Low-Interference Wheelchair Footrest

Biomedical Engineering Design 200/300

Department of Biomedical Engineering

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Abstract

Out of all wheelchair users in the world, nearly one fourth have the capability to walk a quarter of a mile, and more have some degree of ability to utilize their legs. Despite this, very few wheelchair footrests are retractable and allow the users to freely move their legs to interact with the world around them. Many of those that do only have limited capability to vacate the vicinity of their operator's legs or otherwise require a degree of exertion from the legs of the operator that some wheelchair users are incapable of. The following report presents a prototype footrest that has the capability to extend to act as a typical footrest and to retract quickly to allow the user greater usage of their legs. The goal of the final prototype is to create a footrest that can fully extend and retract using only the upper body while also remaining compact and simple to remove from and attach to the wheelchair frame for easy transportation**.** To test this prototype, the team conducted a speed test which timed the user's ability to retract and extend the footrest, and a strength test that measured deformation of the footplate under force. The goal of the testing was to ensure structural stability during use and when in a locked position, as well as establish ease of use throughout the design for the client. In the future, the wheels should be interchanged with higher quality models, and stability of the rail attachment should be improved.

I. Introduction

Motivation

Wheelchairs are some of the most widely accessible mobility aids on the market. Worldwide, there are approximately 131.8 million people who use wheelchairs as their main way to get around in their everyday lives. Additionally, an estimated increase of 2 million people will be in need of assistive devices in the future [1], which creates a large demand for many kinds of assistive devices, such as wheelchairs. Wheelchairs come in all shapes and sizes, with adjustable accessories to fit the needs of the person using them. The benefit to having custom accessories is to avoid injury and increase function to maximize the user's quality of life [2]. Seat cushions, arm rests, and headrests come in varying sizes, heights, and materials to increase comfort and ergonomics, and footrests are also modifiable. Common wheelchair footrests are made of metal or plastic footplates that connect to the base of the wheelchair via metal bars, and most wheelchairs come with footrests already installed. The footplates that are already installed are often made to fit the average person, and do not account for varying leg lengths and foot sizes that can be a result of medical conditions or other factors. Footrests also do not account for ambulation, or having minimal motor function still remaining in the arms and legs, and wheelchair footrests often hinder those movements and discourage use of the limbs. In addition, if the user wanted to change out the footplates, most wheelchairs do not allow for further modifications, or only have select models confined to certain wheelchair models made by a company.

Existing Designs

While there are many wheelchair footrests and leg rests on the market, there is an issue with cross-model compatibility. in many cases, companies will make interchangeable footrests, but these accessories will either be made for the specific models made by that company, or not be compatible between manual and electric wheelchairs. The Hideaway Footrest by the company FOLD & GO [3] is an accessory that can be moved out of the user's way in order to stand and is only compatible with two of the company's own models, but not with any models made by other manufacturers. This is common among wheelchair manufacturers. For example the Invacare Swing-Away Footrest [4] is only made for the select 9000 Series or Tracer Series wheelchairs, both of which are manual wheelchairs, and the footrests are not compatible with Invacare powered wheelchairs. The variability in attachments and different manufacturers for the base of powered wheelchairs makes cross-model compatibility all the more complicated.

There is also variability within the footrests themselves, with all different sizes and stirrups to hold the feet in place. The model from Drive Medical [5] has cloth stirrups to ensure the user's feet do not slide back if the wheelchair has the ability to tilt, a feature that the Invacare also includes, but the Hideaway model does not. Although the model from FOLD & GO does not have stirrups, it does have a single footplate configuration, allowing for it to be removed out of the way in one motion. All three models are mechanically operated, and also all can be removed from their original configuration in front of the wheelchair to allow for actions such as standing. Both the Invacare and Drive Medical models are able to be rotated laterally to the sides of the wheelchair, completely removing them from the front of the wheelchair. However, this simultaneously adds width to the wheelchair, which can hinder the mobility of the user all together. The Hideaway model folds underneath the wheelchair via hinges, which does not add any bulk around the sides, but needs to be operated at the lower leg level requiring the user to bend at the waist. This causes issues if the wheelchair user does not have the mobility or flexibility to bend far enough to access the mechanics of the footplate.

