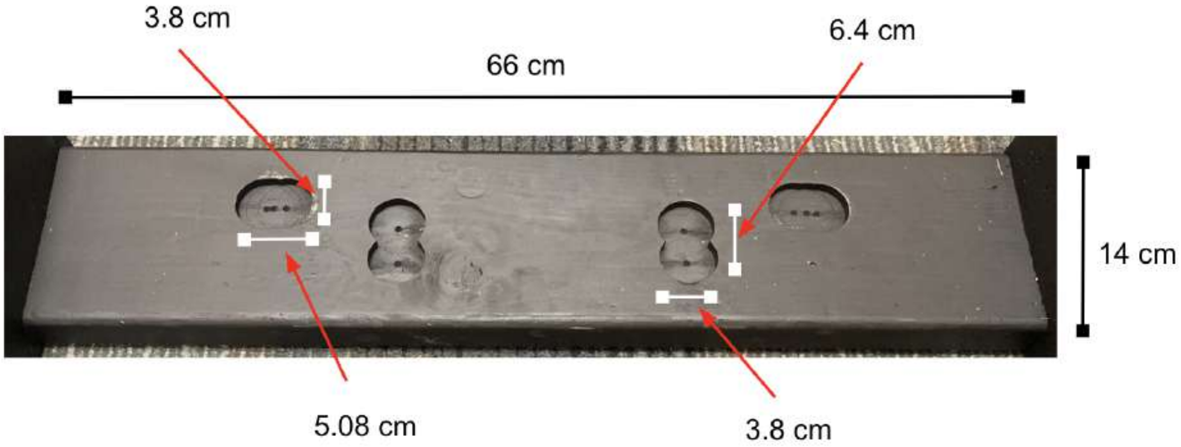


Figure 19. Base Board for Wooden Support. The base board for the wooden support base rests underneath the rowing machine. The divots in the board allow for the rubber supports and wheels of the rowing machine to remain in place without movement during rowing.

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 20**.

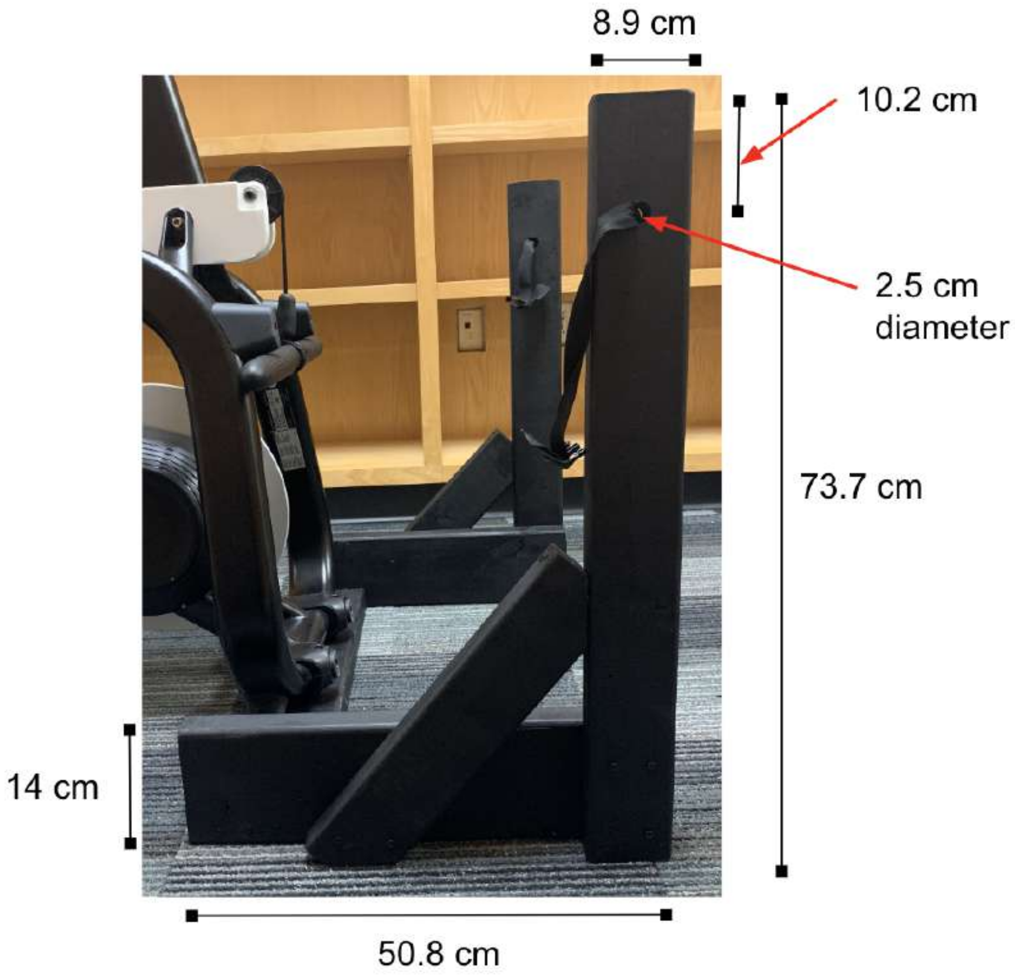


Figure 20. Side View of Wooden Support. The 50.8 cm boards that are attached to the baseboard create separation from the rowing machine to allow for the user to complete the rowing motion comfortably. Additional diagonal supports were added to the base to further enhance the strength and stability of 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 21**). 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.

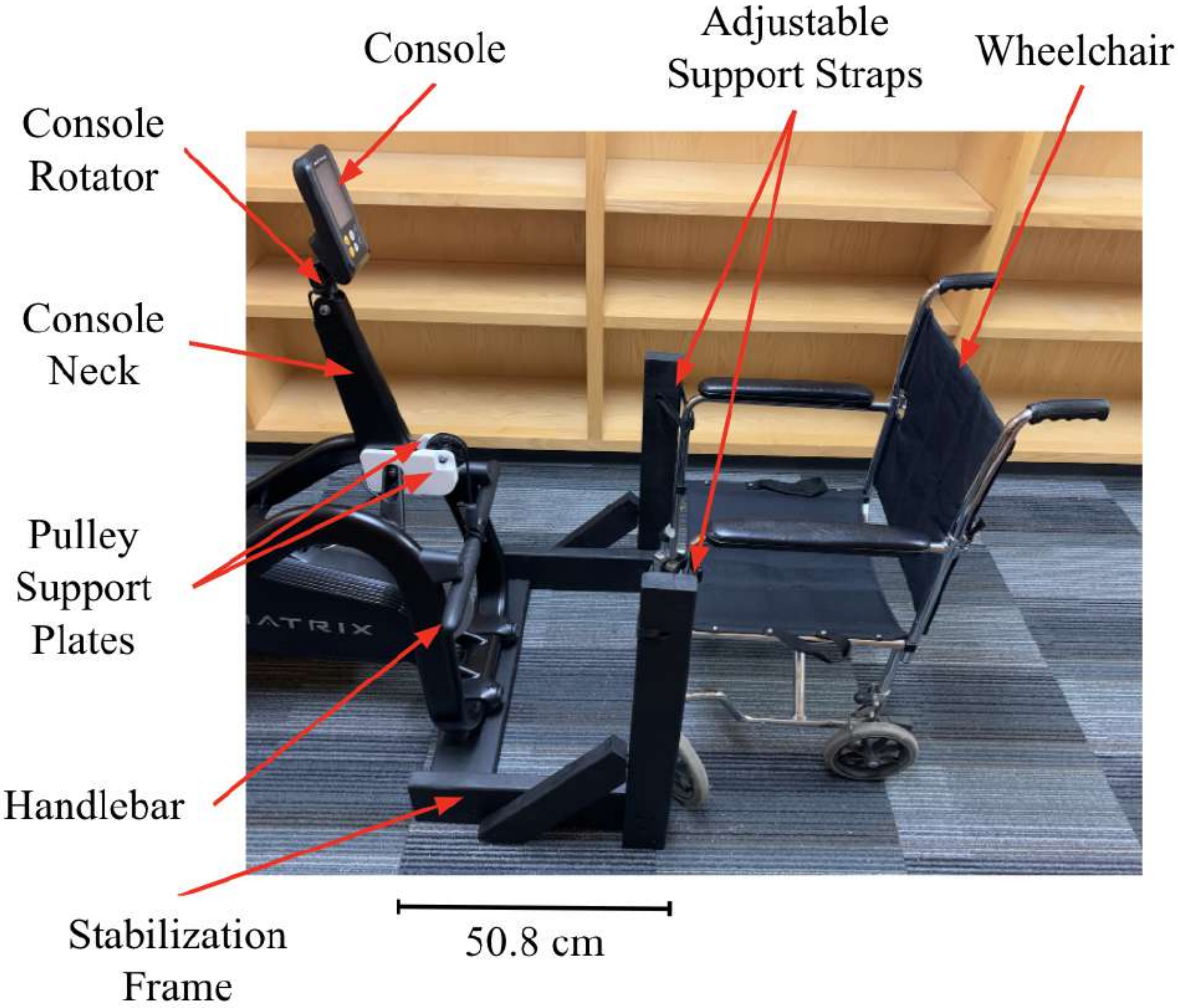
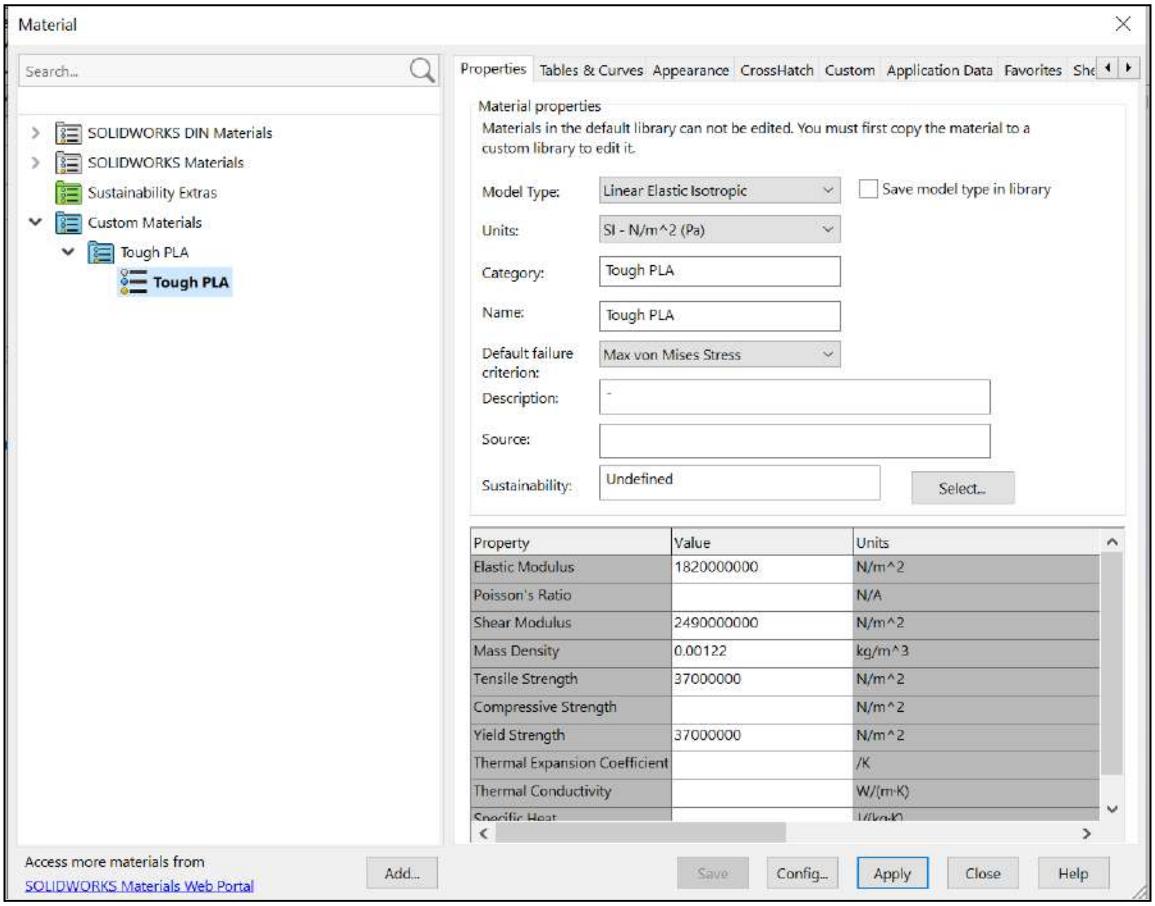


