Low Interference Wheelchair Footrest

Final Report

BME 301
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Abstract

There exists a gap in the electric wheelchair footrest market due to many current footrest models being awkward, heavy, and often lacking user-friendly features for convenient removal and storage. These models specifically limit partially paralyzed individuals to the point that another person is needed when moving a footrest to a new position, or in some circumstances off of the wheelchair completely. Fixing these issues and adding new features catered to the partially paralyzed would help enable them to perform beneficial movements with the comfort of a footrest. The proposed innovative footrest aims to reduce interference with daily tasks, provide adaptability with easy removal and storage, reduce weight, and streamline the design without compromising the essential support functions of traditional wheelchair footrests. The need for a universal footrest is challenging, as many electric wheelchairs are designed with differing frame, structure, wheels, suspension, seating, and user interface/controls. With an electronic design, this project hopes to contribute to the development of an improved wheelchair accessory that better accommodates the diverse needs of many users. A design using two linear actuators was implemented through various fabrication methods and the final prototype was tested and analyzed to ensure the quality. Tests reveal positive results, however, minor downsides show possibilities for continued improvements to make greater impacts.

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Introduction

Motivation/Global Impact

The design project's client, Mr. Dan Dorszinski, has requested a modification to his current wheelchair footrest to enable the ability for him to interact with the surrounding environment more effectively. Currently, Dan uses a power wheelchair with a stationary electric footrest that is able to move forward and backward, along with up and down while being attached to the wheelchair's seat. The main concern is that the current footrest design is unable to move out of the way for the client to transition off of the wheelchair, as the design doesn't enable the footrest to tuck under the wheelchair or be moved to the side. Because of these problems, the client currently doesn't use a footrest at all on his powered wheelchair, as the footrest mostly imposed challenges rather than being beneficial. A new design that would allow for more movement of the footrest would enable partial paralysis users to still have a footrest, but be able to have more leg freedom than a traditional wheelchair footrest often supplies. This modification not only addresses individual user needs but also holds the potential for a global impact by fostering increased mobility and movement independence. The development of a low-interference electric wheelchair footrest could set a precedent for more inclusive and adaptable designs, positively influencing the lives of countless individuals with mobility impairments on a large scale.

Existing Devices

a) b)

Figure 1: Alternative electric wheelchairs with their respective footrests. a) The Matrix Ultra [1] b) the Go-Chair [2]

Electric wheelchair manufacturers all tend to make footrests in a similar way. The footrest comes straight down from the seat of the wheelchair, and the foot pads come out at a ninety degree angle near the bottom of the footrest. A few examples are shown in the figures above. Each footrest is designed alongside a specific wheelchair body. The Matrix Ultra [1] has its own footrest that can be seen in Figure 1a. This footrest is not compatible with the Go-Chair [2] in Figure 1b. Neither the Go-Chairs footrest nor the Matrix Ultra's footrest can attach to the Sedeo Pro body for the Quickie Q700 M [3], which is the wheelchair currently used by the client. These limitations leave only two current designs that can attach to the client's wheelchair, and therefore compete with the team's current design. The Sedeo Pro footrest and the previous Low-Interference Wheelchair Footrest [4].

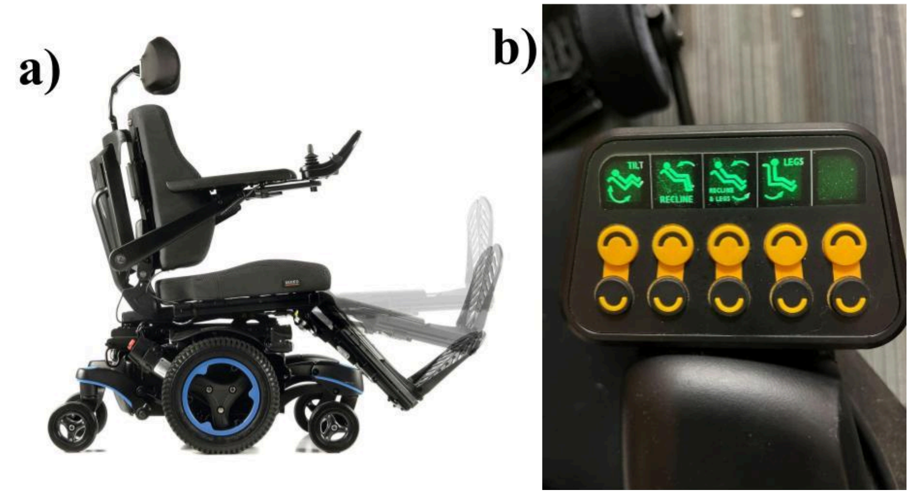

Figure 2: a) The Quickie Q700 M with Sedeo Pro body and footrest [3] b) the Sedeo Pro's user interface

The Sedeo Pro, shown in Figure 2a above, is powered and controlled electronically through the wheelchair. On the right-hand side are buttons controlling the footrest, as depicted in Figure 2b, enabling pivoting around the connection to the wheelchair, albeit with limited motion. No matter the orientation, the foot pads, which are 33 centimeters, block the feet or legs from assisting in any movements. The foot pads are too far to be reached while seated, and require more force to fold up than the client could exert if they were reachable. The wheelchair allows for no orientation where the foot pads are not in the way of the user if they try to lean forward with their feet on the ground or try to transfer off of the wheelchair.

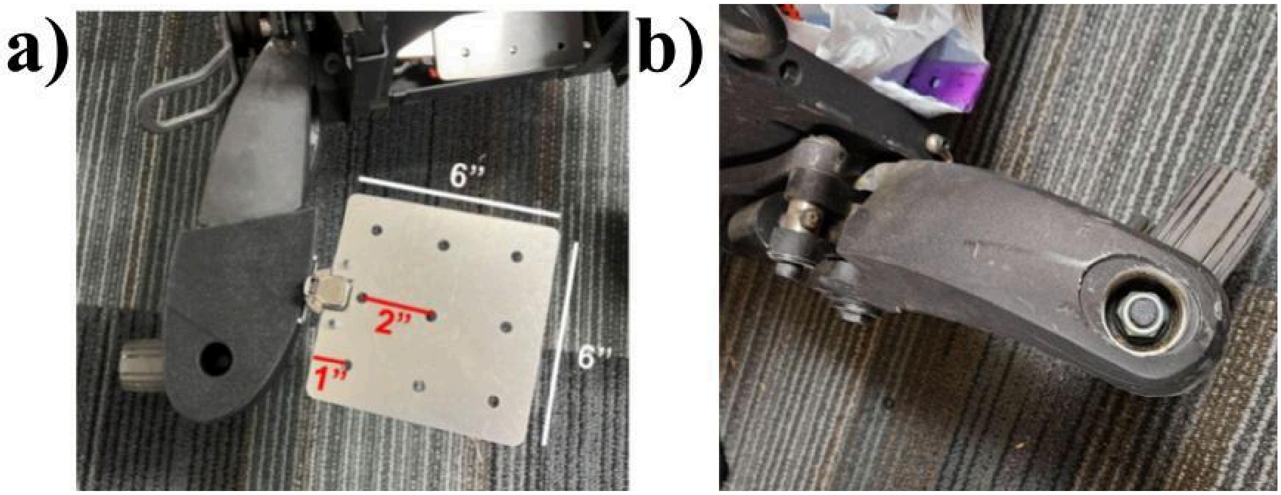

Figure 3: a) Previous Low-Interference Wheelchair Footrest design attached to wheelchair [4]

b) Bolt hole that the castor cap slots into

Previously, there was a manual footrest designed to fix the issues with the Sedeo Pro. This design can be seen in Figure 3a and is lightweight, and easily removable. It consists of two 15.25 x 15.25 centimeter metal plates that are attached individually to two 3D printed PLA castor caps that slot into the bolt holes above the outermost wheels of the wheelchair shown in Figure 3b. The metal plate is the foot pad and is connected to the castor cap by an automatic hinge. The castor cap doesn’t require any bolts or screws to stay in place during use, meaning it can be easily removed. The automatic hinges were meant to allow the foot pads to easily fold up out of the way, however, they require a force in the hinge direction to start the movement process. This force is greater than the force required to fold the Sedeo Pro, and is therefore not usable by the client. The PLA also lacks strength and often snaps before the hinge is able to engage.

Problem Statement

This project aims to create an electric wheelchair footrest design to overcome the limitations of current models which are often cumbersome, heavy, restrict leg movement, and access to the ground. The goal is to create a footrest that is lightweight, detachable, user friendly, provides comfort, and also allows for interactions with the surrounding environment through the footrest itself.

Background

Muscular Dystrophy Research

Becker Muscular Dystrophy (BMD) is a genetic and progressive neuromuscular disease caused by mutations in the dystrophin gene [5]. BMD results in the production of abnormal dystrophin, a protein that protects muscle fibers from breaking down. BMD typically manifests between the ages of 5 and 15, leading to progressive muscle weakness and degeneration [6].

Besides patients with muscular dystrophy, other wheelchair users with a higher level of mobility could also benefit from a footrest design that is less interfering. For example, individuals with partial paraplegia may have some degree of leg function and could use their lower extremities for certain tasks; patients with conditions like Multiple Sclerosis or Spina Bifida, where lower limb weakness is present but not complete may also benefit from the design. In other scenarios, individuals with heart conditions use wheelchairs to prevent overexertion but can still use their feet; and last but not least, some elderly individuals use wheelchairs for mobility assistance but can still use their lower body for various tasks [7].

Design Research

In order to make the design more user friendly and versatile, the footrest should be retractable and electric powered. Upon research, linear actuators and stepper motors are some of the best options to achieve this motion. Linear actuators are a set of devices that create motion in a straight line, and are instrumental in adjusting the footrest position dynamically, thereby offering users the flexibility to use their feet for a range of daily tasks. A stepper motor is a precise motion device that operates in discrete steps, also contributing to the dynamic adjustment of the footrest position. The design approach in this project not only aims to improve the user's independence and quality of life, but also seeks to push the boundaries of conventional wheelchair design.

Codes and Standard Research

The FDA regulation 21CFR890.3920, established in 1983, categorizes wheelchair components as medical devices integral to the functioning of a wheelchair [8]. This includes components that are sold separately. According to these regulations, such devices are exempt from the premarket notification process, which is typically required for medical devices to ensure safety and effectiveness before they are marketed. This exemption allows manufacturers to bring wheelchair components to market more swiftly without undergoing the premarket approval process. Therefore, for the wheelchair component design, no premarket approval is necessary before proceeding with manufacturing and distribution.

The Americans with Disabilities Act (ADA) mandates that individuals using manual or power wheelchairs, scooters, or other manually-powered mobility aids like walkers, crutches, and canes, must have access to all public areas [9]. The ADA defines a "wheelchair" as any wheeled device, whether manually operated or power-driven, that is primarily designed for use by people with mobility disabilities for the purpose of indoor and or both indoor/outdoor locomotion. Additionally, the ADA requires that facilities open to the public accommodate other power-driven mobility devices used by people with disabilities, unless specific devices pose legitimate safety concerns that prevent their use within a particular space. This ensures broad accessibility for individuals with mobility impairments, promoting inclusivity and equal opportunity in public spaces.

Client Information

The client Dan Dorszynski is a Wisconsin native who studied Civil and Environmental Engineering at Stanford University. Since then he has started companies around the U.S. including Moorea Solutions, LLC, which is stationed in Milwaukee. He also suffers from Becker's Muscular dystrophy. Mr. Dorszynski has lost ambulation and requires the Quickie Q700 M [3], shown in Figure 2a. However, Mr. Dorszynski still has enough muscular strength in his lower body to use his legs for certain tasks, but finds the footrest on his wheelchair blocks this ability. To compensate for this, he allows his feet to remain free without the use of a footrest.

Design Specifications:

The improved wheelchair footrest must have the ability to be moved and not interfere with the user's ability to place their feet on the ground. This should not come at the cost of stability, as the footrest must be able to hold the weight of the client's lower body. The footrest is designed for a factor of safety of two for consideration of any misuse. The footrest must also hold both of the client's feet without being too large. This will be accomplished with a footplate around 25.4 centimeters, which is the clients foot size. The footrest will be most useful outside, so it must be durable and corrosion resistant. After those needs are met, the design's user friendliness would benefit from being as lightweight as possible, between 2-7 kg (to save on battery life), and be easily removable for storage. For the full product design specifications, refer to the Product Design Specifications located in **Appendix A**.