In addition to the footrests and footplates on the market, there was a manual footrest designed to improve upon the client's existing footrests on the Sedeo Pro Quickie Q700m [6]. The previous Low-Interference Wheelchair Footrest [7] was electronically powered through the wheelchair's main electronics, and used linear actuators to move an aluminum footrest beneath the wheelchair, allowing for full range of motion in front of the wheelchair. However, from the client's feedback, the footrest was too noisy due to the linear actuators used, and the footrest did not meet weight criteria and deflection requirements.

II. Background

Relevant Biology and Physiology

There are many reasons that a person would need to use a wheelchair in their daily life, such as muscular dystrophy, paraplegia, or spinal cord injuries [8]. With this wide variety of reasons also comes a wide variety in levels of mobility and dexterity. Many wheelchair users also maintain a certain level of mobility, defined as being ambulatory. Those who are ambulatory can, for some period of time, become independent of their wheelchair, but cannot maintain this state for most parts of the day due to factors such as varying energy levels, chronic illnesses, or people who are recovering from surgery [9]. For this product, the aim is to create a footrest that accommodates as many people as possible, such as ambulatory users.

When designing a footrest that needs to be adjustable, certain measurements need to be kept in mind, such as the length of the entire footrest. If the footrests are not in the optimal position for the user's needs such as being too short, the feet and lower legs become unsupported and will transfer most of the weight to the lower back and cause pain as well as offset balance. Alternatively, if the footrests are too long, the weight transfers to the backs of the user's legs, which causes bedsores. Additionally, it is also important to keep the spine and pelvis in a neutral position, especially for those who use wheelchairs exclusively. The spine should keep an "S" curvature to ensure stability, and the shoulders should be square and level with the pelvis to maintain neutral position. The pelvis should remain level, with weight equally distributed on each side, to avoid tilting the spine and causing scoliosis [10]. The footrests must also be of equal height and length to prevent a tilt in the pelvis [11].

Client Information

The client, Mr. Dan Dorszynski, lives in Madison, Wisconsin and has lost mobility in his legs, therefore requiring the use of the Sedeo Pro Quickie Q700m wheelchair seen above [6]. He is looking for a wheelchair footrest that can be removed completely from its original position in front of his wheelchair to be able to use his feet more. He would also like this footrest to be adaptable to his secondary wheelchair, and be easily removable for transfer or storage.

Design Specifications

This product was made specific to the client and his needs and specifications, but there is a possibility for mass manufacturing in the future for those who are having similar problems with current commercial footrests. The requirements for this product given to the team were that the footrest should perform normally as a wheelchair traditional footrest when in the original extended position, then also be able to move out of the typical range of motion for the feet (0.762 m x 0.305 m around the wheelchair) with little to no restriction. The product should also work for as long as the average lifespan of a wheelchair (about 4 to 5 years [12]), weigh under 5 pounds, and should support the feet and lower leg on the backside to ensure support while the wheelchair is tilted. Finally, the client requires the product to be easily removable from the wheelchair and either stored or attached to his secondary wheelchair with minimal exertion.

III. Preliminary Designs

Design 1: Lattice Ball Jointed Footrest

The original concept for this design was built on the principle of a footrest that could change its physical size and shape to allow for easy retraction of the footrest from the user's foot space. A design with the capability to change its dimensions could allow other mechanisms to be considered that would normally be impossible due to the space taken up by the footrest. A footrest of this nature could also work towards adding a degree of customizability and universality to the footrest, allowing more people and wheelchairs to comfortably interact with it.