Figure 21. Full Assembly. The full assembly includes the pulley support plates, the console rotator, and the wooden support base. The wheelchair is locked into the support base using adjustable straps.

C. 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 22**. 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. According to the diagram in **Appendix B**, 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, 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.



Material properties

Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic

☐ Save model type in library

Units: SI - N/m^2 (Pa)

Category: Tough PLA

Name: Tough PLA

Default failure criterion: Max von Mises Stress

Description: -

Source:

Sustainability: Undefined

Property	Value	Units
Elastic Modulus	1820000000	N/m^2
Poisson's Ratio		N/A
Shear Modulus	2490000000	N/m^2
Mass Density	0.00122	kg/m^3
Tensile Strength	37000000	N/m^2
Compressive Strength		N/m^2
Yield Strength	37000000	N/m^2
Thermal Expansion Coefficient		/K
Thermal Conductivity		W/(m·K)
Specific Heat		J/(kg·K)

Figure 22. 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 as documented in **Appendix A**. 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. The full survey can be found in **Appendix D.**

VI. Results

A. SolidWorks Simulation

After completing the SolidWorks simulation testing on the pulley plates, the resulting stresses and displacements were analyzed to determine the strength of the Tough PLA material and the designed geometries. After applying a 1050 N load to the inner bearing surface of the pulley plates, a maximum displacement of 0.7658 mm occurred at the top corner of the left plate, near where the load was applied (**Figure 23**). 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 24**). 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.

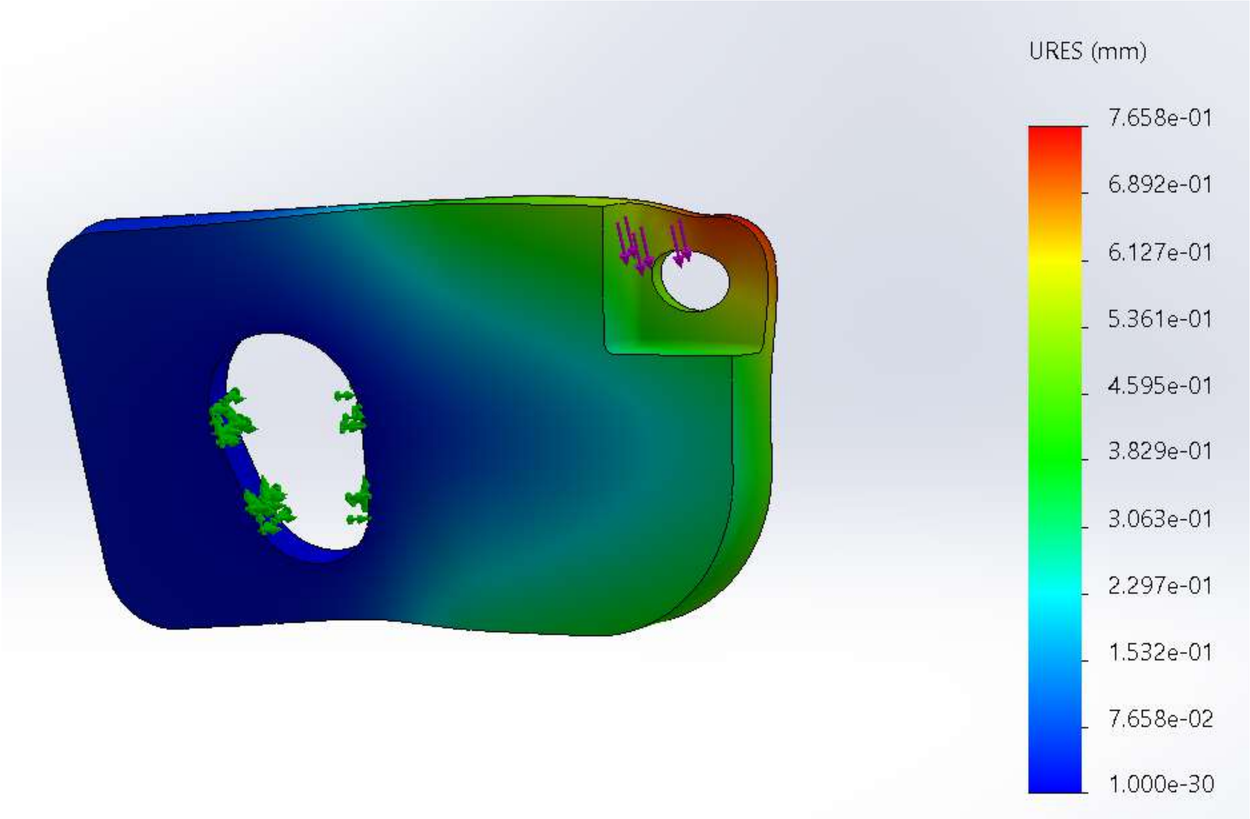


Figure 23. Displacements for Left Pulley Support Plate. The left pulley support plate only experiences a maximum displacement of 0.7658 mm under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

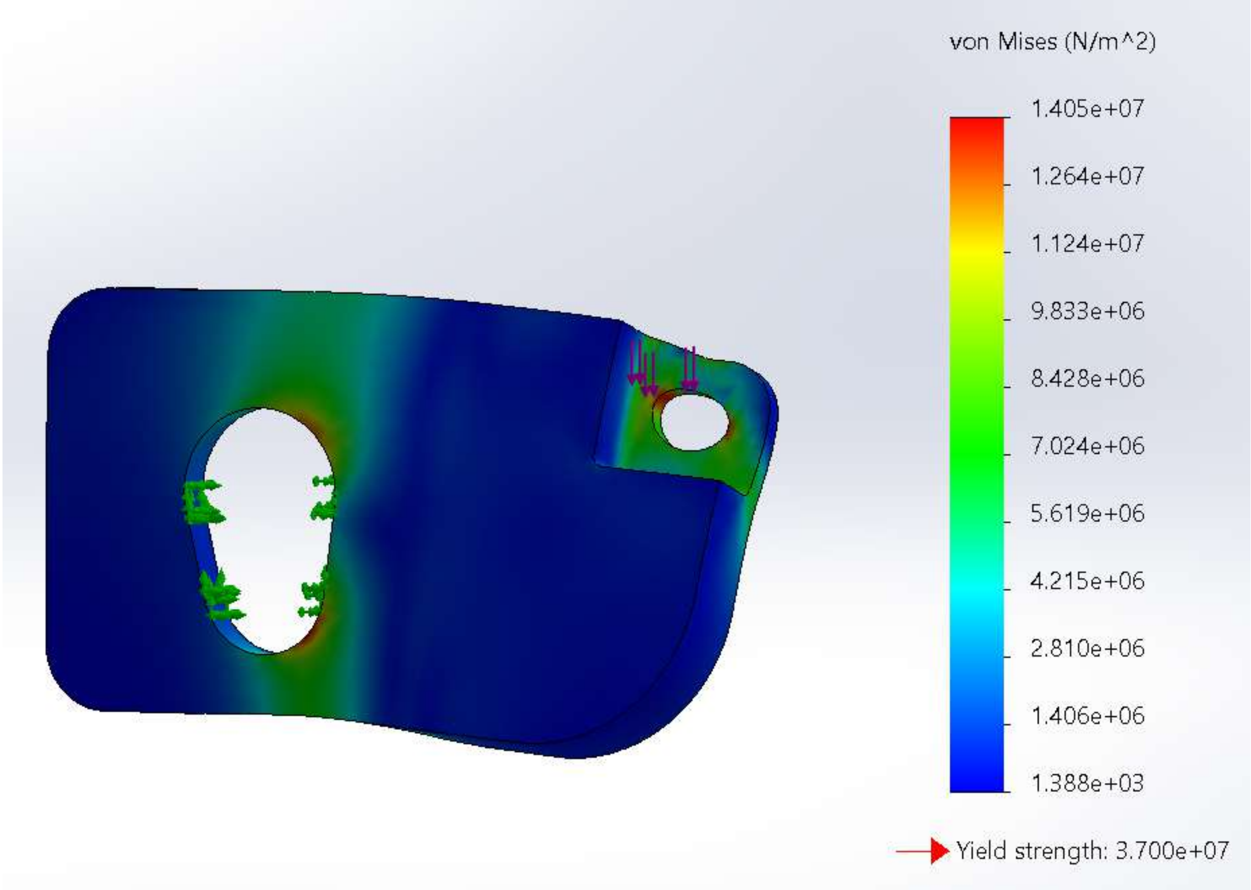


Figure 24. Stresses for Left Pulley Support Plate. The left pulley support plate only experiences a maximum stress of 14.05 MPa under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

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 25**). 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 26**). 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.