Preliminary Designs

Before any specific designs were drawn out, the option between an electric or manual system for moving the footrest was considered. The manual system would be made of cables and pulleys to counterbalance the weight of the footrest, causing it to feel much lighter when being moved by the user. In comparison, the electric system would use the wheelchairs built in buttons or a newly created joystick to control electric components that move the footrest. The wheelchair in use currently uses a variety of built in buttons to interact with the control system. Ultimately, the electric system won due to its ability to interface with how the wheelchair already functions. This also allows the client to more easily adjust the footrest's position to transfer. Further discussion between the two systems and the design matrix can be found in **Appendix C**.

I: Autonomous Footrest

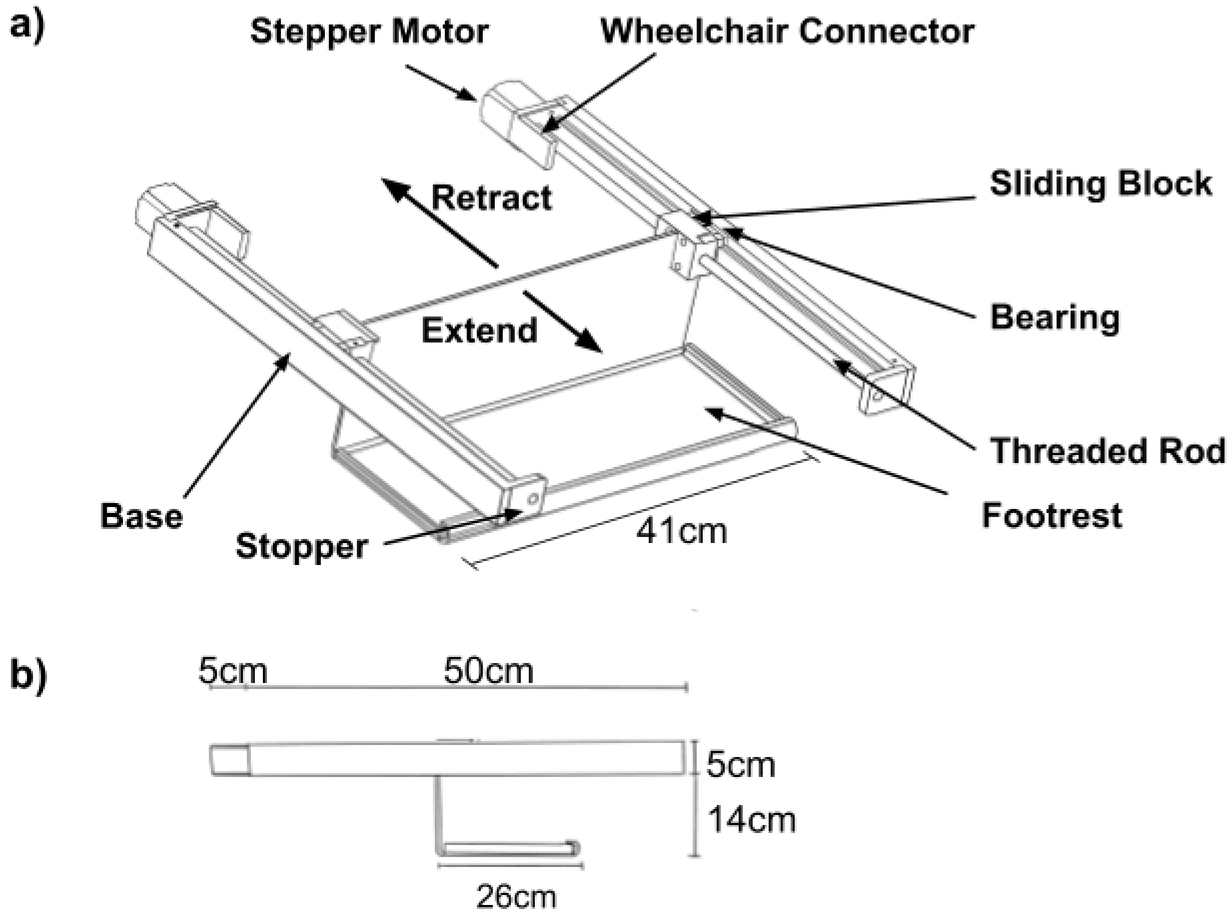

Figure 4: Autonomous Footrest. a) 3D Footrest Design with labels. b) Side view with dimensions

The autonomous wheelchair footrest design, as shown in Figure 4, uses a completely hands free system that is meant to be integrated with the control interface of the wheelchair. Even though the design consists of multiple assembly parts, the overall mechanism can be broken up into two main parts, the footrest and the linear motion slider. The footrest itself consists of welded aluminum that makes the L shaped traditional pattern seen in most wheelchairs. Around the edges at the bottom of the footrest there are edge and flange bends creating a slight curved over pattern instead of flat sharp edges. The footrest is connected to the linear motion slider via threaded nails into the sliding block. The sliding block itself is the bridger of the footrest and the linear motion slider. The block is connected to a linear bearing on its backside to aid with friction and force assistance, while in the middle, the threaded rod is fit to aid in motion, both forward and backward. The threaded rod is often referred to as a lead screw and is driven by a motor to move the block along its path. The stepper motor provides precise and controlled motion by converting electrical pulses into incremental steps, creating the linear motion needed to move the sliding block and footrest, with additional power as needed from the wheelchair battery. Once the stepper motor has reached its maximum forward distance, a stopper is used to cap off the threaded rod. The stopper is also used for support as the footrest cannot go forward anymore. Furthermore, upon switching to the reverse direction, the sliding block and footrest are able to go all the way back under the wheelchair until the stepper motor has fully decreased in steps and the block has reached the wheelchair connector, the limiter of the reverse direction. The wheelchair connector, as the name states, is the final piece of the design, connecting the entire mechanism to the wheelchair. This is done through either a fixed welded connection or multiple pin connections on both sides of the wheelchair for maximum support.

The old motion design in solidworks is listed in **Appendix D.**

II. Lock and Pulley

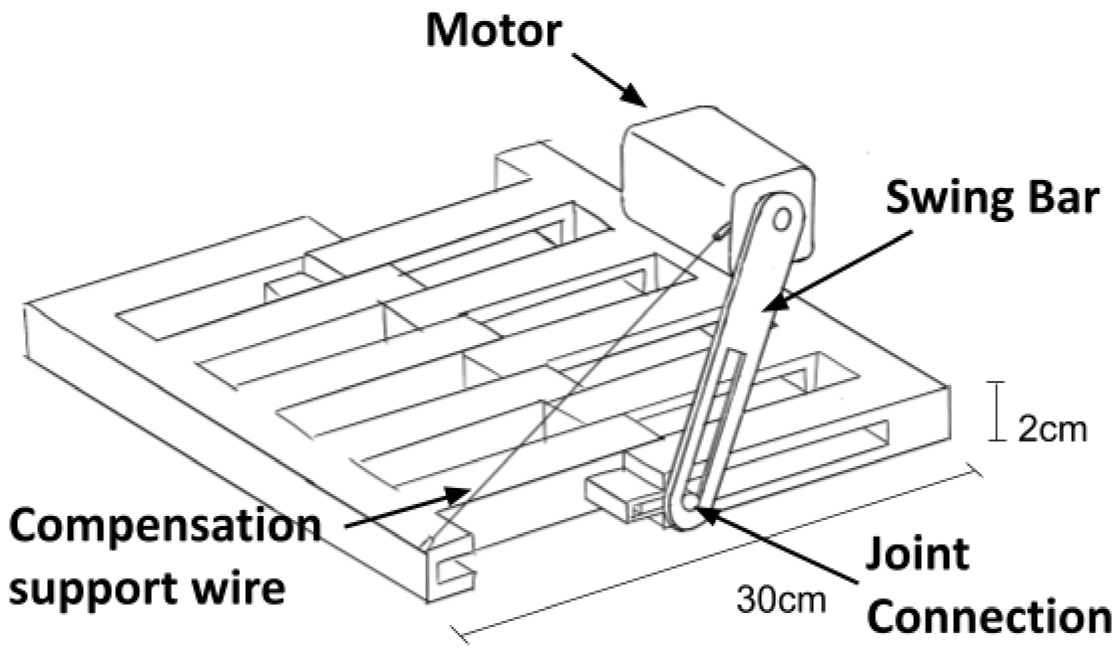

Figure 5: Lock and pulley footrest

The lock and pulley design is aimed to solve the problem that the space underneath the seat of the wheelchair is not long enough to fit a footrest of all standard shoe sizes. The footrest itself consists of two parts, an outer plate and an inner plate, connected in a fork orientation. When being stored, the two plates can be retracted, minimizing space used. When extended, the motor is powered and through the swing bar, pushes the footrest outward. With force applied at the joint of the two pieces of footrest, the outer plate will slide out first, eventually pulling the inner plate along when the ends make contact as shown in Figure 5. When being retracted, opposing force will pull the outer plate backward, eventually pushing the inner plate backward as well. The swing bar has a carved out track that connects to the joint of the two plates and engages in circular motion with respect to the motor. Notably, there is also a compensation wire that holds the outer plate since the outer plate will be floating and static equilibrium is not reached. The compensation wire connects to the motor to provide tensile strength to overcome the force applied by the user.

III. Sliding Footrest

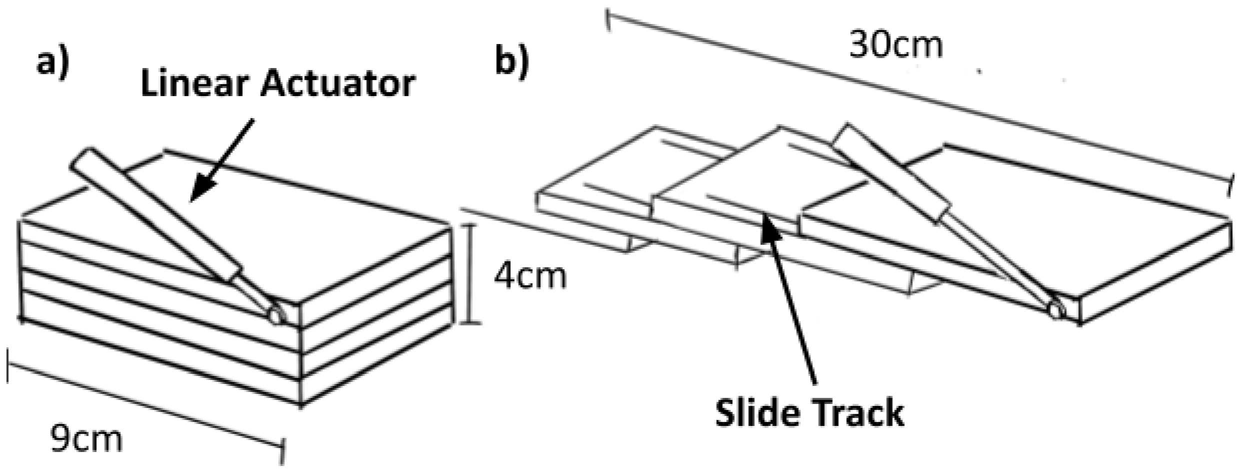

Figure 6: Sliding Footrest. a) Retracted state b) extended state

The sliding footrest design uses a very similar sliding mechanism as seen in design II. The sliding footrest design uses overlapping plates that extend out, at a certain angle to create overall flatness of the footrest, as shown in Figure 6a, that will extend on top of each other to create more space for the user, which is achieved by the linear actuator. The linear actuator is connected to the top most plate thus when extended, pulls the top most plate outwards and brings the rest of the plate one by one through the slide track, eventually making an extended footrest as shown in Figure 6b. The result is a weaker joint at each intersection of the plate but with a better distribution of load on each plate. While this design shows weaker joints, the team suggests using acrylic for the footrest material for its ease of cleanness and aluminum alloy for the supporting structure because of its strength.

Preliminary Design Evaluation

Design Matrix

Table 1: Design Matrix I.