The footrest was proposed to be made of a semi-rigid diamond patterned rubber lattice about an inch tall. Twin lightweight aluminum actuators would be placed below the mesh, with the ends contacting the front of the mesh when fully extended. These actuators would have a dual purpose: to support the weight of the operator as well as to collapse the mesh. As seen in Figure [1], the mesh would be compressed down to a much smaller size and could be moved around with a much higher degree of freedom. It is likely that several cables would be attached spanning the mesh and chair to act as additional suspension and further distribute excess weight as to not strain the actuators.

The mesh would be connected to the chair by two beams protruding downwards from the front of the operator's seat. They would contact the backmost corners of the mesh and connect to the rear of the actuators by a ball joint. Once the footrest is collapsed, the length of the footrest would be small enough to allow the ball joints to rotate the entire actuator-mesh apparatus downwards without contacting the ground. When desired, the inverse of this process could occur, repositioning the mesh footrest back into its original usable orientation.

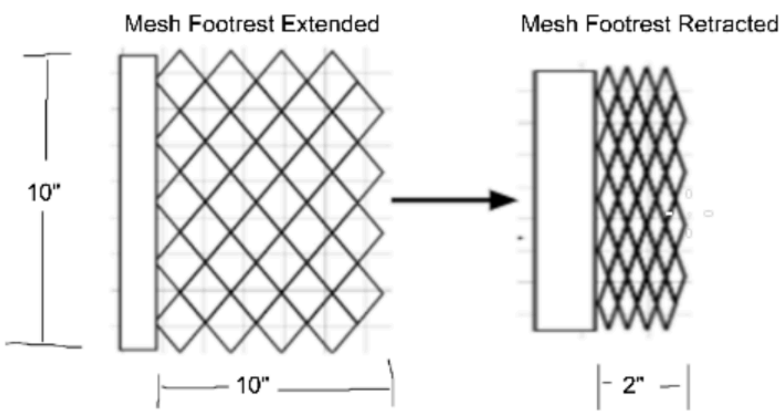

Figure [1]: Top View of the Lattice Footrest in its Extended and Retracted States

Design 2: Telescoping Sunglasses Footrest

The idea for the Telescoping Sunglasses Footrest arose from the thought of having the entire footrest apparatus be movable on multiple different axes. It was perceived that this would allow for a footrest which could much more fully vacate the space of the operator's legs while also allowing for a very high degree of adjustability for the operator. The nickname "sunglasses" came from the unique semi-separate footplate design where two separate panels would be connected by a bar underneath as seen in Figure [2]. Combined with the two telescoping rods ascending from the back corners, the entire apparatus would look very similar to a pair of sunglasses.

To properly move the footrest in the vertical direction relative to the ground, a pair of angled telescoping rods would be used. This would allow the user to pull upwards on the rods and lift the footrest to lie flush underneath the seat of the wheelchair. The telescoping mechanism would also allow for the user to set the footrest at nearly any height off of the ground, only constrained by the angle the telescoping rods were placed at and the maximum limits of their extension and retraction.

In order to move the footrest in the horizontal plane, it was decided that the footrest would be mounted to the rail systems which lie on either side of the operator’s seat on the wheelchair models designated by the client. This would allow the operator to move the entire contraption back and forth with their hands. Combining this feature with the vertical movement of the telescoping rods, the footrest could lie in virtually any place in the foot space in front of the wheelchair when extended and near perfectly flush under the seat of the client when retracted.

It was quickly discovered that both of these separate methods could be interconnected by placing a cable that is anchored to the front of the seat on the wheelchair down through the telescoping rods before finally connecting to the footplate itself. As the contraption would be pulled back along the rail system and farther from the anchor point of the cable on the seat, the tension in the cable would pull upwards through the telescoping rods on the footplate. This would allow for the complete collapse of the rods and the backwards horizontal movement of the whole contraption with a single hand actuated movement from the operator.