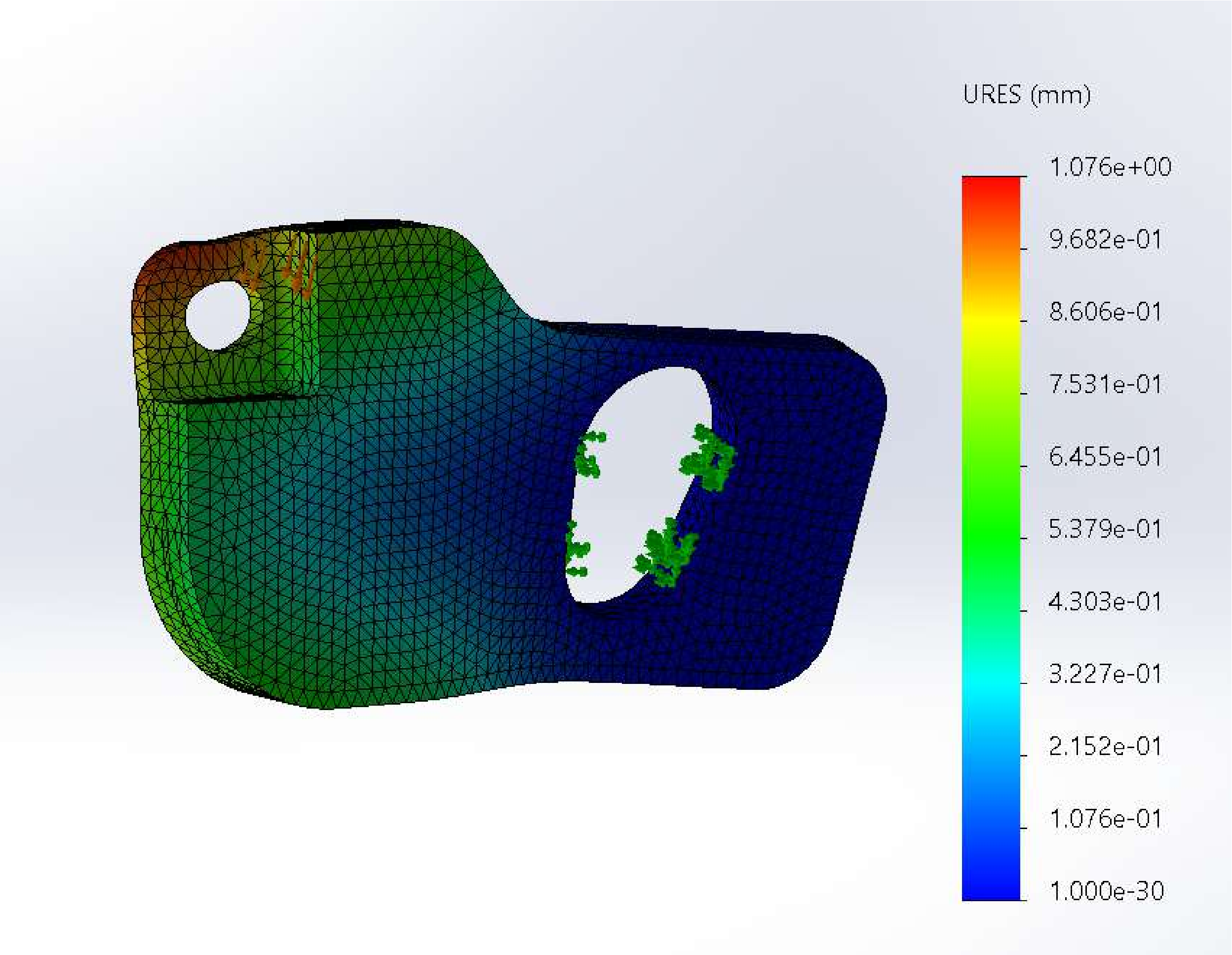


Figure 25. Displacements for Right Pulley Support Plate. The right pulley support plate only experiences a maximum displacement of 1.076 mm under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

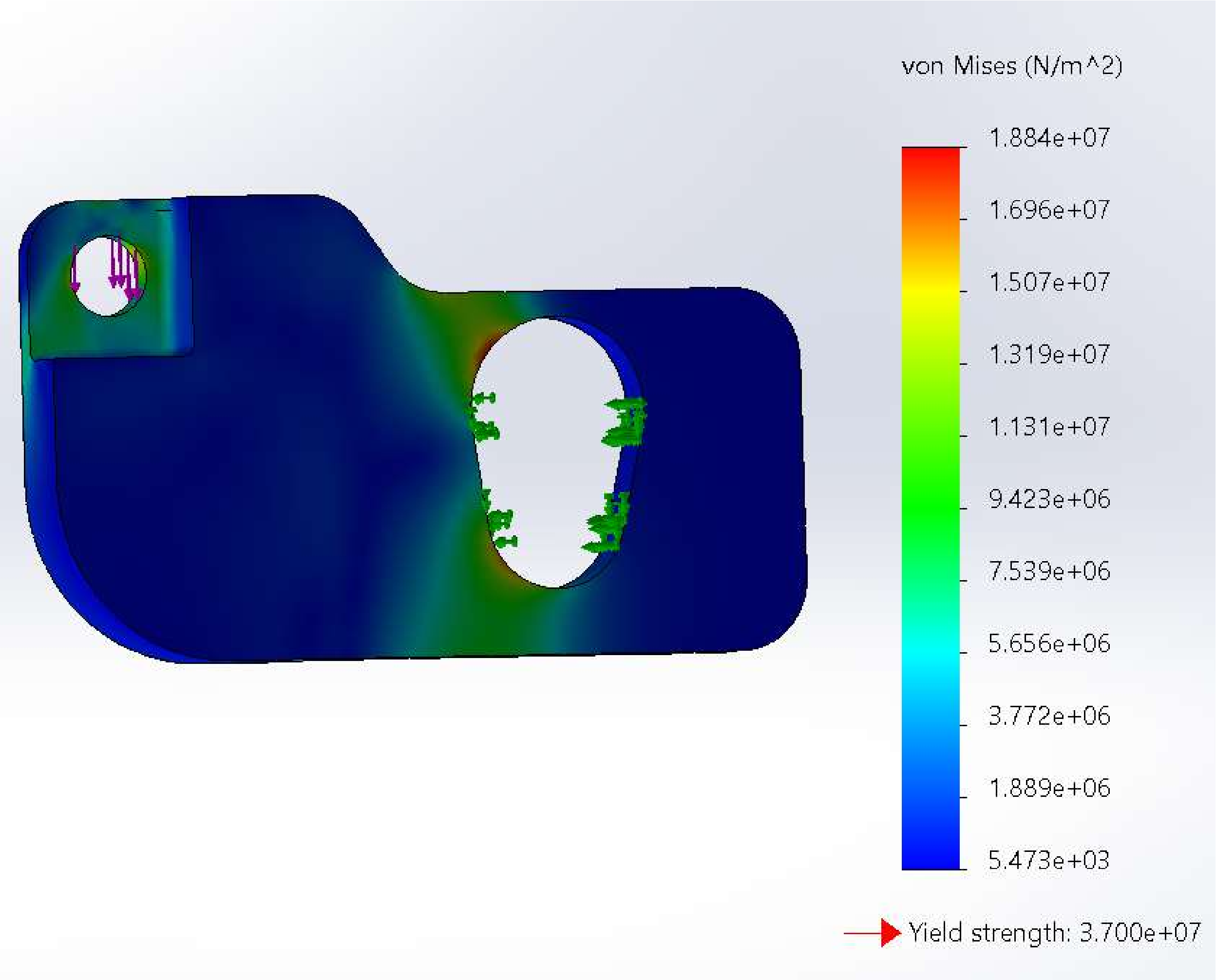


Figure 26. Stresses for Right Pulley Support Plate. The right pulley support plate only experiences a maximum stress of 18.84 MPa under a 1050 N load with a safety factor of two, which justifies the designed geometry and chosen material of Tough PLA for the plate.

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 (**Appendix E**) and plotted in MATLAB (**Figure 27**). 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 27**, 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.

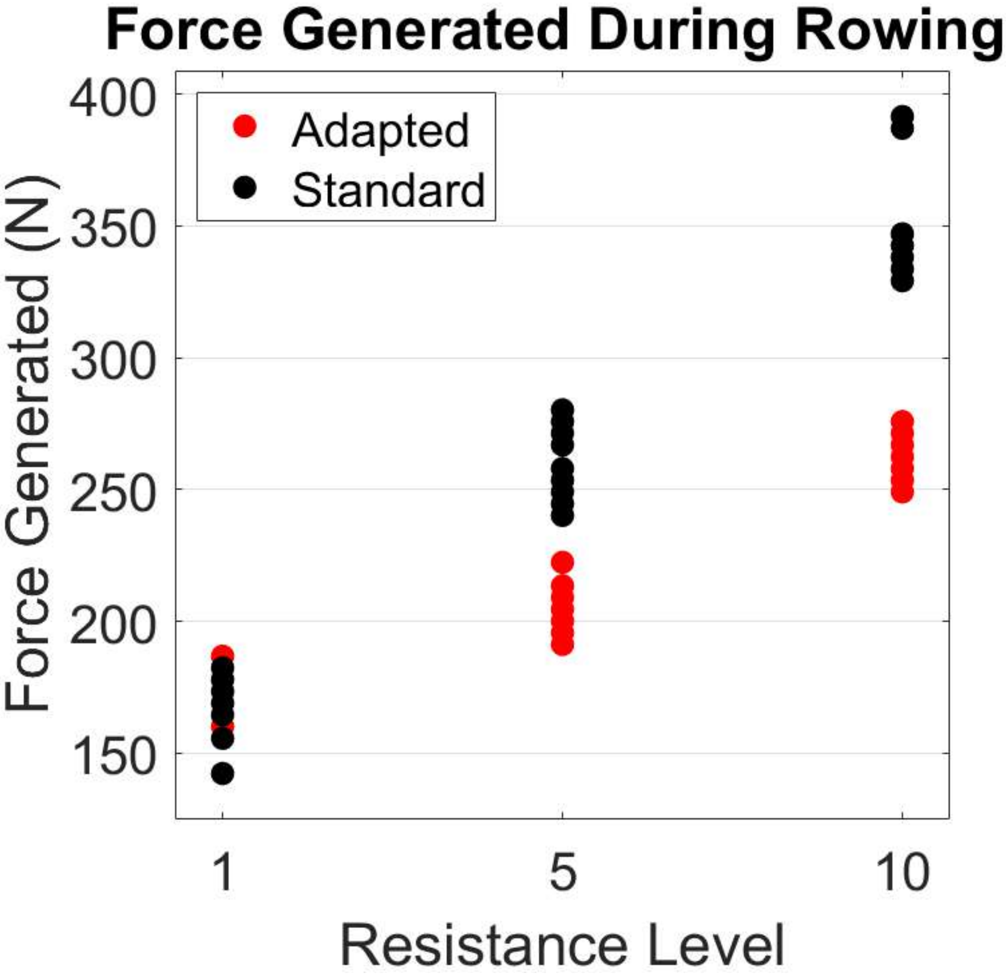


Figure 27. Force Generated During Rowing. The force generated during rowing on each side plotted against the resistance level was taken ten times for resistance levels of 1, 5, 10. More force was generated on the standard side, but the overall force generated increased at each resistance level for both 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 28**). A