Criteria (Weight %)	Autonomous Footrest	Lock and Pulley	Sliding Footrest
Size (35)	3/5	4/5	5/5
Durability (25)	5/5	3/5	4/5
Weight (20)	4/5	5/5	2/5
Cost (10)	5/5	4/5	3/5
Fabrication (10)	4/5	2/5	2/5
Total	80	75	73

Size: This criterion is given the highest weighting because a larger footrest will limit maneuverability under the wheelchair as the increase in area could cause problems upon retraction and room when traveling. The sliding footrest won this category as it is both short and thin when contracted, without compromising usability.

Durability: Durability is paramount in the design of a wheelchair footrest, as the rest must withstand the rigors of daily outdoor use and remain supportive and safe. The autonomous footrest has the most supporting material and therefore scored the highest.

Weight: Lighter footrest designs allow for easier use and less strain on the wheelchair and its power supply. The lock and pulley has the least components and is therefore the lightest.

Cost: A low cost is important to allow as many people to purchase the footrest as possible. Each design uses similar amounts of structural material, however most of the cost comes from the electronic components. The linear motor slider is the least expensive so the autonomous footrest is scored the highest.

Ease of Fabrication: A design with a straightforward production process can be completed more efficiently, smooth replicability, and allow for more testing and changes. Also, a more complex design can lead to more mistakes, wasting time, and raising costs. The simplest design is the autonomous footrest.

Proposed Final Design

After discussing the possible outcomes of each design and evaluating the design matrices, the team has decided to proceed with a modified version of the electronic design I. After doing an initial cost analysis and materials selection process, the design proposed was too expensive and required more materials and modifications to the base of the client's wheelchair. Using design I as a template, the team was able to come up with another autonomous design that used two linear actuators with no rail component. These actuators would connect to the wheelchair via custom 3D printed PLA actuator holders and then be connected to the footrest via custom aluminum brackets. This design aims to interface with the wheelchairs built in control system, using the leg related buttons to control forward and reverse movement just like design 1. The footrest itself would be MIG welded aluminum and consist of a classic L-shaped design with an aluminum cutout on the back that would be screwed into the actuator brackets. At the other end of the wheelchair towards the back, the linear actuators would be connected to a voltage divider circuit that would half the 25V input from the wheelchairs battery. This is due to the linear actuators each having a voltage limit of 12V. Furthermore, on the circuit board, the plug in to the wheelchairs control system would be connected to the actuators, allowing for interface between the actuators and the leg buttons on the chair. More can be seen on the final design in the Fabrication and Testing sections of the report.

Fabrication/Development Process

Materials

The team had chosen aluminum for the main body of the footrest. Aluminum is notably lightweight, yet offers substantial strength and durability, with a modulus of elasticity of 68.9GPa, a bearing yield strength of 386MPa, as well as a relative light density of 2.7g/cc [10], making it an ideal choice for stress bearing components of the design. Additionally, the material's ease of fabrication allows for efficient shaping and assembling processes, which is critical in meeting project timelines. Aluminum also has stable chemical properties, it does not rust, and it forms oxide layers at the surface to further resist corrosion, making it ideal for outdoor usage [11]. The widespread availability and cost-effectiveness of aluminum further justified this selection, the appearance of aluminum material also matches with the wheelchair's overall aesthetic. Three 30.48 x 30.48 cm, .635 cm thick aluminum plates were purchased from the Makerspace at the University of Wisconsin Madison.

Linear Actuators were chosen to provide powered movements for the footrest. Two 25.4 cm stroke linear actuators were ordered from DEMOTOR PERFORMANCE, this particular model was selected for its relative low cost, low noise for the design to be less disturbing when used, water resistance for outdoor usage, low power consumption, relatively fast extension and retraction speed, as well as its ability to support 1000 N of load [12].

The team also used 3D printing to fabricate the holders for the prototype. 3D modeling and 3D printings provide fine details to a piece that can be dynamically altered to fit more scenarios. This allows less limitation of the design and thus provides a more universal/inclusive design to more wheelchairs. In the consideration of cost and product strength, the team used

Polylactic acid (PLA) with 50% infill to ultimately maximize between cost efficiency and structural strength. It is found that 3D printing with PLA is the most commonly used in the Makerspace and thus ideal for prototyping, allowing more room for trial and error.

A voltage divider circuit is built to convert the battery voltage of 25 volts to the linear actuators' operating voltage of 12 volts. 2 breadboards, 50 1 kilo ohms resistors, and numerous jumper wires are used for its construction. All circuit components are ordered from Sparkfun, for their affordability, as well as the team's familiarity with Sparkfun products.

Besides material mentioned, a selection of hardwares is also used for connection and mounting, including brackets, screws, nuts etc. Quality parts are selected for reliability. See **Appendix C** for the complete list.

Methods

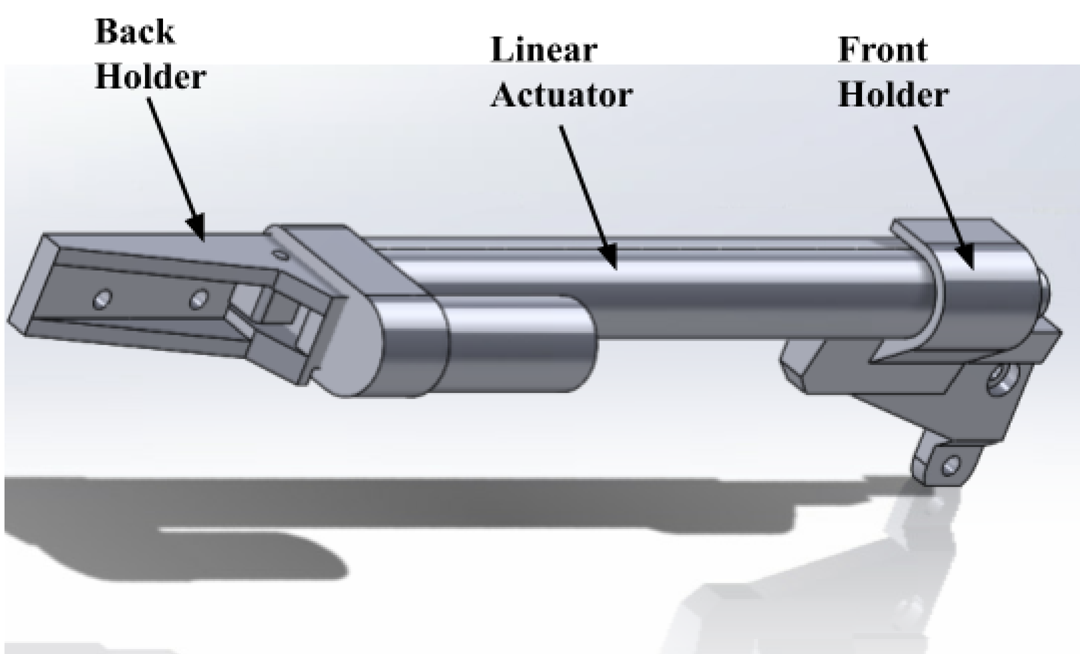

Figure 7: 3D model of linear actuator and holders. The back holder attaches to the backside of the wheelchair and the front holder attaches to the front. Both holders use 8mm screws. Linear actuator model is constructed using given dimensions from the provider.

In order to attach the linear actuators to the wheelchair, two holders are used for the connections on each side, the back holder and the front holder. The back holder serves mainly as counter movement restriction, and possible moment created by applied force to the footrest. The front holder serves to create more structural support to rotation of the linear actuator. It is found that on each side of the wheelchair, underneath the seat and above the wheels, there are unused screw holes that are available for linear actuator attachment. The screw holes are oriented in a complex shape due to the manufacturing design. Thus the team first used solidworks to map out the usable screw holes, created models for the linear actuator as shown in Figure 7 above, developed 3D models for the linear actuator holders, and 3D printed with PLA (50%) that is tailored to the linear actuator and the wheelchair screw holes used as shown in Figure 7. 3D printing was ideal for this scenario because of its cheap cost and room for trial and error. Through the process, multiple versions/design alterations must be made to accommodate for the tolerance of 3D printings that resulted in minor errors that cause a mismatch to the screw holes. The team replicated one side of the holders to the other side only after reassuring that the holders fit seemingless and ready for final production to reduce material wastes.

The footrest is constructed from three aluminum parts, all .635 cm thick. The foot pad is 28 x 25.4 cm and sits low enough that it is comfortable for the user. The back plate is 28 x 28cm, and hangs down from the actuators so the foot pad is low enough when connected. Finally, there is the 35 x 5 cm bar that is screwed to the back plate. The bar's extra length is needed as the plates are too short to connect to each actuator by themself. Each piece had its shape and screw holes cut out of a 30.48 x 30.48 cm aluminum plate using a water jet. There were also larger sections cut from the inside of the plates to reduce weight, and stop dirt from building up on the footrest.

Originally, standard steel actuator brackets were intended to be used to connect the bar to the actuators. These brackets were found to perform below design specifications, even after they were modified using a steel band saw and drill press. While trying to find a solution the team found the caps of the actuators unscrewed. This led to the solution where two 6.35 x 3.18 cm custom aluminum brackets were cut with a water jet from the same plate used for the footrest bar. Two holes were cut into each bracket, one small hole to connect to the bar, and one large hole to be screwed between the actuator and its cap. This allowed for much more resistance against bending at the bracket.

A simple voltage divider circuit was constructed on two bread boards. The wheelchair power, and the actuators were connected to this circuit. The breadboards were placed into a 10x20 cm plastic box. An 8mm hole was drilled into the side of the box with a drill press, and a screw was placed through the box and into a screw hole in the back of the wheelchair. Another hole was drilled into the side, and a third into the roof of the box to allow wires from the wheelchair and actuators access to the bread boards.

Final Prototype

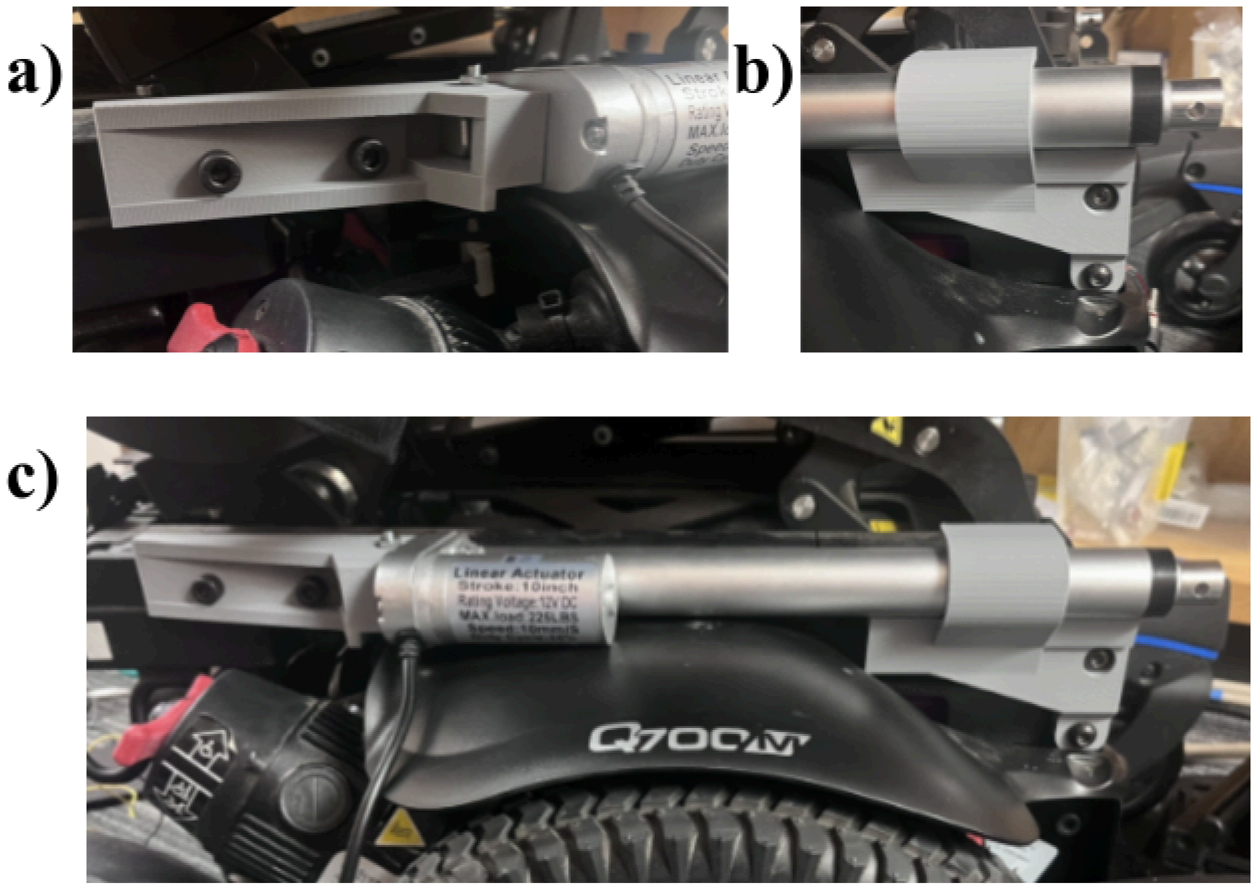

Figure 8: Linear actuator holder assembly. a) Back holder attached b) front holder attached c) full picture of the assembled holders on the linear actuator