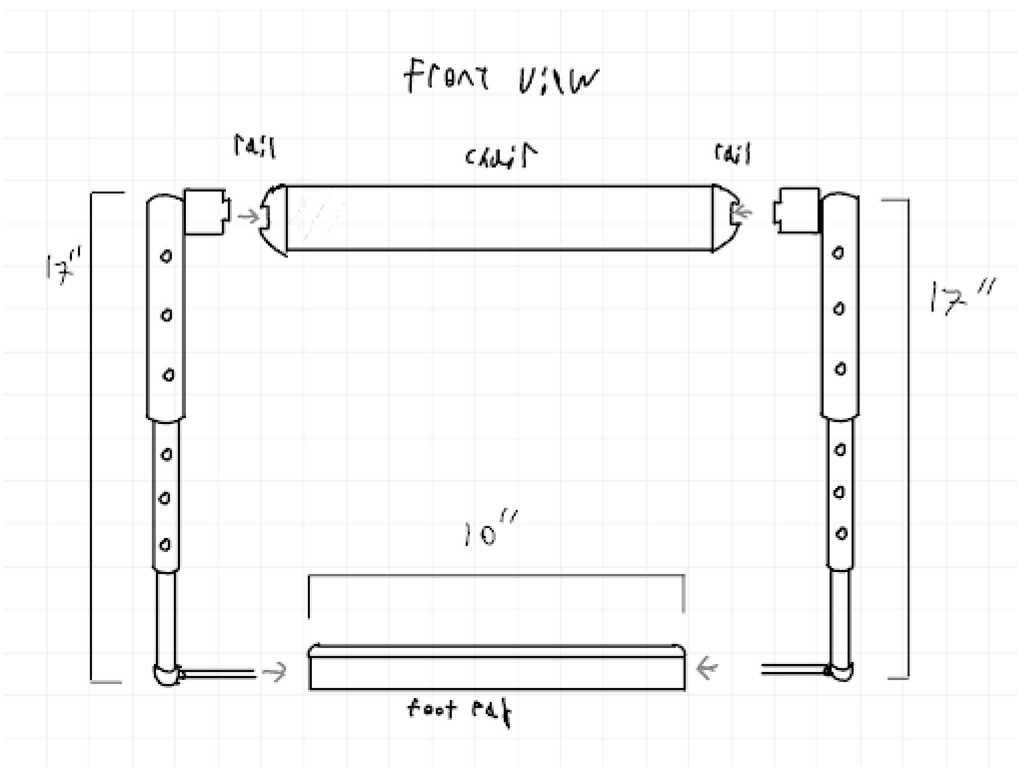

Figure [2]: Front view of the Telescoping Mechanism and Rail System

Design 3: Hand Crank Panel Footrest

The Hand Crank Panel Footrest design was made to be an easy and reliable mechanism above all else, with little chance of failure either mechanically or structurally. The design consisted predominantly of metal plates, hinges, and a single winch and cable mechanism. The footrest would consist of two separate plates and a main backplate which would lie perpendicular to the ground directly behind the legs of the operator and would connect the footplates to the underseat of the wheelchair.

Each footplate would be connected to the backplate by a hinge along their back edge, allowing the footplates to fold upwards and flush with the backplate as seen in Figure [3]. The footrest would extend slightly lower than the point at which it connected to the footrest. This would allow a set of triangular supports to be placed under the footplates and attached to them by hinges. As they would not be connected to the backplate, this would allow the downwards force on the footplates to be handily converted to backwards force on the rigid backplate while still allowing the footplates to fold upwards. The hinges connecting the supports to the footplates would allow the supports to also fold flush to the footplates.

The footrest would also exhibit a winch system attached to the side of the chair. This winch system could be either mechanical or electrical, but the overall function would remain the same. The winch would connect to the bottom of the backplate by a cable. The entire backplate would be attached to the wheelchair itself by a hinge system, allowing the entire backplate to rotate up and under the seat of the wheelchair when the winch is activated. This would allow the backplate to fully evacuate the area of the operator's legs.