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

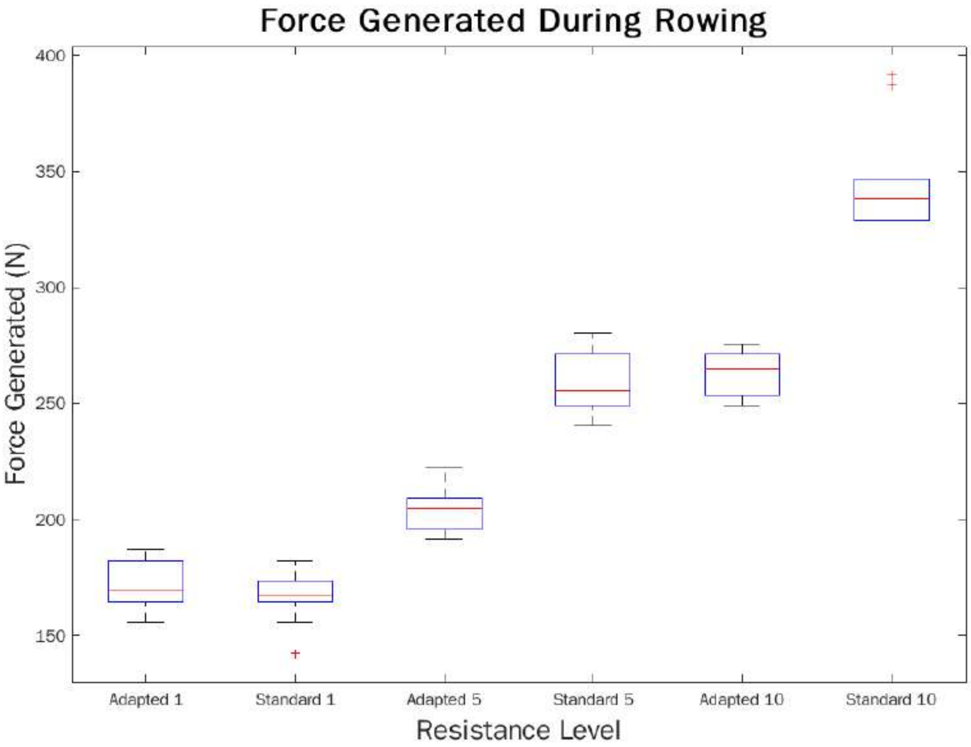


Figure 28. Box Plot of Force Generated During Rowing. The box plot for the rowing conducted at resistance levels of 1, 5, 10 demonstrates the general increase in force generated for each resistance level. The red asterisks indicate outliers in the ten data points for each side at each resistance level.

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 (**Appendix A**). 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 29**. 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 30**. 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.

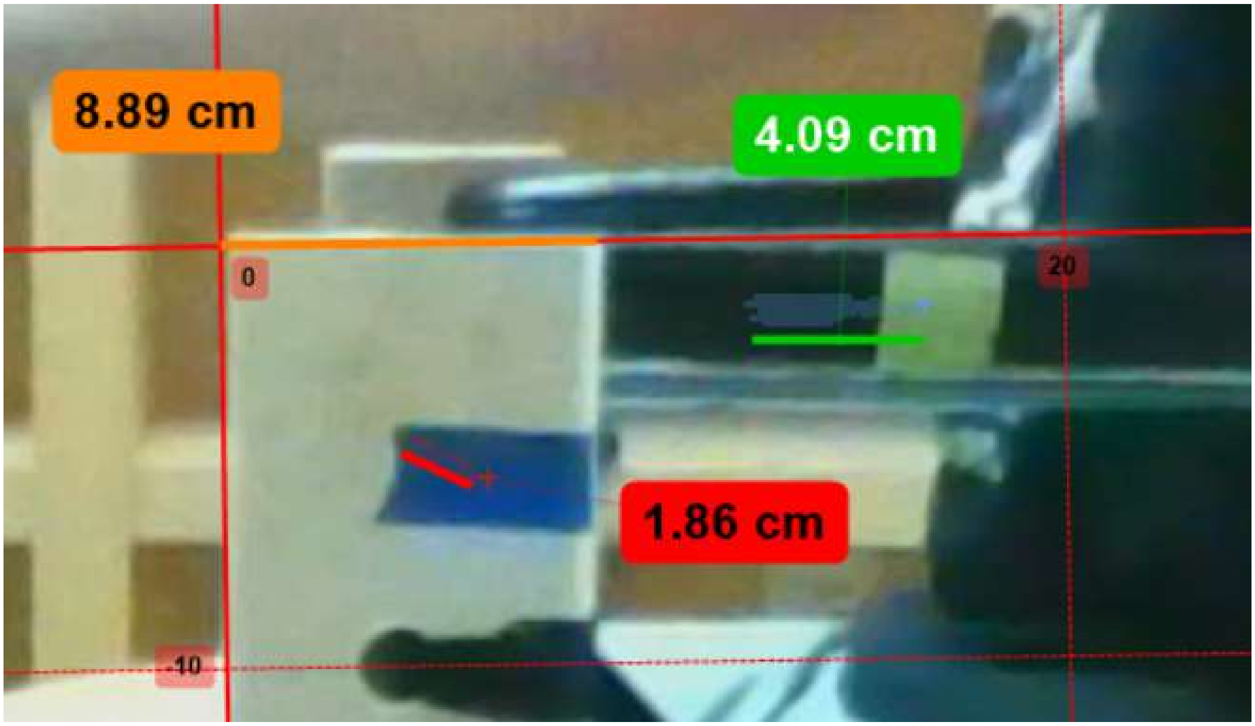


Figure 29. Maximum Displacement in Vertical Support of the Wooden Base and Wheelchair. The orange label and line contain the known distance for the calibration curve. The green label and line highlight the displacement of the wheelchair. The red label and line indicate the displacement of the vertical support of the wooden base.

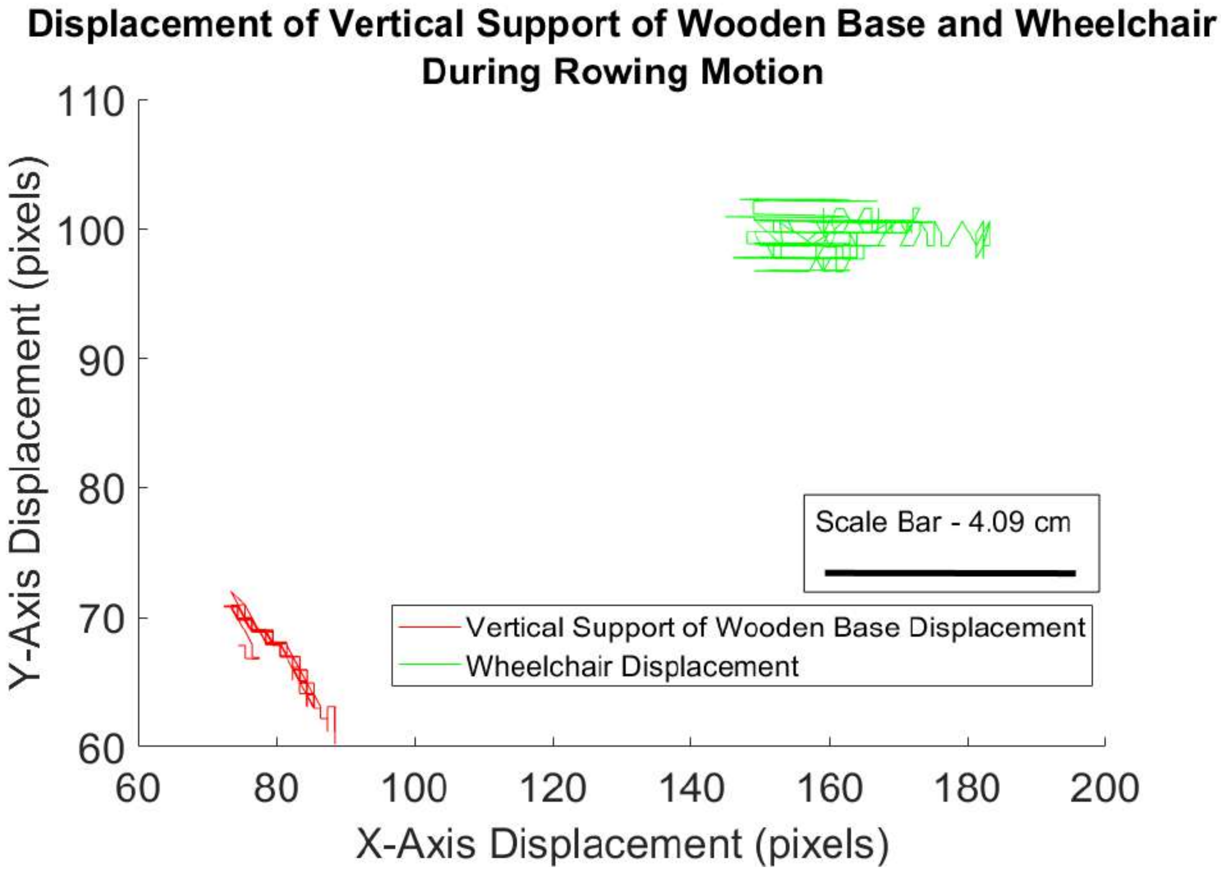


Figure 30. Movement Data Plot for Vertical Support of Wooden Base and Wheelchair. The red line represents the movement exhibited by the vertical support of the wooden base. The green line represents the movement exhibited by the wheelchair.

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 31**. A full list of the survey questions can be found in **Appendix D**.