The printed holders, as shown in Figure 8, are a great fit for the linear actuator and the screw holes on the wheelchair. The same oriented mirror duplication is assembled on the other side of the wheelchair. Detailed SolidWorks drawing with dimensions can be found in **Appendix H.**

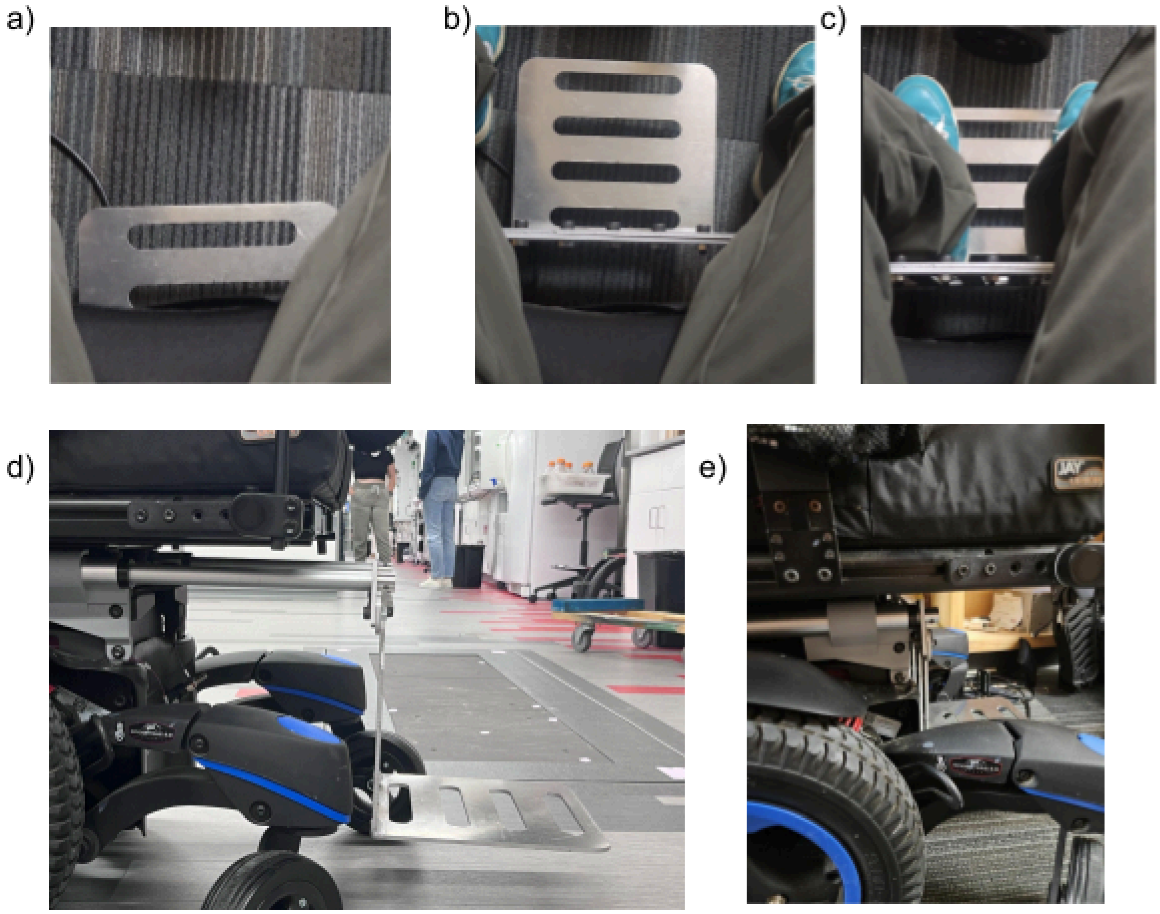

Figure 9: Footrest Final Product a) Unloaded Footrest Fully retracted, user perspective
b) Unloaded footrest fully extended, user perspective
c) Loaded footrest fully extended, user perspective
d) Unloaded Footrest fully extended, side view
e) Unloaded footrest fully retracted, side view.

The footrest final prototype, as shown in Figure 9, is capable of extending entirely out from under the seating of the wheelchair to a functional location for feet to be placed, providing not only sufficient support, but also added comfort. The prototype is also capable of retracting to a non-interfering location, for users to perform daily tasks with ease. SolidWorks drawing with dimensions can be found in **Appendix H.**

Testing

Bending Deflection and Rotation Test

Figure 10:. Linear actuators are extended to around 250mm and various combinations of weights are put on the footrest and allow the linear actuator to bend

The bending deflection and footrest rotation is an essential evaluation to the structural integrity of the linear actuator and the design criteria. As specified in the Product Design Specification, **Appendix A**, the footrest system needs to withstand 250N. This is calculated using the anthropometry table with a total body weight of 80kg and a factor of safety of 2. The testing setup consists of three main components: video taking camera, known weights, and the footrest system with linear actuators. The team gathered known weights form the Universities teaching lab, that are 10lb, 12lb, 15lb, and 25lb. The conversion of units to newtons can be found in **Appendix E**. These weights alone aren't sufficient to reach a desired maximum testing value of 250N. In order to achieve a desired value of weights, the team made combinations of these existing weights to create better data trends. The video taking camera is an iPhone 13 that is placed around 1 meter away from the footrest, taking in the sagittal plane so the side view of the linear actuator and footrest system is available to analyze, as shown in Figure 10. The linear actuator is extended to the maximum to provide maximum deflection. The more detailed testing protocol can be found in **Appendix E**.

Footrest Extension & Retraction Test

Figure 11: Leg load with no voltage divider.

The footrest extension and retraction test aimed to compile more information about a dynamic setting as opposed to static testing at full extension as seen in the bending deflection and rotation testing section. This series of testing used weight and motion under the various wheelchair conditions of no loading and loading, along with the condition of with or without a voltage divider implemented. Figure 11 shows an example of the leg loaded no voltage divider situation. The purpose of this testing was to find out if the linear actuators would be able to extend and retract the full distance under varying conditions as the client would be using the footrest daily. Using the four testing conditions as given: (1) Voltage divider no weight, (2) Voltage divider with weight, (3) No voltage divider no weight, and (4) No voltage divider with weight, the team was able to determine if more powerful actuators were needed along with the possibility of changing the design in the future to account for better load distribution. Each of the four tests were done a total of three times and an average was compiled for the times and distances recorded, refer to the results section for the complete data.

Results

Bending deflection and rotation testing results

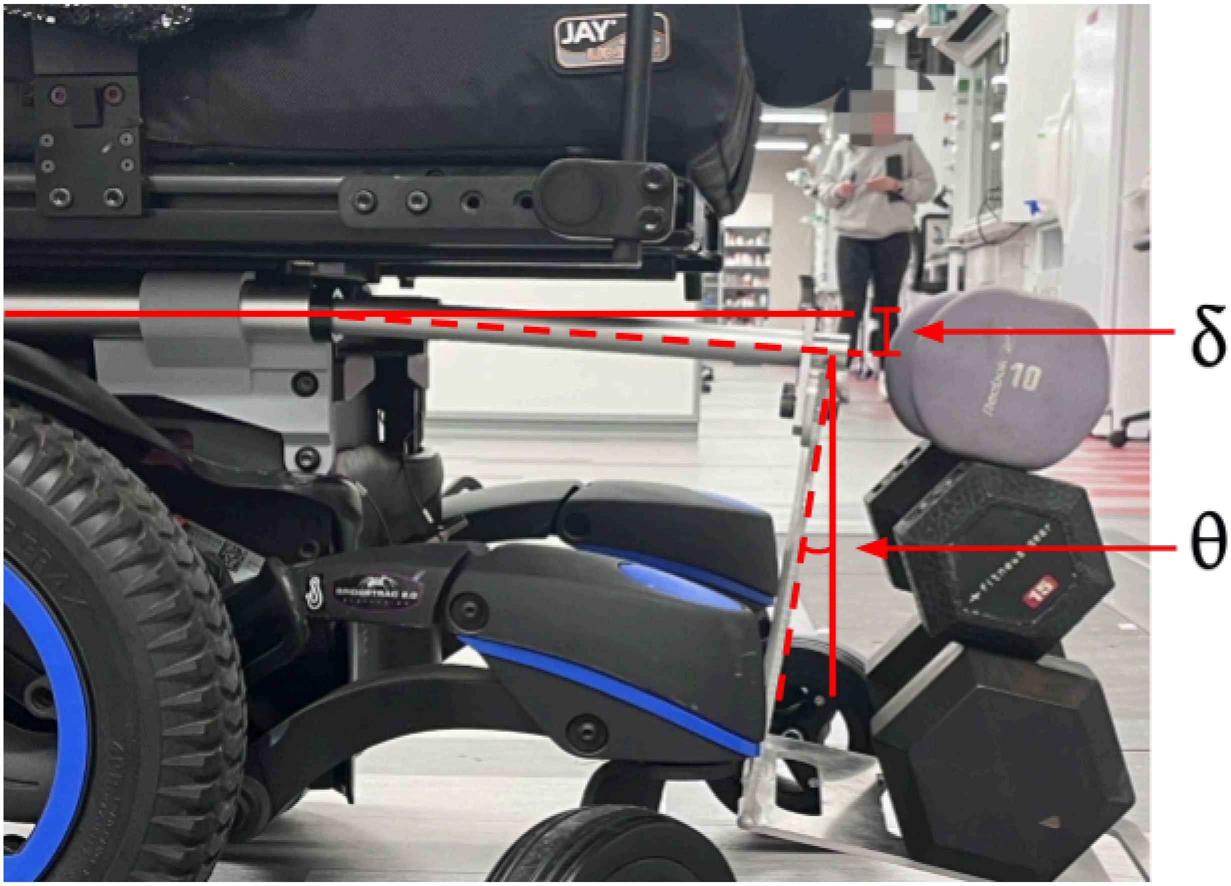

Figure 12: Bending test analysis. The bending analysis is conducted using ImageJ, an imaging analysis software. Though due to image quality, the method is replicated using google drawings. δ represents the linear actuator deflection with respect to the neutral horizontal axis. θ represents the footrest rotational angle with respect to the neutral vertical axis.

The snapshots of each weight applied to the footrest are captured and analyzed using ImageJ to measure linear actuator deflection and rotation angle. The applied forces are various combinations of available weights, specifically 45.8N, 52.4N, 64.4N, 113N, 158N, 177N, and a maximum applied force of 223N. Deflections and rotations at each of these increments are plotted on google sheet to visualize the trend.