The method by which the contraption would collapse would be by a two part process. Firstly, the operator would fold up the footplates to lie flush against the backplate. They would subsequently fold the supports to the side as well, allowing the entire contraption to lie flat directly behind the legs of the operator perpendicular to the ground. Then, the operator would activate the winch system either by hand or at the press of a button, pulling the entire flattened contraption up underneath the seat of the wheelchair. This process could easily be reversed afterwards to reposition the footrest back into its extended position.

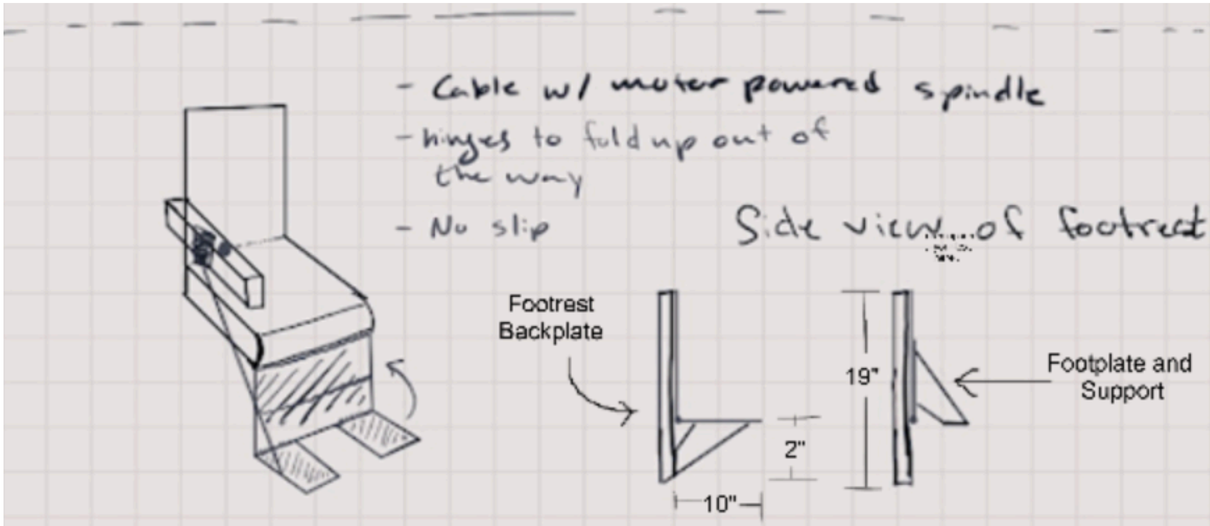

Figure [3]: Hand Crank Panel Footrest Initial Design and Collapsing Mechanism

IV. Preliminary Design Evaluation

	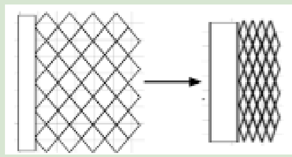		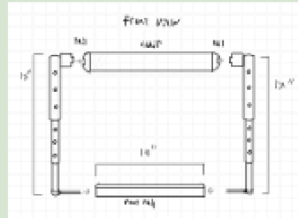		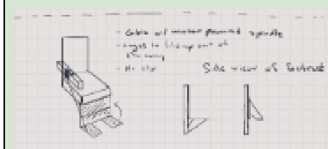	
Design Criteria	**Design 1: Lattice Ball Joint Footrest**		**Design 2: Telescoping Sunglasses**		**Design 3: Hand Crank Panel**	
Ease of Use (25)	3/5	15	4/5	20	4/5	20
Client Comfort (20)	4/5	16	5/5	20	3/5	12
Safety (20)	4/5	16	4/5	16	5/5	20
Compactability (15)	3/5	9	4/5	12	3/5	9
Cost (10)	3/5	6	3/5	6	4/5	8
Ease of Fabrication (10)	1/5	2	3/5	6	2/5	4
Total (100)	64		80		73	