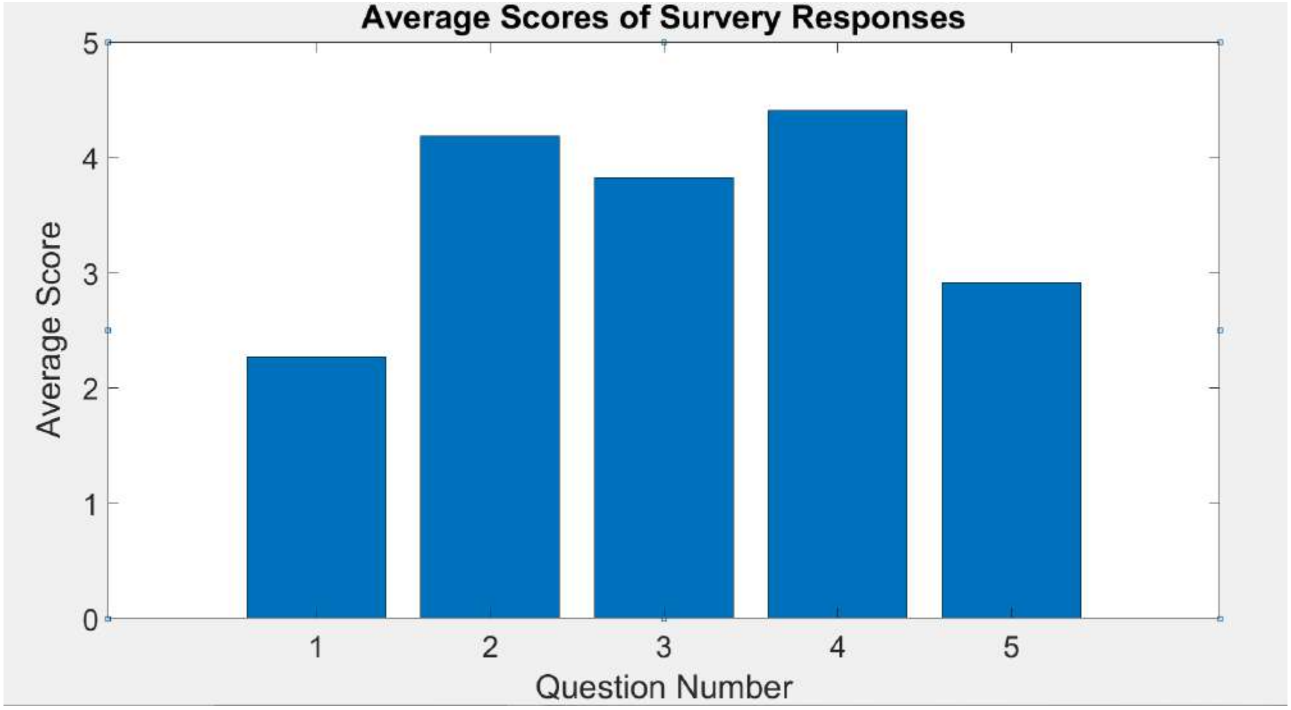


Figure 31. Average Score of Survey Responses. The average responses to each of the five numerically rated questions are displayed to summarize user feedback from using the Adaptive Rower.

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.

VII. Discussion

After completing all analysis on the device, the adaptive rowing machine proved to be a successful means to allow for rowing on both the standard and adaptive sides. After conducting the tests on the adapted rower design, the data was collected and analyzed. The SolidWorks testing revealed that the additional pulley system and the rigid support plates can support up to 1050 N of force while still maintaining a safety factor of two. This testing proves that the support plates will not yield under the greatest force developed during rowing. Additionally, since the maximum displacements of the left and right pulley support plates were only 0.7658 mm and 1.076 mm, respectively, the geometries and chosen Tough PLA material successfully endured the 1050 N load applied. The MATLAB evaluation of the maximum force developed during rowing on each side shows that the workout can be modified to the users' desired level of difficulty. However, while the average maximum force developed on each side increased as the resistance increased, the force generated on the adapted side was generally less. This can be explained by the decreased tension developed on the adapted side as a result of the decreased distance and inability of the user to use their leg muscles during the exercise. The Kinovea analysis demonstrates that the maximum force from rowing on the adapted side results in displacement of both the wheelchair and the vertical supports. The survey results reveal that the final design emulates traditional rowing on the adapted side, but could be improved for user comfort and needs additional improvements to enable an easier transition between rowing modes.

Varying sizes of wheelchairs were not addressed by the final design. This consideration must be accounted for due to the large variation of heights and sizes of various users to improve the inclusivity of the device. By including a larger demographic of wheelchair users, the final design will offer a more welcoming and accessible experience to the wheelchair community in comparison to the products that are currently offered. In terms of testing, it was crucial to make sure that the participants were not harmed in any way throughout the rowing duration or by transitioning the rope from the standard to adapted side. Specifically, the slit that was implemented into the neck of the rower needs to be sanded to dull any sharp edges that could result in harm to the user.

Some potential sources of error that could have led to inaccuracies for both the tension and Kinovea results are the spring gauge altering the natural rowing motion, the user straying from the baseline stroke rate, the user unintentionally relying on their legs for stability and power, improper calibration, and worn out braking mechanism of the wheelchair. The 45 kg (100 lb) spring gauge that was used to collect the rowing data could have impeded the accuracy of the collection of these results. The spring gauge was large and bulky, creating an awkward hand hold while executing the rowing motion. This could have prevented the user from correctly executing the rowing motion, thus creating inaccuracies in the data. Another possible source of error could have occurred from the test participant not maintaining the 22-25 stroke per minute rate, thus inputting different efforts during the trials. There were points during data collection in which this stroke rate was not maintained, which could have impacted the tension data collected. While users were instructed not to use their legs while rowing on the adapted side, no measures were taken to ensure that this was followed. Any lower extremity muscular effort by the test participant during rowing could have skewed the results of both the Kinovea and tension tests. Inaccurate placement of the calibration line used in the Kinovea analysis could have also led to an unreliable reading of the displacement created during the maximum rowing intensity trial. Finally, the brakes of the wheelchair used in all tests were worn out. This could have contributed to additional displacements of both the wheelchair and vertical supports that would not have occurred if testing was conducted with a fully functioning wheelchair.

VIII. Conclusion

Currently, there is a lack of modified workout equipment that is accessible for individuals in wheelchairs. In order to increase the accessibility of gym equipment for wheelchair users, adaptations to current, traditional exercise machines are necessary. One such machine that is in need of an adaptive form is the standard rowing machine. As requested by the client, a standard rowing machine will be converted into a transformable rowing machine, capable of accommodating both traditional and adaptive rowing. This device will enhance the experience of exercising for wheelchair users, and provide a means to actively engage their upper body and core muscles via rowing which will improve their exercising experience. The original preliminary design included using both the 2 Pulleys with Slit design and the Highway Ridges design. The 2 Pulleys with Slit concept allows for the transitioning of the rope and handle from standard to adaptive use. Instead of the Highway Ridges design, the Armrest Hooks / wooden base was deemed sufficient to prevent the user from tipping during rowing by providing a forward reaction force to the wheelchair. Another component of the final design is the console swivel, which allows for the user to rotate the console between both the standard and adapted sides.

The final design was evaluated using multiple methods. An initial SolidWorks simulation was run to test the durability of the pulley support plates, which were fabricated out of Tough PLA, with a safety factor of two which resulted in minimal deformation. Force generation was then tested between the two sides of the rower which resulted in increasing tension with an increase in resistance for both sides. Displacement measurements were tracked using Kinovea. Excess motion of both the wheelchair and wooden base was recorded. Lastly, a survey was issued to voluntary participants that rated the final design on various user experience criteria. Feedback from the survey indicated that the traditional rowing mechanics were not compromised, but improvements to the rope transitioning mechanism are needed.

The analysis of the existing adapted rower design reveals clear successes and areas for improvement. This design was successful in allowing the conversion from a standard rower and an adapted rower with minimal permanent adaptations made to the rower. Additionally, a wheelchair bound user could successfully complete a rowing workout using the adaptive rowing machine. Facilitating improved access to workout equipment, as completed with this adaptive rowing machine, will allow wheelchair users to pursue a more active lifestyle, contributing to the overall improvement to quality of life.

IX. Future Work

In terms of prototype improvements, constructing the pulley support plates, console rotational mechanism, and support base from steel will provide more strength to the design. An additional support mechanism must be added to the final design as well to improve the stability of the user. A strap or support plate that connects to the user's chest to prevent them from slipping from their wheelchair will provide additional security while rowing. To further increase the safety of the product, the edges created by the slit in the neck of the console arm will be sanded down or lined with rubber to prevent the possibility of abrasions to the user and rope. Additionally, a mechanism must be added to remove the tension from the rope while converting the rower from the standard to adapted mode. This will enable a single user to transition the rowing machine from the standard to adaptive side without external assistance. To make the design more versatile, fabricating the support base out of adjustable components will allow for users in different sized wheelchairs to comfortably use the adaptive rowing machine. In order to more securely hold the handle in place when the machine is not in use, a holding mechanism for the handlebar could be fabricated on the adaptive side. Currently, the resistance can only be changed from the standard side of the rowing machine. For the last prototype improvement, a mechanism must be developed to allow adjustment of the resistance level from the adaptive side, such as a robotic arm that reaches around to the resistance dial. In terms of testing improvements, obtaining wheelchair users will provide the most accurate and representative results for the tension and survey results. For non-wheelchair users that participate in testing, an EMG will be connected to their legs to ensure that no lower extremity effort aids their rowing motion and force output. Lastly, attachment of the spring gauge directly to the rowing handlebar will allow for the testing participant to more accurately replicate the traditional rowing motion during testing. These prototype and testing improvements will help to enhance the adaptive rower to better extend its accessibility and functionality.

X. References from BME 301 Report

[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).

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

[5] "VassarStats: Statistical Computation Web Site." http://vassarstats.net/ (accessed May 02, 2022).

XI. Appendices from BME 301 Report

Appendix A: PDS from BME 301

Johnson Health Tech: Adaptive Indoor Rower for Wheelchair Users

Product Design Specifications

May 4th 2022

Client: Mrs. Staci Quam (staci.quam@johnsonfit.com)
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Lab: 305

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]. The Adaptive Rower will secure the wheelchair into the rowing machine, preventing the user from tipping backwards during the course of the workout. This modified design will increase the accessibility and ease of use of a rowing machine by individuals in wheelchairs, 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. Ideally, the machine should be able to be adjusted to allow for usage from non-wheelchair individuals.
- Individuals in wheelchairs, if possible, will be able to insert themselves into the machine without assistance.
- The rowing machine will be user friendly, and not add complexity to perform proper rowing technique.
- 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.