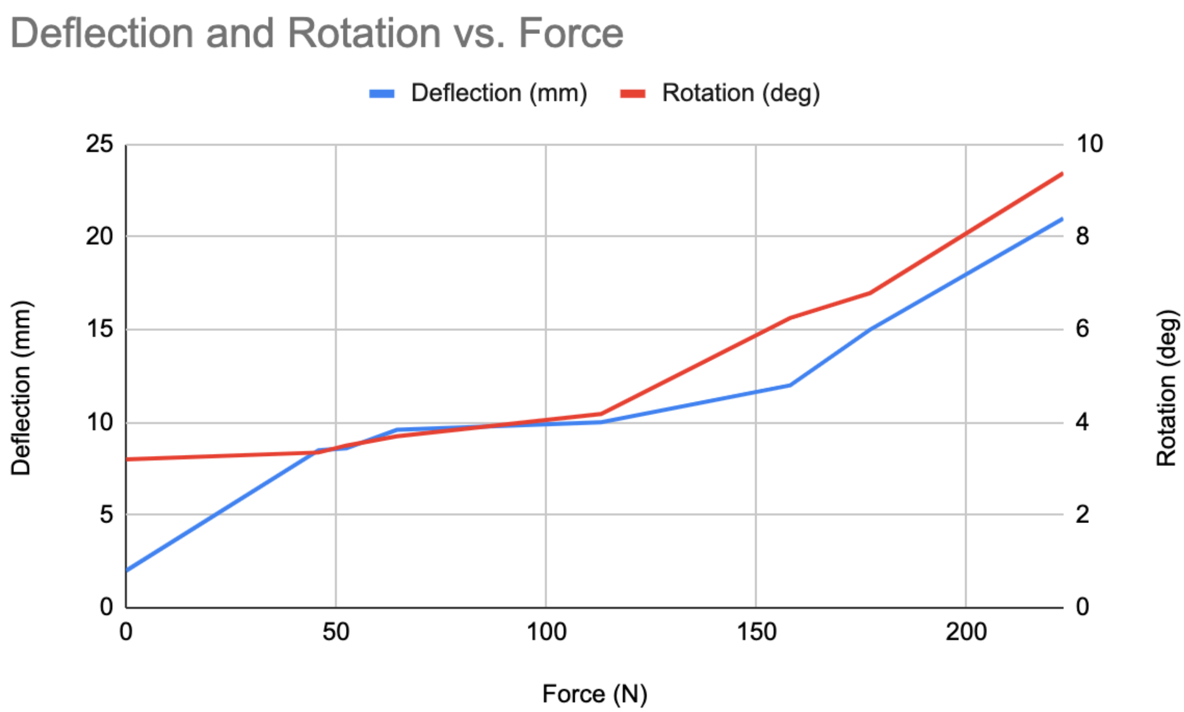

Figure 13: Bending test analysis results, deflection and rotation vs. force. The bending and rotation measurements are conducted using ImageJ. With a range of forces from 0N to 223N, deflection (mm) in blue and rotation (deg) in red is plotted. Raw data found in **Appendix E**.

In Figure 13 above, the general trend of deflection and rotation is observed when force is applied to the footrest. Deflection started out relatively low but non-zero due to the weight of the footrest itself applied to the linear actuator. Rotation is also observed. Between 50N and 100N, both rotation and deflection are relatively smooth and no significant changes are observed. Pass 150N, an increase in both deflection and rotation is observed, relatively linear. The deflection is due to the force applied to the footrest resulting in internal shear force. Due to the relatively low moment of inertia of the linear actuator, elastic deformation occurs in the linear actuator. The rotation is due to the moment about the joint between footrest and linear actuator, also caused by the applied force to the footrest. At maximum force applied, 223N, the linear actuator exhibits 21mm of deflection and footrest experiencing 9.4 degrees of rotation. From these results, the team concluded that the amount of deflection and rotation raises some problems to the user and is not ideal, however, the deflection is still relatively low compared to the size of the linear actuator and thus does not affect the use of the product.

Extension & Retraction Testing Results

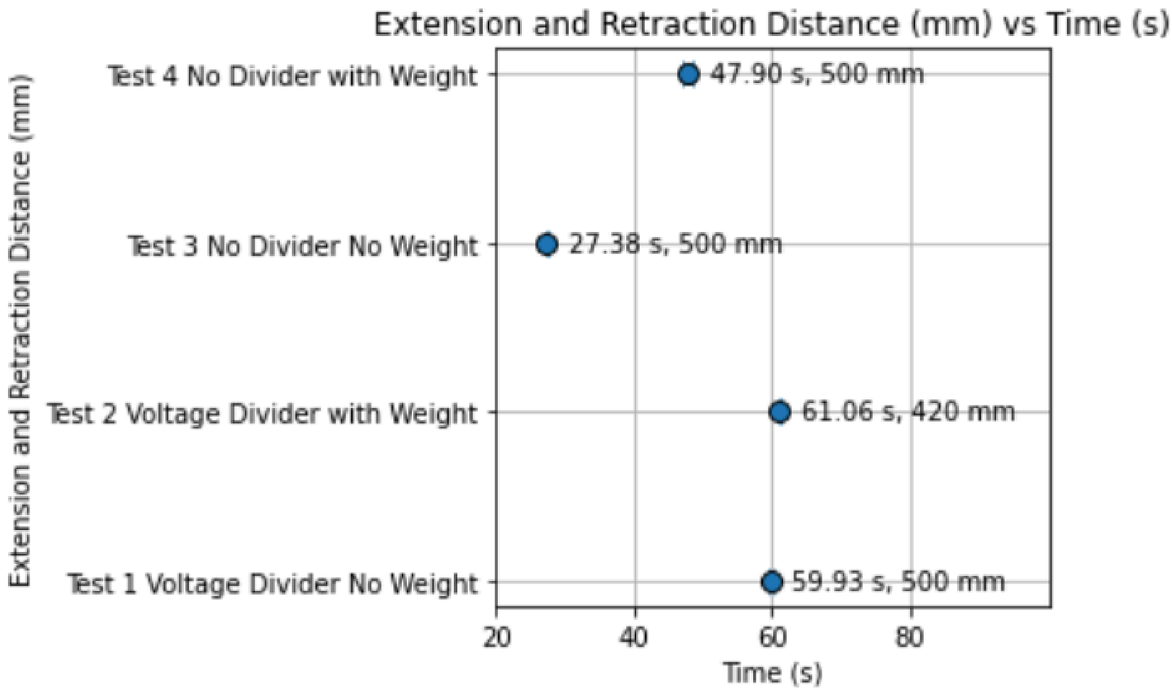

Figure 14: Extension and Retraction Distance (mm) vs Time (s)

From the extension and retraction testing results, it was concluded that the team needed more powerful actuators to account for the distributed load on the footrest. In Figure 14, the results from the four tests can be seen. The times and full distances covered are an average of three trials for each test. As stated previously, each test was done three times to ensure that the data collected was an accurate representation of time and full distance traveled. The code for creating this testing plot is seen in **Appendix F**, while the testing protocol is seen in **Appendix G**.

In test 1, the average time to complete the full distance of 500mm was about 60 seconds. The goal of test 1 was to get a feel for the speed of the actuators when the recommended amount of voltage was supplied. The noise of the actuators were much quieter as compared to without the divider, but the overall speed was much slower. The conclusion that more powerful actuators are needed first arrived from test 2. In this test a standard leg load was applied as seen in Figure 11 from the testing section. While using the voltage divider, the speed began to slow down as load was applied and around 420mm on three different occasions, the linear actuators stopped working and the footrest came to a complete stop. Upon trying to reverse the direction, it was noticed that the actuators took a few seconds to get going again as the system could not handle the load at that distance. This was a problem as the client wouldn't be able to extend the footrest the full distance if a voltage divider was used, which in terms of longevity, has to be applied, otherwise too much voltage would be powering each actuator for long term use. As for this project, the team decided to conduct more testing without the voltage divider for tests 3 and 4 to build on the conclusion of the need for more powerful actuators. In test 3, the speed of the actuators were doubled as compared to test 1, while the actuators were still able to go the entire distance of 500mm. This was an important observation in the testing process, but needed to be elaborated upon in test 4 with weight. When applying a leg load in test 4, the actuators were able to go the entire extension and retraction distance 13 seconds faster than in test 2 and 80mm further forward. From these observations it was concluded that to get the total distance of actuator extension and retraction, the team would need to have actuators able to support 25V of power. This is due to the 12V actuators currently not being able to go the entire distance of extension when applying a standard leg load and voltage divider. Over time the 12V actuators will continue to be damaged as the eternal resistance of the DC motors is not capable of handling that much power for years to come.

Holder stresses and deformations simulation

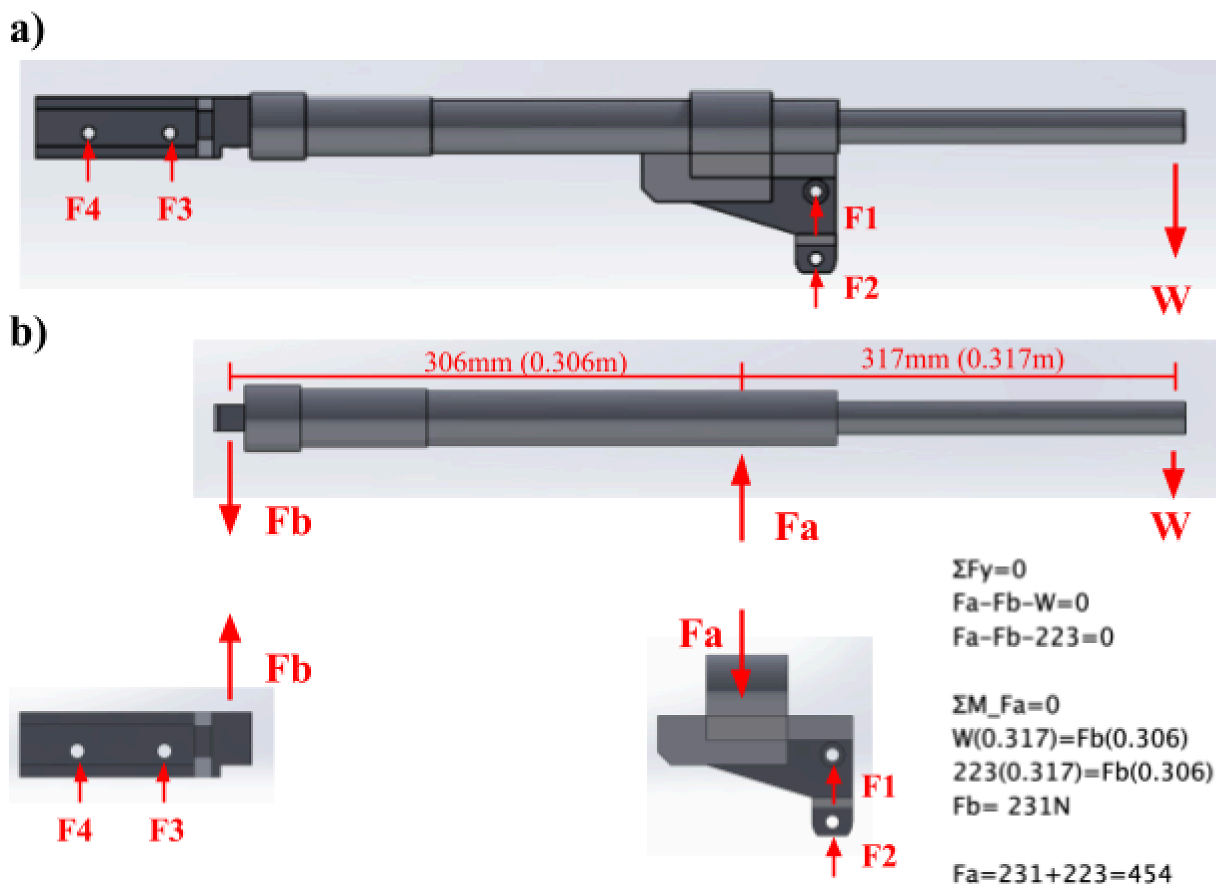

Figure 15: Force distribution of the linear actuator and holder support system (both actuators).
a) single body force distribution
b) force distribution by parts.
Note: this is only a visual representation of the scenario and thus the extension of the linear actuator is not exactly to scale and the only supports are the front and back holder. W=223N (maximum applied force from bending test to both linear actuators). Fa=454N and Fb=231N. F1-4 are arbitrary.

In this simulation, both the front holders and back holders are simulating using SolidWorks to determine deformation and stresses occur and thus some design alternatives and modifications that can be done to improve the structural integrity and mechanical properties of these holders. In Figure 15b, the linear actuator scenario can be modeled as a three point bending thus able to calculate the amount of force applied to each holder at maximum force applied condition. It is found that each of the back holders will share the total of 231N of force thus each withstanding 115.5N. Each front holder withstands 227N. It is determined from solidworks that the contact surface area between the linear actuator and backholder is 463mm^2 and 2160mm^2 in the front holder thus the equivalent pressure to each holder, given by the formula Pressure=Force/Area, are 0.25MPa and 0.11MPa respectively. Customized elastic modulus and yield strength are 1.23GPa and 7.92MPa respectively [13]. Using these values and proper fixture in solidworks simulation, the stresses and deformation information can be gathered.