Figure [4]: Low Interference Wheelchair Design Matrix

Figure [4] depicts the design matrix the team used to judge three designs against six different criteria. The criteria are weighted more by the value at which the team and the client categorize as the most crucial (25 points) to the least crucial(10 points). The most important criteria was ease of use. This is defined as the client's ability to operate the footrest and retract or detract the mechanism when the footrest is in or out of operation. Client comfort and safety both are weighted at 20 points. Client comfort is defined as the client's ability to operate the device using the least amount of mobility as possible to prevent injury or discomfort. In addition to this, client comfort is also general comfort of the client and how the legs feel when the footrest is in use. Safety is defined as the client's ability to use the footrest with no threat of pinching from joints that aren't completely hidden away or injury due to electronics and wiring. Compactability is defined as the ability of the footrest to fully fold up and not be an obstacle or hindrance to the client in any way while not in operation. Cost and ease of fabrication are weighted the lowest with 10 points. Cost is defined as the cost of materials that will be used or implemented during the manufacturing of the footrest. This is not weighted highly because the $200 that is funding this project will be sufficient enough funds to see the project through. Ease of fabrication is defined as the team's ability to design, manufacture, and test the product in the timeframe of one semester during BME 200/300. This criteria was weighted amongst the lowest because the given time frame should be adequate for the production of each of the three designs.

Design 1 did not score highest in any of the criteria. It received a ⅗ in ease of use because the lattice mechanism is more complicated than design 2 and 3 and the design itself is very unstable with no clear way to extract and retract the footrest. It scored a ⅘ in client comfort because all designs didn't vary much and the lattice design made an angle from the knee to the ankle more accessible that could help reduce swelling in the client's feet. This design scored a ⅘ in safety because overall it didn't have any excess parts that could pinch and if electronics were implemented the wires could easily be stowed underneath the chair. Design 1 scored ⅗ in compatibility because the legs condense against the side of the chair whereas designs 2 and 3 are primarily under the chair. It scored ⅗ in cost because the design is primarily made up of steel bars and the lattice mechanism would be an added cost to manufacture. This design scored lowest in ease of fabrication because the lattice design would be an added difficulty in the limited time span of one semester.

Design 2 scored highest in ease of use, client comfort, compatibility, and ease of fabrication. This design tied with Design 3 in the ease of use criteria because both designs are easily capable of retracting and extracting based on the client's needs when the client requires. This is because both designs have features where the client will not need excessive range of motion to operate the footrest mechanisms. Design two scored highest in client comfort because of its ability to create an angle to help elevate the legs and reduce swelling in the feet. This design also scored highest in compatibility because of its ability to completely fold up and out of the way underneath the chair in order to get rid of an added obstacle for the client. It also scored highest in ease of fabrication because this design has the least amount of moving parts and should be relatively easy to manufacture in the specified time.

Design 3 scored highest in ease of use, safety, and cost. This design tied with the highest score for ease of use as stated earlier in the text because of the reduced mobility needed to operate the footrest. Design 3 scored highest in safety because like design 2 it is capable of folding under the chair and therefore will not create added obstacles for the client, in addition to this, design 3 does not require any electronics that might injure the client making this the safest design. This design also scored highest in cost because it would have primarily been manufactured with a metal sheet behind the legs and wooden footplates to make the design cheaper but this also sacrifices the sturdiness of the structural integrity.

Proposed Design

The results of the design matrix concluded that Design 2, having the highest score in four of the criteria and also receiving the highest score at 80 points, will be the final design that will be utilized for the rest of the semester. This design includes two foot plates, a mechanism that will be easy for the client to operate, and added features such as the angle to prevent swelling in the feet for comfortability, making this the obvious design to move forward with.