Design Requirements:

1. **Physical and Operational Characteristics**
    a. *Performance Requirements:*
        i. The modified rower will enable people in wheelchairs to use the machine. The device will be able to easily attach / detach the wheelchair to / from the rowing machine. The attachment to the rowing machine should keep the wheelchair from tipping over backwards.
        ii. The modifications made, to allow for attachment of the 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 up to 1050 N [2].
            2. The modifications made to the machine should be able to endure the fatigue due to the repetitive rowing cycle.
        iii. The device will be used daily.

b. *Safety:*
    i. The modifications made to the rowing machine, to allow for attachment of a wheelchair, 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 or from the machine during normal use of the rower.

c. *Accuracy and Reliability:*
    i. The adapted rowing machine should accurately simulate the feeling of a normal rowing machine. Thus, the loading and recoil motions should accommodate pulling the handle bars back to approximately one arms length and should be smooth and absent of excessive friction.
    ii. In order to prevent backwards tipping, a mechanism should be included that provides forward force to counteract backwards accelerations. The 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.

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 [3]
        2. At least 8 million meters [3]
    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 around the users 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 attach the wheelchair to the adaptive rower. This action will utilize only hands and arms and will be possible in an upright sitting position.
    ii. A locking system will ensure the user will not move during use. A harness, support, and latch mechanism will be used.
    iii. External addition to the rower will not inhibit comfort to the user. Stability measures will enhance experience for wheelchair users.
    iv. After the user is secured into the machine, only the hands and arms will be used to complete the rowing motion. In addition, the user will be in an upright position.
    v. The user will grip the handlebars to complete rowing movements. The wheelchair and the adaptive rower machine will remain stationary during the arm movements.
    vi. No leg movements will be required during the use of the machine.
    vii. 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].
    viii. Users will not need to reach more than 70 cm (2.3 ft) from the front of the wheelchair to grab the handlebar [4].

- h. *Weight*
    - i. The current weight of the design is 158.76 kg (350 lbs) [1].
    - ii. A maximum of 7 kg of mass will be added to the existing rower.
- i. *Materials:*
    - i. The adaptations will be fabricated out clean, polished, or painted metal for support and durability.
    - ii. Hard plastics for strength and affordability
    - iii. Rubber for traction.
    - iv. After application of 1050 N (safety factor of 2) onto the plates supporting the additional pulley is applied, a maximum deformation of 2.0 mm will be allowed.
- j. *Aesthetics, Appearance, and Finish:*
    - i. Adaptations made to the machine will have a smooth finish to prevent abrasions or lacerations to the user.
    - ii. 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 $200 will be used for development of the fixture to the rowing machine structure.

3. **Miscellaneous**
    - a. *Standards and Specifications:*
        - i. The International Organization for Standardization (ISO) entry 20957-7:2005 stipulates the safety requirements for rowing machines, specifically rowing machines within classes S and H and class A 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 7.6 cm 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 could be a unique deliverable for this project.

References for BME 301 PDS

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

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[4] J. Looker, "Reaching for Holograms: Assessing the Ergonomics of the Microsoft™ Hololens™ 3D Gesture Known as the 'Air Tap,'" Oct. 2015.

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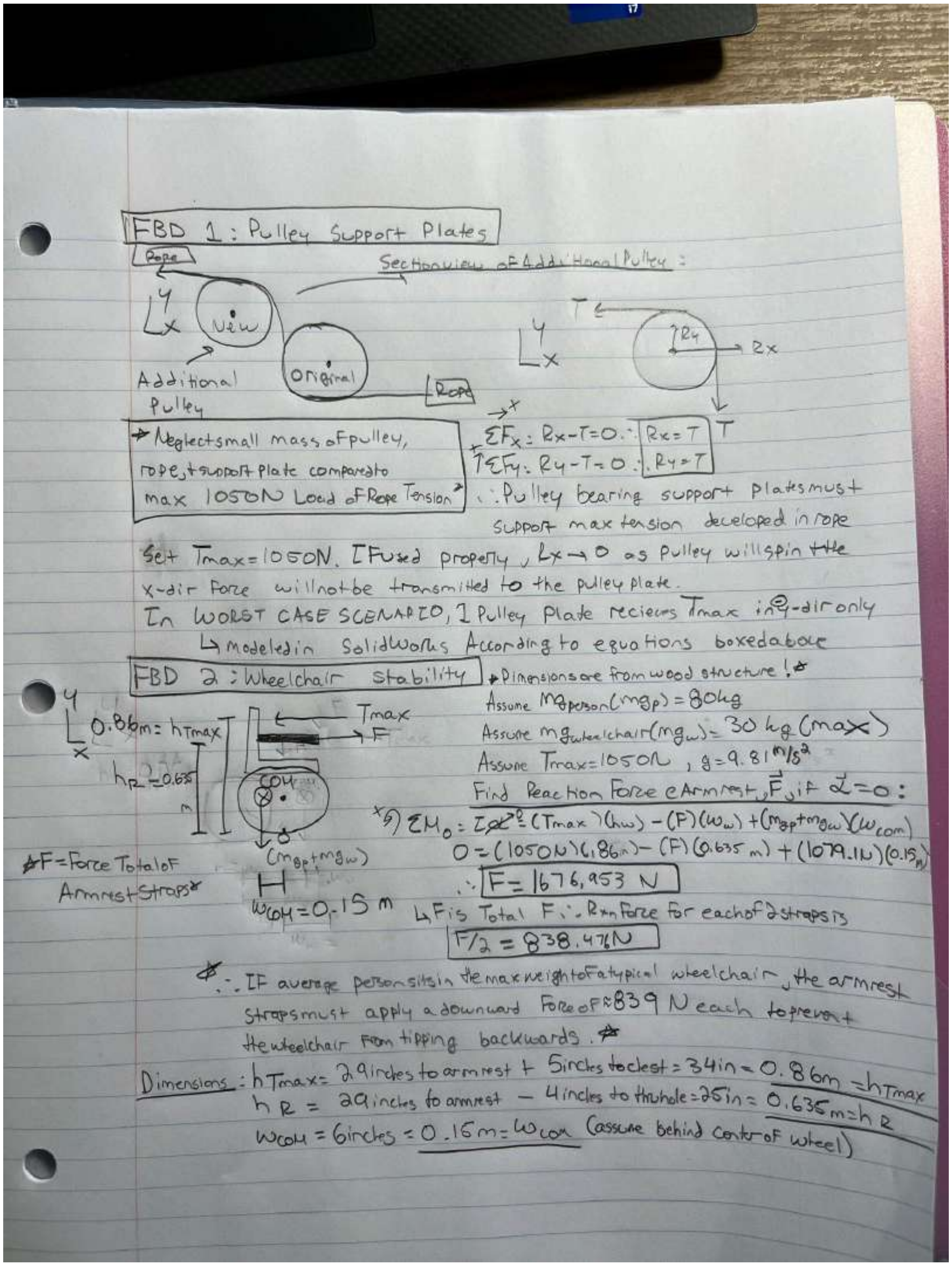
[9] 박대성, 김민, 정다운, and 이범석, "Rowing machine for paraplegic patient," WO2012008664A1, Jan. 19, 2012 Accessed: Feb. 09, 2022. [Online]. Available: https://patents.google.com/patent/WO2012008664A1/en

Appendix B: Final Design FBD



FBD 1: Pulley Support Plates

Section view of Additional Pulley:

★ Neglect small mass of pulley, rope, + support plate compared to max 1050N Load of Rope Tension ★

$\xrightarrow{+} \Sigma F_x: R_x - T = 0 \therefore \boxed{R_x = T}$

$+\uparrow \Sigma F_y: R_y - T = 0 \therefore \boxed{R_y = T}$

∴ Pulley bearing support plates must support max tension developed in rope

Set Tmax = 1050N. If used properly, $R_x \to 0$ as pulley will spin the x-dir force will not be transmitted to the pulley plate.

In WORST CASE SCENARIO, 1 Pulley Plate recieves Tmax in y-dir only

↳ modeled in SolidWorks According to equations boxed above

FBD 2: Wheelchair Stability

★ Dimensions are from wood structure! ★

Assume $m_{g\,person}(m_{gp}) = 80$ kg

Assume $m_{g\,wheelchair}(m_{gw}) = 30$ kg (max)

Assume $T_{max} = 1050$ N, $g = 9.81\ m/s^2$

Find Reaction Force @ Armrest, $\vec{F}$, if $\alpha = 0$:

$\circlearrowleft \Sigma M_O = I\alpha \overset{0}{=} (T_{max})(h_w) - (F)(w_w) + (m_{gp}+m_{gw})(w_{com})$

$0 = (1050\,N)(.86\,m) - (F)(0.635\,m) + (1079.1\,N)(0.15\,m)$

$\therefore \boxed{F = 1676.953\ N}$

★ F = Force Total of Armrest Straps ★

↳ F is Total F ∴ Rxn Force for each of 2 straps is

$\boxed{F/2 = 838.476\,N}$

★ ∴ If average person sits in the max weight of a typical wheelchair, the armrest straps must apply a downward Force of ≈ 839 N each to prevent the wheelchair from tipping backwards. ★

Dimensions: h_{Tmax} = 29 inches to armrest + 5 inches to chest = 34 in = 0.86m = h_{Tmax}

h_R = 29 inches to armrest − 4 inches to thru hole = 25 in = 0.635 m = h_R

w_{COM} = 6 inches = 0.15 m = w_{COM} (assume behind center of wheel)

Figure 32. Final Design FBD. This FBD shows the math developed to assess the forces developed in the additional pulley rope and in the stabilizing frame. After analysis in this FBD, we saw that the straps needed to withstand around 840N each.