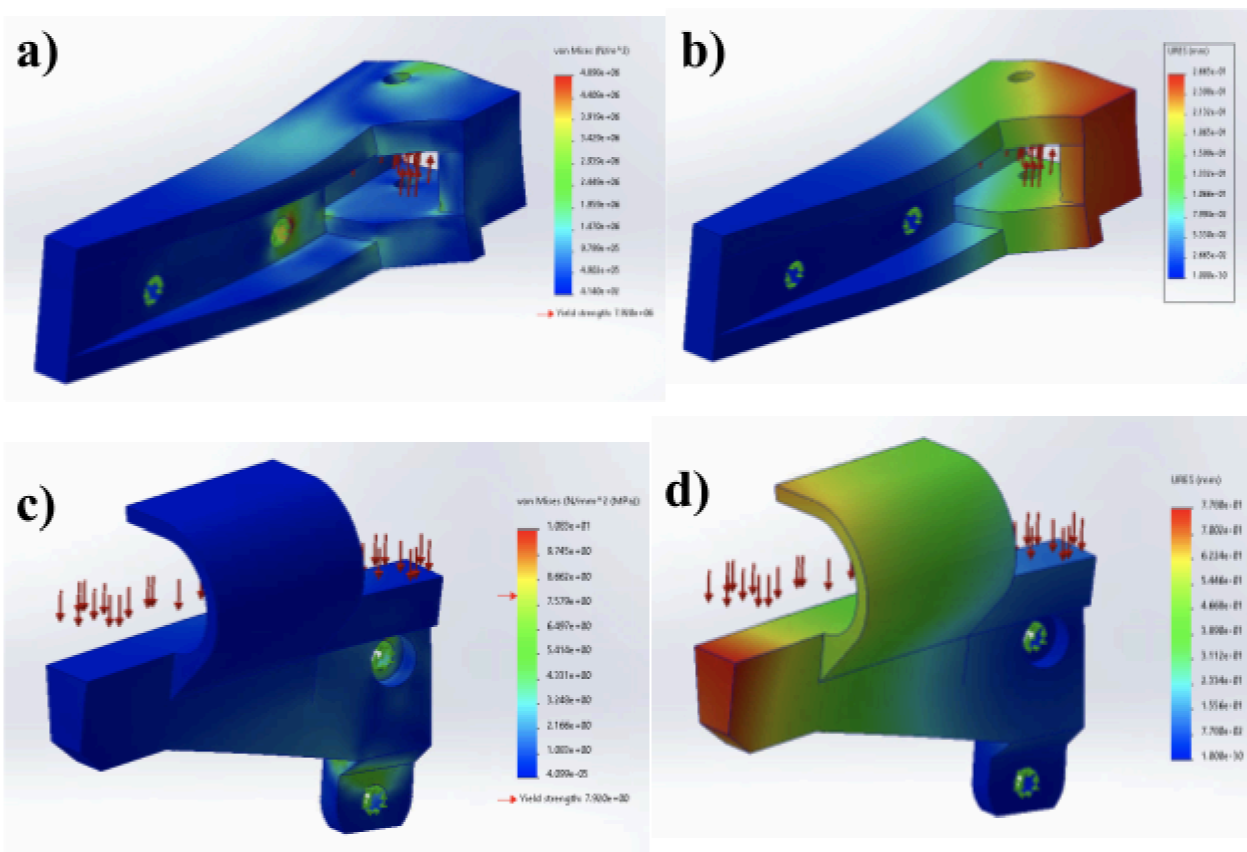

Figure 16: Solidwork simulation results assuming uniformed pressure applied. a) stress of back holder b) deformation of back holder c) stress of front holder d) deformation of front holder

Solidworks simulation showed deformation occurs at the contact surfaces between the linear actuator and the backholder and stresses mainly occur at the screw holes. For the front holder, stress mainly occurs at the screw holes and deformation occurs near the end of the holder where there is no support from the wheelchair.

Future Work & Discussion

When it comes to the future work and discussion section of this report, the team would make a few changes to the current design if given more time and an increased budget. The first change the team would make is to order more powerful linear actuators that are similar in dimension to the current ones. Instead of using 12V linear actuators, 25V actuators would allow for optimal power and speed, making the actuators capable of extending and retracting the maximum distance of 500mm without wrecking their internal resistance. The more powerful actuators would also be able to handle more load, thus decreasing the amount of deflection the actuators currently undergo. Another change the team would make is replacing the material of the linear actuator holders, both front and back, to a metal such as aluminum or steel. The current material, PLA, does not have as good of strength and hardness properties as metal. Metal actuator holders would also allow for the team to create much finer cuts, allowing for them to fit much tighter around the linear actuators. This would improve the load bearing capabilities of the actuators as an applied force from the holders would resist the deflection and rotation more efficiently than the PLA holders. A third improvement to the current design would be to add a rubber coating to the footrest. This rubber coating would be a plasticized resin in addition with epoxy components, allowing for less slip and more comfortability for the user. A fourth addition to the current design would be to create a more stable footrest. This would include utilizing the remaining space in front of the wheelchair to make the backstop of the rest larger. This would spread out the stress of the applied load more efficiently and create less opportunity for internal bending. Instead of being welded, the footrest could be held together by a hinge design that uses a microcontroller as a mechanism for folding. This would maximize the space under the wheelchair and decrease the amount the current footrest design sticks out, which is about five cm. Lastly, this footrest design is tailored to the client of the project. In the future it would be beneficial to consider making a design that is more universal to other wheelchair users, as many individuals face the same problem of having a footrest that is interfering with their daily activities and lives.

Conclusion

Everyone deserves comfort in their day to day life, and a footrest is necessary for any wheelchair bound person to be comfortable. Footrests are also necessary to brace against when leaning forward, so without them getting around and playing sports becomes even harder. Anyone who requires an electric wheelchair, but not an attendant, has to choose between comfort and mobility in the chair, and their mobility outside the chair. Because currently manufactured electric wheelchair footrests are not designed to give the user the ability to move the foot pads how they see fit, it is clear that current footrest designs do not account for partially paralyzed people. The manufacturers expect every user to have an attendant. The autonomous footrest design aimed to solve this problem by allowing the user to push buttons that retract the footrest underneath the wheelchair when it isn't needed and extend the footrest out when it is.

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Appendices

Appendix A: Product Design Specifications

Low Interface Wheelchair Footrest

PRELIMINARY PRODUCT DESIGN SPECIFICATIONS

BME 301

Lab Section #: 302

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Client

Dan Dorszynski

Advisors

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Sarah Edwards

February 8th, 2024

Function:

Currently, there is a noticeable absence in the market of wheelchair footrests that facilitate individuals who are not fully paralyzed to execute beneficial movements, such as using their feet to open doors or retrieve objects from the floor. Moreover, existing footrest models exhibit drawbacks, as they tend to be cumbersome, weighty, and lack user-friendly features for convenient removal and storage during periods of non-utilization. While footrests play a pivotal role in providing support when the wheelchair tilts or reclines, it is imperative to devise an innovative wheelchair footrest that accommodates enhanced foot mobility for users as needed, while offering seamless storage options. The refined footrest should possess adaptability to suit an individual's necessities, have effortless removal and storage capabilities, reduced weight, and a more streamlined design, all while retaining the essential benefits of a traditional wheelchair footrest.

Client requirements:

- Total weight of less than 5 pounds
- Must have the ability to detach from the wheelchair
- Must be able to withstand 250 N
- Has the ability to move with the wheelchair during reclining or uprising position
- Still be able to provide the benefit of a traditional wheelchair footrest

Design requirements:

1. Physical and Operational Characteristics

    a. *Performance requirements*:

        The wheelchair footrest must have a lifespan of at least five years, corresponding to the average time duration that a wheelchair base lasts [1]. To preserve reproducibility, currently, the production cost should remain under $200. The footrest should be lightweight and durable, weighing under 5 pounds total while being strong enough to hold the user's weight on a continuous basis. The rest should promote user comfort and accessibility, with adjustable features to adapt to individual needs. Lastly, the footrest needs to be easily storable, preferably on the side of the wheelchair.

b. *Safety*:
   The materials used when creating the footrest must not be sharp or be able to cause injury to the user. The storage mechanism should be user-friendly and secure, preventing any accidental deployment or collapse during storage, and minimizing the risk of pinching hazards. While also being durable, the material used for the footrest should be as anti-slip as possible, mitigating the risk for falling. If electronics are used in the footrest design, the wires should not be visible or have the ability to be tangled in the footrest. The footrest design must comply with relevant wheelchair safety standards and regulations to guarantee a high level of safety and reliability for users.

c. *Accuracy and Reliability*:
   The footrest should be able to securely connect to the wheelchair for its entire lifespan. All joints and plates should stay unbent and at desired angles under normal conditions.

d. *Life in Service*:
   The footrest will mostly be used outdoors, and will be repeatedly packed and unpacked during transport when it isn't needed on the wheel chair. This processes is expected to happen hundreds to thousands of times over the life of the footrest, as it should last at least as long as the wheel chair it is designed for, so 5-10 years [2]

e. *Shelf Life*:
   The footrest will fold into itself to allow for easy storage, and transportation. It will need to withstand being transported in suitcases or bags. All parts should hold together when folded so as to not have bending or tearing of joints connected to pieces that hang off the main body. The components of the footrest will be durable metals with centuries of shelf life, and motors or linear actuators that have at least 5 year life spans as long as the sensitive insides are kept sealed.

f. *Operating Environment*:

The footrest will be used inside and outside at all times of the year. This means it must function in any weather, and will encounter water, dust, mud, bumps and should be able to support the clients throughout.

g. *Ergonomics*:

The footrest should be able to support the clients legs and feet, which is estimated to be 12.2% of their body weight [3], while the footrest itself remains lightweight to allow it to be removed and transported easily. The footrest must require little force to be moved out of the way to limit its interference with everyday activities such as leaning forward, transitioning out of the wheelchair, or opening doors. All edges should be sanded down or covered to stop injury opportunities.

h. *Size*:

The design should take a client specific approach when considering the size. The footrest should account for the coverage of the entire feet according to client specific shoe size, excluding margin of error from the shoes. According to Nike's shoe size chart, the corresponding length should be at least 31.3 cm in length [4]. Due to personal habits, the actual feet size is smaller than given on the chart. The aim is to provide a necessary amount of support while resting, while keeping as minimum for portability.

i. *Weight*:

The design should take into account the client's specific condition: muscular dystrophy, and the client's request to disassemble and reassemble for packaging. Common wheelchair footrest, made from various types of a combination of plastic and metals, ranges from 3-10 lbs. The footrest will aim to minimize burden during transportation and the process of disassembling to ensure proper alignment with portability. Thus 3-5 lbs is a reasonable range for the design.

j. *Materials*:

Since, by client request, the footrest is mainly used outdoors, the footrest should be constructed using high quality and corrosion resistant materials. This provides services to various weather conditions. Frame can be designed from aluminum alloy for its exceptional strength-to-weight ratio [5], allowing movability along with durability. Since the footplate is meant to be de-attachable, the footplate should use non-slip, easy to clean material to provide a clean surface to the user, using acrylic to PVC. For better ease of fabrication, tough PLA can be considered using 3D printing to provide dynamic shapes [6].

k. *Aesthetics, Appearance, and Finish*:

The aesthetic and appearance of the stamp will be uncomplicated, it will be a silicone item with no finish to minimize contamination during use. It will be a ductile design that is meant for multiple uses.

2. Production Characteristics

   a. *Quantity:*
      The client aims to create an initial prototype as an attachment to their current wheelchair. Upon the successful development of this prototype, there is potential for scaling production to serve a larger user population.

   b. *Target Product Cost:*
      The final market product cost aims to be less than 10% of the development cost, including materials fees during the design process.

3. Miscellaneous

   a. *Standards and Specifications*:
      ISO 7176: This is the international standard that outlines the testing protocols for different mechanical elements of a wheelchair. Sections 1[7] and 2[8] pertain to the wheelchair's static and dynamic stability during motion. Additional sections address specifications related to the wheelchair's size, required space for maneuvering, durability, among other characteristics. It is crucial to acknowledge these factors, as the testing equipment could influence the wheelchair's inherent physical attributes.