V. Fabrication/Development Process

Materials

The budget for this project was a ceiling of $200 for all materials, stated in the Product Design Specification, found in appendix A. The main expense for this project were the three 6005A-T61 aluminum telescoping rods. The rods were present in all final design iterations, and thus the team had decided to purchase telescoping rods with a low tolerance for the final prototype. Aluminum rods were chosen as opposed to other materials because of the relative cost, high tensile strength, and longevity with corrosion resistance. With the ultimate tensile strength of 6005A-T61 being 262.0 MPa and a yield strength of 241.317 MPa, it far exceeded this project's need and will be able to withstand the weight of the user's feet [13]. The footplate was made out of aluminum as well, found in the Makerspace materials store as a 30.48 cm by 30.48 cm plate of which a half was used for each foot. The decision was made for this material to be consistent throughout the design to streamline the welding process, which was simpler because of like materials. Inside the telescoping rods, there is a carbon steel wire tasked with pulling the footplates up underneath the wheelchair seat. The wires were added early in prototyping and were deemed critical for the retraction phase of the design. This particular product, found on Grainger, has a load rating of 977.492 kg maximum, far more than what is necessary for this project [14]. The wheels on the underside of the footplate were added later on in the designing stage in order to take strain off of the telescoping rods by having contact with the ground. The wheels were decided because of their 360 degree movement, aimed to be able to handle any terrains that the client would encounter. To secure loops on the cable, the wire rope sleeve from Grainger was chosen for its simplicity and ease of use. In order to attach the rods to the wheelchair rails, the team acquired aluminum stock from Makerspace Lab to keep materials the same for welding purposes. Finally, the team ordered seat belt extenders as a method of locking the footrest in the retracted stage. The goal of this component was to be able to quickly and easily release the footrest from the locked position, yet have it be stable enough to remain locked while the wheelchair is in motion. An in-depth list of the materials used can be found in Appendix C.

Methods

The fabrication of this prototype required the use of the machines and stock supply of the Makerspace on the University of Wisconsin - Madison campus. The main alterations needed for this device were making the telescoping rods stop at certain points to allow for maximum extension without the middle rod falling down to the footplate, seen in Figure [5]. The channels were cut out using a mill in the Design Lab, allowing for a cylindrical piece of metal to be inserted and sit flush to the outer diameter of the rods. The hole for the metal to fit into was fixed at the proximal end of the middle and smallest rods. The hole was drilled and underreamed to allow for a low tolerance, securing the cylinder. The wheels were attached to the footplate using bolts and nuts, with the attachment bracket being bent to match the angle in which the footplate attached to the distal end of the smallest rod. On the wheelchair rail, the proximal end of the largest rod and front side of the seat belt locking mechanism are attached to the stock aluminum, which is attached to the inner sliding pieces provided by the wheelchair manufacturer. The slider pieces were originally used for a seatbelt attachment option for the user, but the client allowed for modifications so the sliders were repurposed, seen in appendix D, part number 6. The rod is attached to the metal piece via tungsten inert gas (TIG) welding. All welding done on this device was done by UW - Madison Design Innovation Lab Instrument Maker, Mike Hughes. The locking piece is secured to the metal by a bolt and nut drilled into the metal by a drill press. For the back locking piece, the seat belt extender had a further metal piece attached to the railing through the slider pieces, secured with a bolt, and fixed in place. It can be moved based on the desired position of the footrest when fully retracted (Figure [6]). Finally, the wire used to pull the footrest toward the wheelchair and up under the seat was looped through holes drilled into the footplate, and the loop is closed with the aluminum sleeves, secured to the base of the wheelchair under the seat with a bolt.