Appendix C: Final Cost Table

Item	Description	Manufacturer	Part Number	Date	QTY	Cost Each	Total	Link
Modeling Purchases								
Adaptable Pulley Stabilizer 3D-Print - Iteration 1	The initial 3D print of the component that attaches to the rower and stabilizes the second pulley for adaptable use	Makerspace	Transaction Number: 6907	3/30/2022	1	$15.44	$15.44	Printer Link
Adaptable Pulley Stabilizer 3D-Print - Iteration 2	The second 3D print for the stabilizing component. Adjustments were made to certain dimensions of the model to ensure a proper fit.	Makerspace	Transaction Number: 6948	3/31/2022	1	$15.28	$15.28	Printer Link

Adaptable Pulley Stabilizer 3D-Print - Iteration 3	This print was a similar print to the interation 2 print, but it was for the other side of the rower. Some minor changes are present in this print due to differences present on this specific side of the rower. Basic structure and model is the same.	Makerspace	Transaction Number: 7061	4/6/2022	1	$28.16	$28.16	Printer Link
Swivel Design - Iteration 1	This was the first iteration for the swivel design. However, some dimension issues caused the team to reprint it after making updates. The eventual goal is to use this to control the orientation of the console display.	Makerspace	Transaction Number: 7239	4/18/2021	1	$5.34	$5.34	Printer Link
Swivel Design - Iteration 2	This design was made in order to allow the display on the standard matrix rower to change orientation if needed. Therefore, a user on the adapted and standard side can see the display.	Makerspace	Transaction Number: 7260	4/19/2022	1	$5.52	$5.52	Printer Link
Final Design Components								

Additional Pulley For Adaptive Side	This pulley was used in conjunction with the pulley plates to form the adaptive side of the rower.	Johnson Health Tech	N/A	3/25/2022	1	$0.00	$0.00	N/A
Adaptable Pulley Stabilizer 3D-Print - Iteration 3	This print was a similar print to the interation 2 print, but it was for the other side of the rower. Some minor changes are present in this print due to differences present on this specific side of the rower. Basic structure and model is the same. (Same as Above).	Makerspace	Transaction Number: 7061	4/6/2022	1	$0.00	$0.00	Printer Link
Wood for Side Handle Bar - Stabilization	Wood was obtained in order to build the side handle bars which will be used to prevent tipping while using the adaptable rower.	Menards	2x4-8' STUD/#2+BT R SPR 1021101	4/3/2022	1	$7.74	$7.74	2x4-8
Wood for Side Handle Bar - Stabilization	Wood was obtained in order to build the side handle bars which will be used to prevent tipping while using the adaptable rower.	Menards	2x6-8' STUD/#2&BT R SPF 1021758	4/3/2022	1	$11.99	$11.99	2x6-8

Spraypaint for Side Handle Bar	In order to make a streamlined model, spraypaint was bought to paint all wood components black. This matches the rower and wheelchair.	Ace	Part Number: 1396050	4/12/2022	1	$5.99	$5.99	Spraypaint
Screws for Side Handle Bar	Screws were necessary to fabricate the Side Handle Bar design	Ace	Part Number: 5327176; WD PH CS 8x3 50 piece	4/12/2022	1	$7.59	$7.59	Screws
Buckle and Straps - Securing for wood stabilization	These buckles will be used to secure the wheelchair to the wood which will in turn be held in place by the rower.	CooBigo	CS023-25	4/11/2022	1	$8.03	$8.03	Buckle Link
Swivel Design - Iteration 2	This design was made in order to allow the display on the standard matrix rower to change orientation if needed. Therefore, a user on the adapted and standard side can see the display.	Makerspace	Transaction Number: 7260	4/19/2022	1	$0.00	$0.00	Printer Link

						TOTAL:	**$111.08**	

Appendix D: Survey Questions

1. Throughout the duration of the rowing, how much were your legs used for stability? OR Throughout the duration of the exercise, how much did you feel like you required the use of your legs for stability?
2. How stable did the wheelchair / you feel during rowing? OR How secure did you feel in the wheelchair from tipping backwards throughout the duration of the session?
3. How well did the adaptive side emulate the action of rowing? *minus the use of lower body
4. How intuitive was the adaptive side to use?
5. How easy did you find it to transform the rower from regular use to adapted use?
6. How would you compare the upper body workout you received on the adapted rower to the upper body workout you receive during a standard rowing session?
7. Did you experience any discomfort during use? If yes, please describe what you experienced.
8. Do you have any suggestions for the team? (Examples: ergonomics, material use, stability issues, etc.)

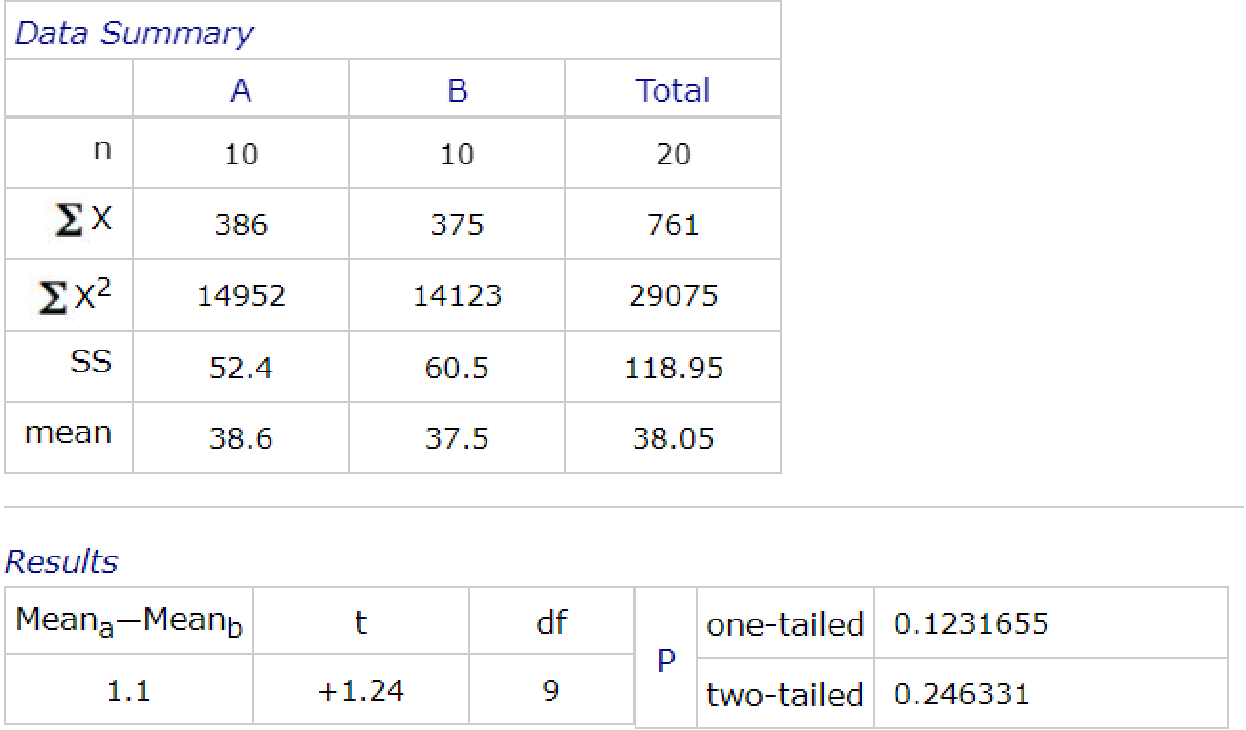
Appendix E: MATLAB Code

```
clear all

close all

x1 = [1 1 1 1 1 1 1 1 1 1 5 5 5 5 5 5 5 5 5 5 10 10 10 10 10 10 10 10 10 10]

adaptedPounds = [35 38 37 38 42 36 39 41 38 42 45 48 46 43 46 47 44 43 46 50 62 58 56 60 57 62 61 57 61 59]



x2 = [1 1 1 1 1 1 1 1 1 1 5 5 5 5 5 5 5 5 5 5 10 10 10 10 10 10 10 10 10 10]

standardPounds = [32 35 39 37 40 39 37 38 41 37 60 56 54 62 63 57 58 55 61 56 78 87 88 76 75 76 74 77 74 74]



adaptedNewtons = convforce(adaptedPounds,'lbf','N')
```

```
standardNewtons = convforce(standardPounds,'lbf','N')

plot(x1,adaptedNewtons,'DisplayName','Adapted Side', 'Color','r', 'Marker','.', 'LineStyle','none', 'MarkerSize',30)
hold on
plot(x2,standardNewtons,'DisplayName','Standard Side', 'Color','k', 'Marker','.', 'LineStyle','none', 'MarkerSize',30)
hold off

set(gca,"XGrid","off","YGrid","on")
xlabel("Resistance Level", "FontSize",20)
ylabel("Force Generated (N)", "FontSize",20)
title("Force Generated During Rowing ", "FontSize",24)

xlimit = [1 5 10]
set(gca, 'XTick', (xlimit))

legend("show", "FontSize",14)
legend("Position",[0.1479,0.73049,0.32097,0.12805])

aN1 = [adaptedNewtons(1:10)]
aN5 = [adaptedNewtons(11:20)]
aN10 = [adaptedNewtons(21:30)]

sN1 = [standardNewtons(1:10)]
```

```
sN5 = [standardNewtons(11:20)]
sN10 = [standardNewtons(21:30)]

x = [aN1; sN1; aN5; sN5; aN10; sN10]
xfinal = x'

figure
boxplot(xfinal)
set(gca,'XTickLabel',{'Adapted 1','Standard 1','Adapted 5','Standard 5','Adapted 10','Standard 10'}, 'fontsize', 12)
xlabel("Resistance Level", "FontSize",20)
ylabel("Force Generated (N)", "FontSize",20)
title("Force Generated During Rowing ", "FontSize",24)
```

Appendix F: MATLAB Table Analysis



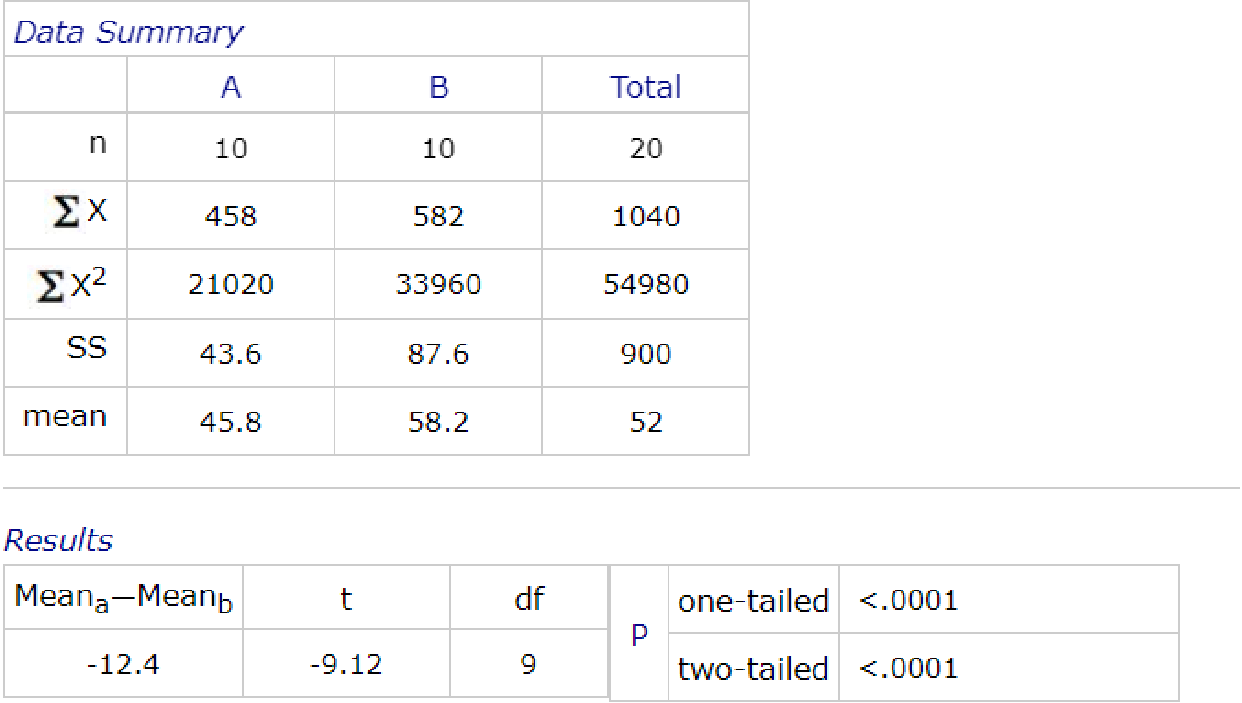
Data Summary

	A	B	Total
n	10	10	20
$\sum X$	386	375	761
$\sum X^2$	14952	14123	29075
SS	52.4	60.5	118.95
mean	38.6	37.5	38.05