      CFR890.3920: This is the FDA regulations regarding wheelchair components. A wheelchair component is defined as a medical device that's an integral part of a wheelchair, including those sold separately, which applies to our design. These devices are not required to undergo the premarket notification process,[9] subject to limitations.

   b. *Customer*:
      The footrest is specifically designed to fit the needs of our client, Dan Dorszynsk, who has expressed dissatisfaction with existing footrest options, which limit his capacity to perform small daily tasks, like opening doors. With that said, the design principles and solutions the teams develop could be applicable to a broader audience, as other wheelchair users with varying degrees of mobility may experience similar challenges and could benefit from the final design.

c. *Patient-related concerns*:

This footrest is designed for patients like our client, whose legs still have some strength and can perform lighter duty tasks and support the body without the footrest when sitting. These patients do not need the footrest for the majority of the time, and will only need them when traveling. Hence it should be easily removable, for packing when traveling. The height of the footrest should also be adjustable, as study has shown improper height of the wheelchair footrest may lead to increased average pressure, potentially leading to ulcers and other problems for patients with less mobility of the lower bodies[10].

d. *Competition*:

Most wheelchairs footrests come with the wheelchairs themselves, [9] although there are still a wide variety of footrests available on the market. Prices range from 30 dollars[11] to 120 dollars[12]. Most of the footrests share a similar design. With metal frames for support and connection, and plastic or metal footrest itself attached to the frame that can fold up sideways. Some premier ones come with cushions or paddings for legs.

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Appendix B: Electronic versus manual design matrix

Table 1: Design Matrix II

Criteria (Weight %)	**Design 1: Electric Footrest**		**Design 2: Manual Footrest**	
Ergonomics (35)	5/5	35	4/5	28
Weight (25)	4/5	20	2/5	10
Adjustability (20)	3/5	12	2/5	8
Cost (10)	2/5	4	4/5	8
Ease of Fabrication (10)	3/5	6	3/5	6
Total = 100	**77**		**58**	

Ergonomics: The number one goal of this design is to make the footrest feel light to the user and easy to move. Though the counter balance could be constructed for this purpose, the electric system would use buttons or a joystick similar to the system used by the rest of the wheelchair, and therefore intuitive to any user. The electric system would also require less force to use.

Weight: The actual weight of the design is ranked as the second most important factor, as this will affect how easy it is to handle when detached from the wheelchair, as well as how much extra power will be drained when accelerating. This is the main deciding factor as the manual system must use weight to counterbalance the footrest, where the electric system can be designed much lighter and closer to the center of gravity of the rest of the wheelchair.

Adjustability: This is the ability for the design to be used on other wheelchairs besides the clients Quickie Q700 M. Research hasn't shown a lot of promise for either system to be very adjustable, but the more compact electric system would have an easier time.

Cost: The cost of certain electric components such as a linear actuator, or motor is significantly higher than the cost of materials such as cables and pulleys.

Ease of Fabrication: The Quickie Q700 M has built in circuits and logic that can be adapted into the electric system design, unlike the manual design which would have to be crafted around the limitations of the wheelchair.

Appendix C: Materials and expenses

Table 1: Material/Expense Sheet

Item	Description	Manufac-turer	Mft Pt #	Vendor	Vendor Cat#	Date	#	Cost Each	Total	Link
Linear Motion										
Linear	A device that	Demotor				3/15/202	2	$35.68	$71.36	https://www.

Actuator	converts rotational motion into linear motion to move or control objects in a straight line.	Performance				4				amazon.com/Linear-Actuator-Stroke-Output-12-Volt/dp/B00VFXIRW4?th=1
Breadboard - Self-Adhesive (White)	For building a voltage divider to convert the battery voltage of 25V to 12V for the Linear actuators						2	5.5	11	https://www.sparkfun.com/products/12002
Jumper Wires - Connected 6" (M/M, 20 pack)	‘’						1	2.1	2.1	https://www.sparkfun.com/products/12795
Resistor 1K Ohm 1/4 Watt PTH - 20 pack (Thick Leads)	‘’						3	1.05	3.15	https://www.sparkfun.com/products/14492
Raw Materials										
Aluminum	½‘’x36”x1/8”	MakerSpace				3/15/24	3	33	$99	
Mounting Bracket for PA-14, PA-14P, PA-08		PROGRESSIVE AUTOMATIONS				3/18/24			$13.92	link
Zinc ⅜ inch threaded screws	Zinc screws	Everbilt				3/18/24	1	$8.98	$8.98	https://www.homedepot.com/p/Everbilt-6-x-3-8-in-Zinc-Plated-Phillips-Pan-Head-Sheet-Metal-Screw

										-100-Pack-8 23322/31747 9248
MakerSpace Hardwares + 3D Prints										
3D prints	3D prints	MakerSpace				Varies		$28.1	$28.1	N/A
Hardwares	Screws, Caps, etc	MakerSpace				Varies		$1.25	$1.25	N/A
Current Total								**Total**	**$238.86**	

Appendix D: Previous SolidWorks Model of the Autonomous Footrest Design

The old autonomous design was too expensive and required too many modifications to the wheelchair to be used.

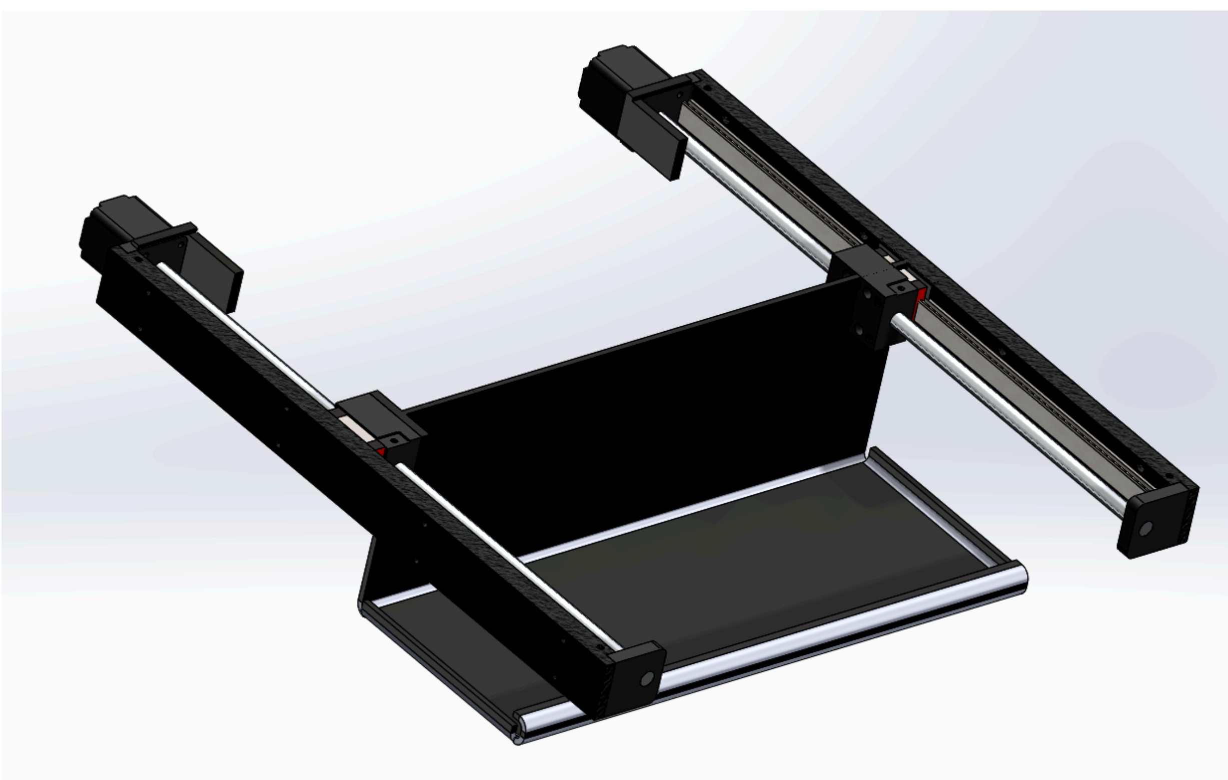

Figure 1: Original SolidWorks model for the autonomous footrest design.

Appendix E: Bending test protocol and raw data

Protocol

Materials: linear actuators (assembled), video taking cameras (iPhone), loads (with known mass, this can be switched based on the discretion of the test, unless otherwise stated, keep to consistent masses and available resources to the maximum extent).

Software: Image J

Testing procedure:

1. With the linear actuators assembled to the wheelchair, holders in place, securely screwed, assemble the footrest and attach to the linear actuators as shown in fabrication.

2. Place one of the video taking cameras less than one meter away, in the sagittal plane (side view), and allow the camera frame to capture the entire linear actuator on one side as shown in Figure 1 below.

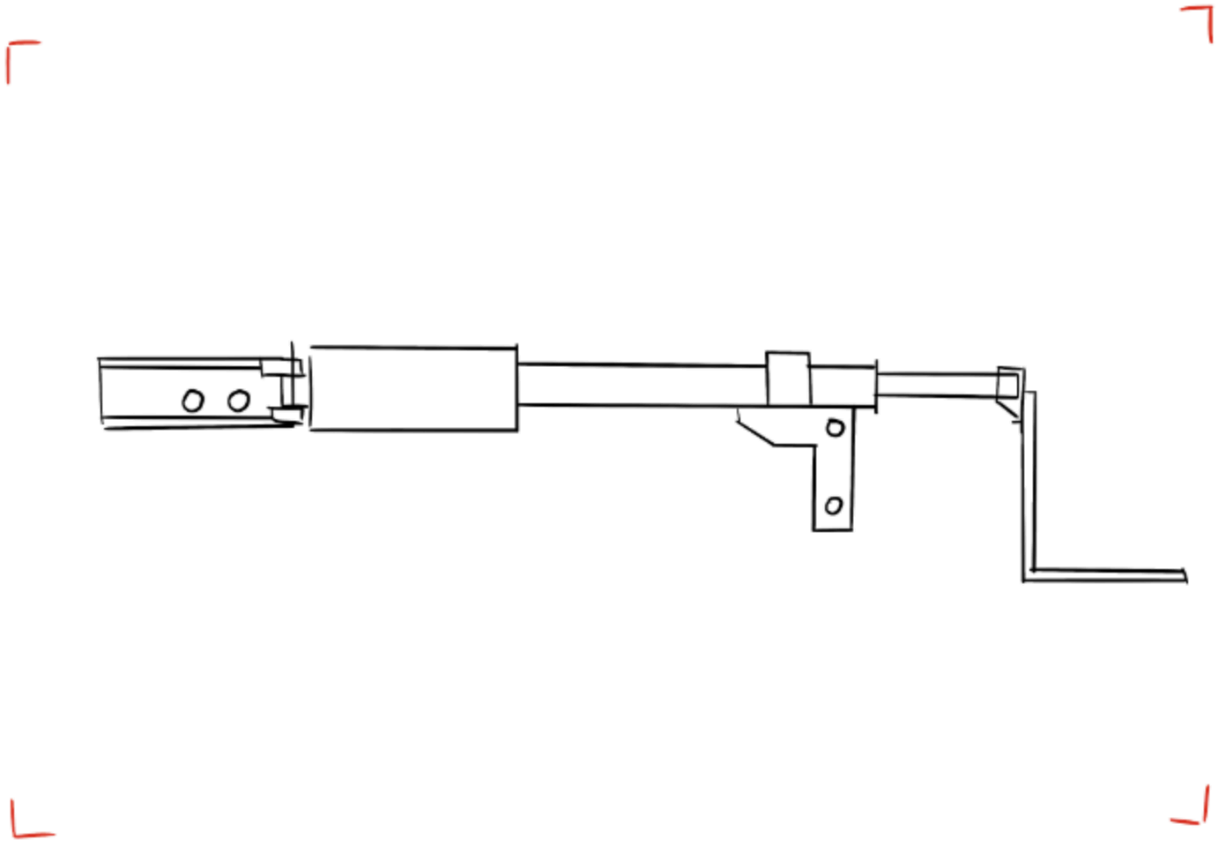

Figure 2: Overall frame. Zoom out view of the linear actuator as a whole. Use for correction/reduce error.

3. Place one of the video taking cameras less than one meter away, in the sagittal plane (side view), and allow the camera frame to capture only half of the linear actuator, as shown in the Figure 3 below.