Results

$\text{Mean}_a - \text{Mean}_b$	t	df	P	one-tailed	0.1231655
1.1	+1.24	9		two-tailed	0.246331

Figure 33. Paired Sample T-Test for Resistance Level 1. A Paired Sample T-Test was completed for the tension data on resistance level 1. A p-value of 0.123 was calculated for this T-Test, which does not indicate a significant difference between the standard and adapted side's means for the tension data [5].



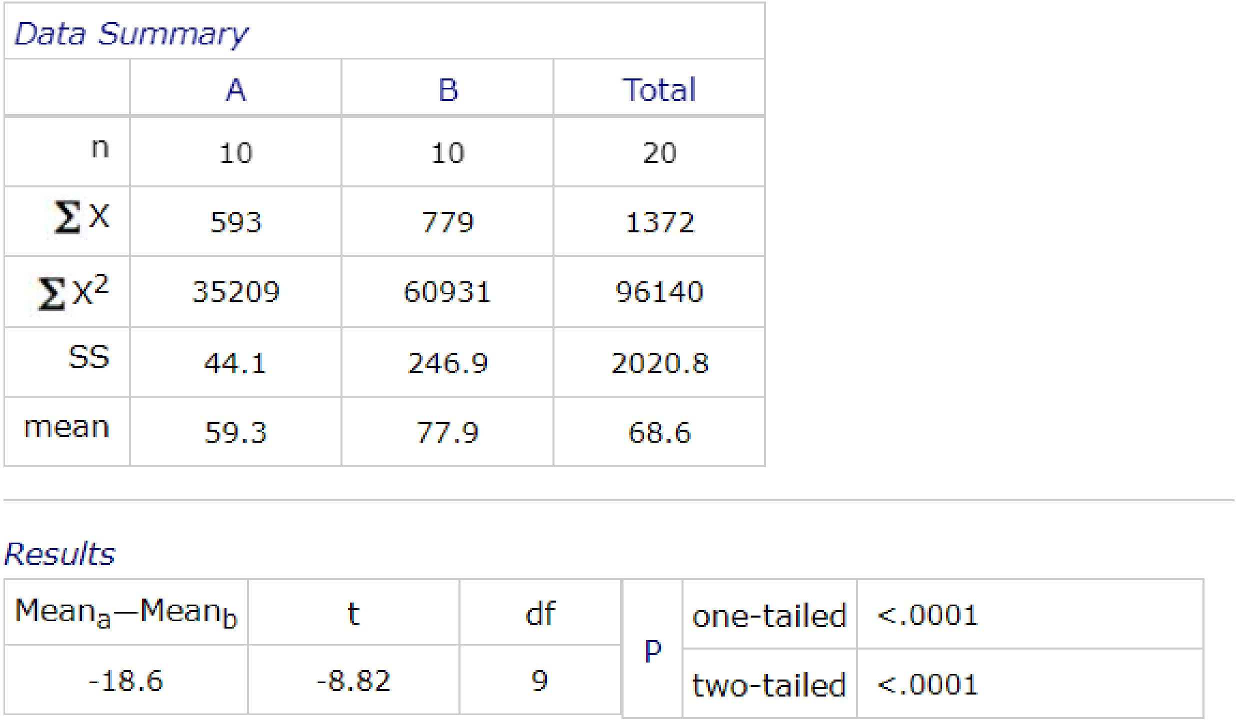
Data Summary

	A	B	Total
n	10	10	20
$\sum X$	458	582	1040
$\sum X^2$	21020	33960	54980
SS	43.6	87.6	900
mean	45.8	58.2	52

Results

$\text{Mean}_a - \text{Mean}_b$	t	df	P	one-tailed	<.0001
-12.4	-9.12	9		two-tailed	<.0001

Figure 34. Paired Sample T-Test for Resistance Level 5. A Paired Sample T-Test was completed for the tension data on resistance level 5. A p-value of less than 0.0001 was calculated for this T-Test, which indicates a significant difference between the standard and adapted side's means for the tension data [5].



Data Summary

	A	B	Total
n	10	10	20
$\sum X$	593	779	1372
$\sum X^2$	35209	60931	96140
SS	44.1	246.9	2020.8
mean	59.3	77.9	68.6

Results

$\text{Mean}_a - \text{Mean}_b$	t	df
-18.6	-8.82	9

P		
	one-tailed	<.0001
	two-tailed	<.0001

Figure 35. Paired Sample T-Test for Resistance Level 10. A Paired Sample T-Test was completed for the tension data on resistance level 10. A p-value of less than 0.0001 was calculated for this T-Test, which indicates a significant difference between the standard and adapted side's means for the tension data [5].

Appendix C: Arduino Sketch

```
// Written by: Annabel Frake
// Class: BME 400
// Purpose: Rotate the console of a Matrix rowing machine between the standard and adaptive
sides.

// Define digital pins for the three limit switches.
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.
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.

// 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);
  pinMode(transitionSwitchPin, INPUT_PULLUP);
```

```
  // Delay to allow program time to start up. Avoids misreading of the transition limit switch state.
  delay(500);
}

void loop()
{
  // Check the position of the console and react accordingly.
  checkConsolePosition();
}

// A function that checks the current position of the console and rotates accordingly when and if necessary.
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 (!digitalRead(transitionSwitchPin) && digitalRead(standardSwitchPin)) // Note: logic is flipped because of INPUT_PULLUP.
  {
    // Call the function that rotates the console to face the standard side.
    rotateToStandard();
  }

  // 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.
  if (digitalRead(transitionSwitchPin) && digitalRead(adaptiveSwitchPin)) // Note: logic is flipped because of INPUT_PULLUP.
  {
    // Call the function that rotates the console to face the adaptive side.
    rotateToAdaptive();
  }
}

// A function to rotate the console to face the standard side of the machine.
void rotateToStandard()
{
  // 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()
{
  // 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 D: Final Cost Table

Table 1. Final Cost Table. Each material bought for this project was tracked and listed. The expenses for the Fall 2022 semester totaled to $297.83.

Item	Description	Manufacturer	Part Number	Date	QTY	Cost Each	Total	Link
Component 1: Motor Components and Circuitry								
Stepper Motor	Hybrid Bipolar 12V Stepper Motor	SparkFun Electronics	1568-1105-ND	10/21/2022	1	$27.20	$27.20	Link
Arduino	ELEGOO UNO R3 Board ATmega328P	ELEGOO	EL-CB-001	10/21/2022	1	$17.99	$17.99	Link
12V Power Supply	12V 5A Power Supply by SANSUN	SANSUN		4342705952	1	$9.59	$9.59	Link
Motor Controller	Qunqi L298N Motor Drive Controller Board	Qunqi	MK-050	10/21/2022	1	$6.99	$6.99	Link
Shipping and Tax (Arduino, Power Supply, Motor Controller)	N/A	N/A	N/A	10/21/2022	1	$8.22	$8.22	N/A
Stepper Motor Driver	New motor controller which solves previous heating issue			11/6/2022	1	$22.02	$22.02	Link
D-shaft Stepper Motor	D-shaft stepper motor (this geometry is needed for the current design)	STEPPERON LINE	17HS16-2004S	11/11/2022	1	$20.02	$20.02	Link
Relay	Purchased a relay from the MakerSpace to help with motor heating issue.	Sipytoph	SP5251	10/31/2022	1	$2.11	$2.11	Link
Heat Shrink and Wire	Components necessary for final circuit fabrication	N/A	N/A	11/18/2022	1	$3.37	$3.37	N/A
Component 2: 3D Prints - Pulley Plates / Antler / Console Design								
Initial SolidWorks Print	Initial 3D print of the antler and pulley plate design (out of a less durable material	N/A	N/A	10/19/2022	1	$24.00	$24.00	N/A

	and lower infill to reduce preliminary costs)							
D-shaft Console Field Goal Posts	3D Print of the field goal posts for use with our new D-shaft stepper motor	N/A	N/A	11/10/2022	1	$2.48	$2.48	N/A
Motor Box and Lid Print	Another test print of the motor box with the added lid following adjustments from the preliminary print	N/A	N/A	11/14/2022	1	$11.04	$11.04	N/A
Preliminary Fitting Prints	Printed sections of the pulley and antler plates to ensure fits, as well as an initial print of the circuitry/motor housing and console pivot bracket.	N/A	N/A	11/01/2022	1	$14.00	$14.00	N/A
Final 3D Prints I	Final 3D Prints	N/A	N/A	11/18/2022	1	$27.52	$27.52	N/A
Final 3D Prints II	Final 3D Prints	N/A	N/A	11/21/2022	1	$93.92	$93.92	N/A
Final 3D Prints III	Reprint of the fieldgoal posts	N/A	N/A	11/29/2022	1	$2.80	$2.80	N/A
Final Fieldgoal Post Print	Reprinted the fieldgoal posts slightly thicker for a better fit in our design	N/A	N/A	11/30/2022	1	$2.72	$2.72	N/A
Reprinted Fieldgoal Posts	Last print of the fieldgoal posts with altered dimensions	N/A	N/A	12/2/2022	1	$1.84	$1.84	N/A
TOTAL:								**$297.83**