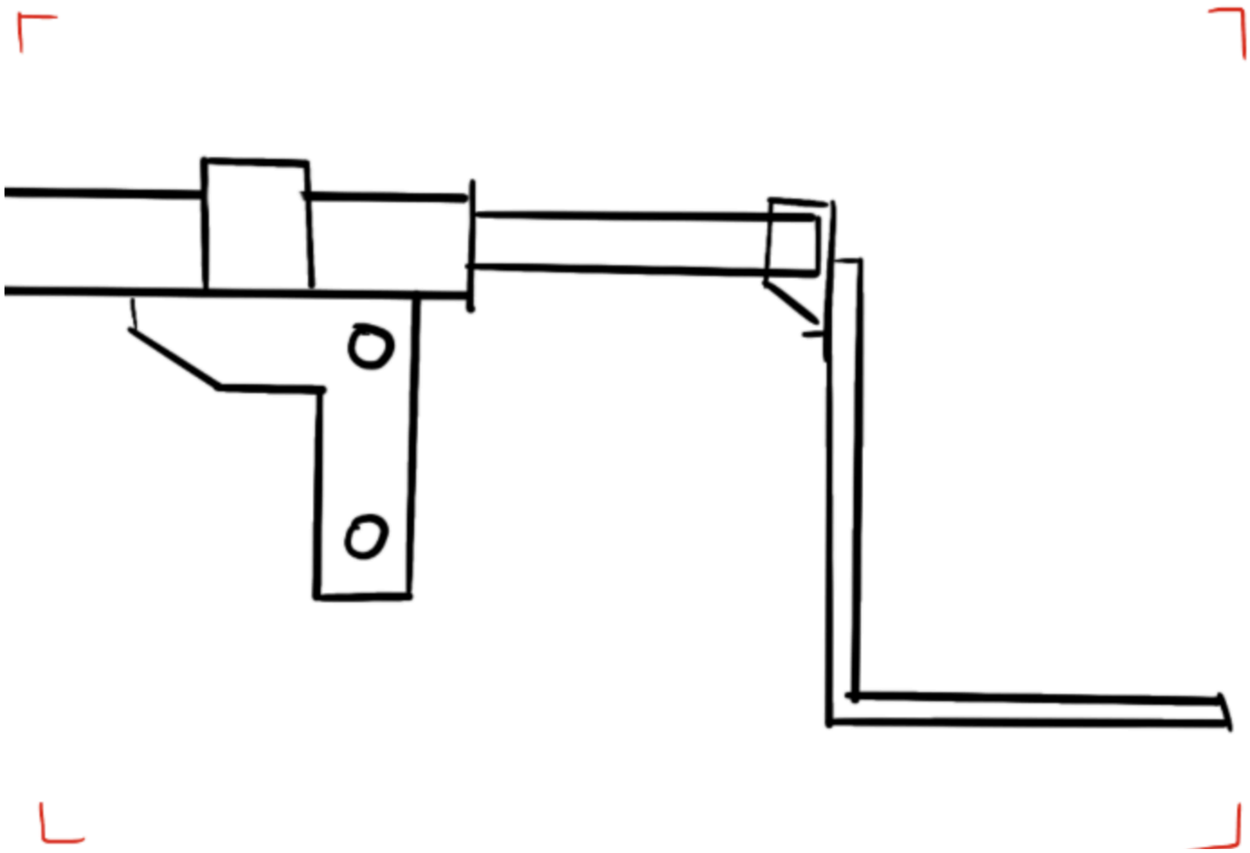

Figure 3: Close up view. In order to obtain more accurate pictures/video of the bending and rotation.

4. After the cameras are set up, check if videos are running and start recording.

5. Extend the footrest to the optimal position (the position where the patient is comfortable using with)

6. Gradually place the known masses (loads) onto the footrest, with consistent increments between each load until the sum of the loads reaches a value desired (determined by the factor of safety), or the bending on the linear actuator starts to exceed its limit visually.

7. Unload all the masses from the footrest and stop video recording.

Analysis procedure:

1. With the video open, take a snapshot of the video at the time after each mass is placed on the footrest.

2. Upload a snapshot to ImageJ.

3. Use the line tool to line up a known dimension in the snapshot, in analysis, set scale to the known dimension with units.

4. Measure the deflection of the linear actuator and record the deflection in a spreadsheet.

5. Plot the data and determine the relationship between deflection and mass applied.

Table 1: Raw data of bending deflection and rotation vs. force.

Force (N)	Deflection (mm) δ	Rotation (deg) θ
0	2	3.2
45.8	8.5	3.35
52.4	8.6	3.5
64.4	9.6	3.7
113	10	4.18
158	12	6.25
177	15	6.79
223	21	9.38

Appendix F: Python Code for Extension & Retraction Testing

```
# Plots for BME 301

import numpy as np

import matplotlib.pyplot as plt

from scipy import stats



# Data for each test

test_data = {

    'Test 1 Voltage Divider No Weight': {'distances': [500, 500, 500], 'times': [60, 60.5, 59.3]},
```

```python
    'Test 2 Voltage Divider with Weight': {'distances': [420, 420, 420], 'times': [61, 60.75, 61.42]},
    'Test 3 No Divider No Weight': {'distances': [500, 500, 500], 'times': [27.4, 27, 27.73]},
    'Test 4 No Divider with Weight': {'distances': [500, 500, 500], 'times': [48, 46.6, 49.1]}
}

# Calculates means and confidence intervals for each test
means = []
std_errs = []

for test, data in test_data.items():
    mean_time = np.mean(data['times'])
    mean_distance = np.mean(data['distances'])
    std_err = stats.sem(data['times'])
    means.append(mean_time)
    std_errs.append(std_err)

# Plotting
plt.errorbar(means, range(1, 5), xerr=std_errs, fmt='o', capsize=5, markersize=8,
markeredgewidth=1, markeredgecolor='black', linestyle='None')
plt.title('Extension and Retraction Distance (mm) vs Time (s)')
plt.xlabel('Time (s)')
plt.ylabel('Extension and Retraction Distance (mm)')
plt.yticks(range(1, 5), list(test_data.keys()))
```

```
plt.xlim(20, 100)
plt.xticks(np.arange(20, 100, 20))
for i, test in enumerate(test_data):
    plt.text(means[i] + 3, i + 1, f'{means[i]:.2f} s, {np.mean(test_data[test]["distances"]):.0f} mm',
ha='left', va='center', fontsize=10)
plt.grid(True)
plt.tight_layout()
plt.show()
```

Appendix G: Simple Protocol for Extension and Retraction Testing

Protocol

Materials: Quickie Q700 M Wheelchair, completely assembled body with interfaced actuators, actuator holders, and footrest.

Measuring devices: A stopwatch of some sort, could be a traditional stopwatch or an app on a phone. A ruler that can measure 0 to 61 cm.

*Testing procedure***:**

Step 1: Turn on the wheelchair using the control button on the top right hand side near where one's arm would rest.

Step 2: Place feet on the foot rest comfortably.

Step 3: Press the legs button to begin extending the footrest. Once clicked, begin the timer.

Step 4: Once the actuators are fully extended, click the reverse button under legs and retract the linear actuators. The timer should be going still at this point.

Step 5 (Optional): If the actuators stop short of the required distance, pause the timer and measure the distance. Record and then begin retracting the actuator. The actuator should still go the distance in the opposite direction, once fully retracted multiply the distance you originally had by two to get the total distance traveled by the actuators. The actuators shouldn't stop if they are the right voltage power and have the load capabilities of lower extremities, hence this step is usually not needed, but in case it happens, the actuators will need to be replaced.

Step 6: Repeat the process various times and collect data of time (s) and extension & retraction distance (mm).

Step 7: Record data in a table of choice and create a plot using excel, python, google sheets, etc.

Step 8: Analyze data and create conclusions. If the timing and distance requirements are all met, then the product is successful in this aspect of the design process. If the timing and distance requirements are not met, errors will be seen in the data and a re-design and or ordering of new materials is needed to move forward with fabrication.

Appendix H: SolidWorks Drawings

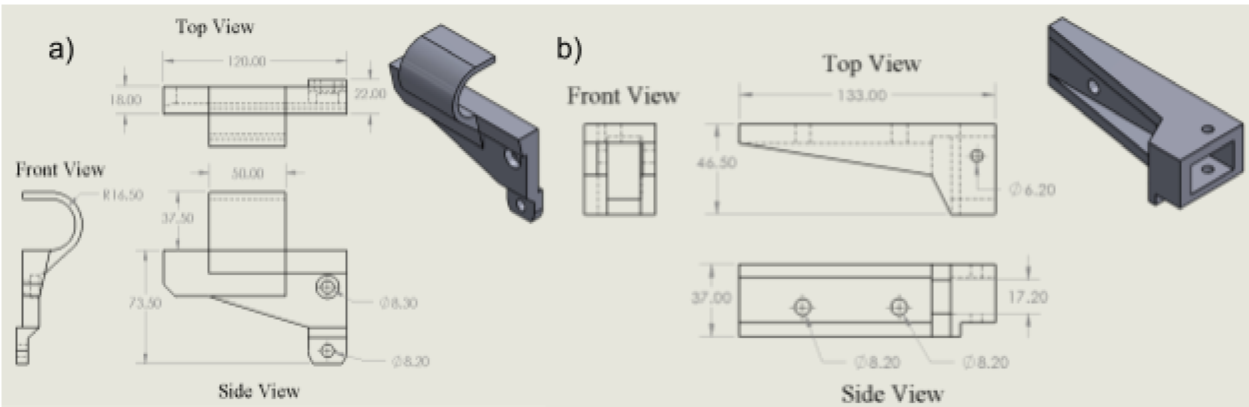

Figure 4: Solidworks drawings for a)front holder, b) back holder. Units: mm

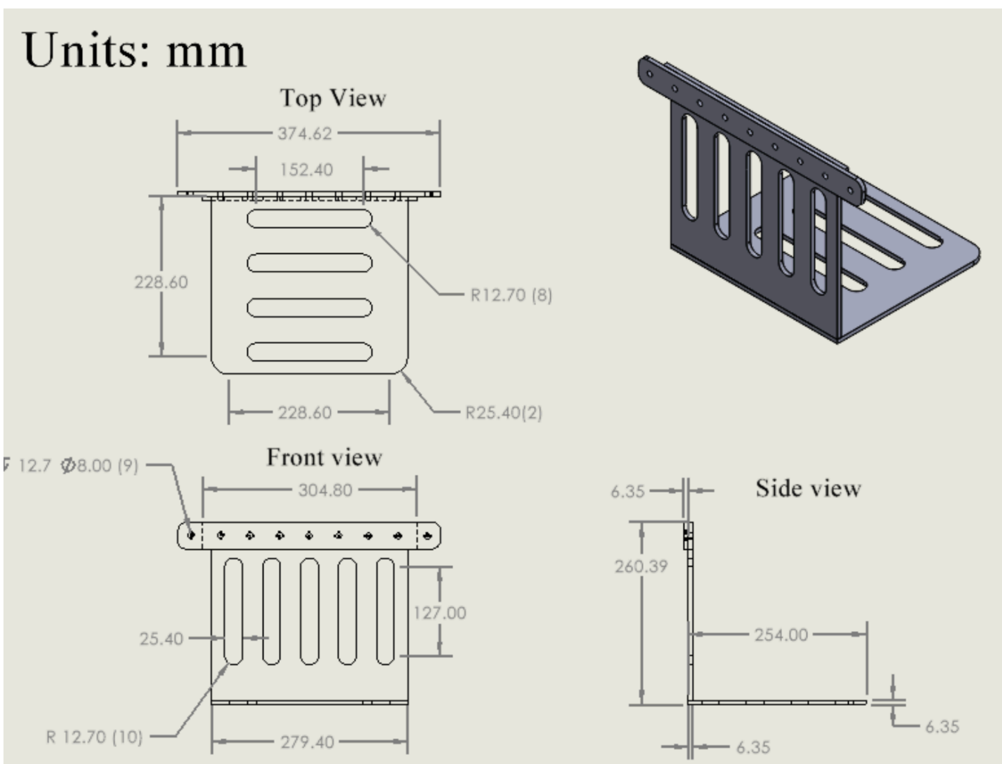

Figure 5: SolidWorks drawing for the footrest