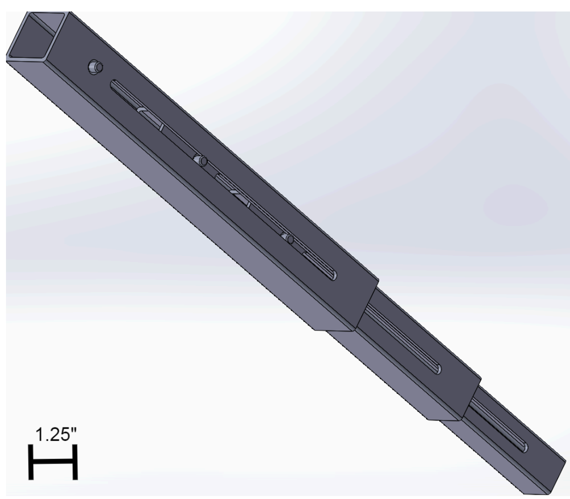

Figure [5]: CAD model of the telescoping rods after fabrication.

Figure [6]: Enlarged view of the locking mechanism on the left footrest.

Final Prototype

The final prototype's main movement lies in the horizontal translation of the proximal side of the telescoping rods as well as the vertical translation of the footrest itself until it sits underneath the seat, seen in Figure [7]. The user's feet are separated, one on each footrest, and both footrests can be moved independently. The three telescoping rods collapse into each other allowing for a smaller extension when fully retracted. When fully extended, the carbon steel wire is held taut. This combined with the pins in the rods prevents the footrest extending further than desired. In addition, the footrest will stop when the wheels are touching the ground, ensuring consistency throughout use. The user can then place their feet on the footplates and can use the device as a traditional wheelchair footrest. Once the user desires to move the footrest and their feet are off the device completely, the device can then be pulled from the top of the telescoping rods back towards the locking mechanism that is fixed in place on the rail system. As the user is pulling the rods back, the action shortens the amount of wire inside of the rods, pulling the footrest towards the underside of the wheelchair. Once the piece with the locking mechanism and rod attached reach the buckle, the footrest locks in place and cannot move any more. The wheelchair can be moved as the user desires with both of their legs free to move without obstruction.

Figure [7]: Right side view of the footrest fully retracted and locked

Figure [8]: Right side view of the footrest fully extended

VI. Testing/Results

Testing

Testing was performed with the goal to find metrics that fit within the team's goals for the semester and to quantify the quality of the final prototype. The tests performed were done in two sections: the speed test and the force test. The goal for testing was to be able to find the average time it takes to use the footrest for the average person, and to find out how much weight the footplates could hold without permanent deformation.

Speed Test

The first test run was to collect data on how long it took to fully extend the footrest as well as how long to fully retract and lock it into a fixed position. The test was run for a total of eight trials, four for extending and four retracting and locking. To simulate most accurately how a user might use the device, the test participant sat in the wheelchair in a relaxed position to begin. For consistency purposes, the participant did not use any movement of their legs throughout the test and any runs that did were omitted. The participant was then timed on the speed retracting, beginning when the foot was completely off the footplate and ending when the locking mechanism was fully in place and the footplate cannot move any further. For the extension portion, the time began when the button on the back lock piece was pressed and ended when the footrest was fully in contact with the ground. Data was collected into a chart and an average of the four runs was calculated, shown in Figure [9] in the Results section.

Force Test

The second test aimed to measure the deflection of the footrest under various amounts of weight. The starting height off the ground was measured prior to the test beginning as a base measurement. The location of the measurement was consistent throughout the test, being at the far end of the footplate where the toes would rest and in the middle of the width of the footplate. For each run, a fixed amount of weight was added to the center of the footplate and the distance between the ground and the footplate was measured. Then, the deflection was calculated by subtracting the distance of the weighted footplate off the ground from the base measurement, which was taken at the beginning of the test. This test was then repeated over increasing weights and plotted onto a chart, shown in Figure [10].

Results

For the speed test, the data collected is displayed in a chart with the average times listed on the bottom row. For the force test, the deflection calculations are shown in a plot of weight (lbs) vs. deflection (inches).

Trial	Time to extend (s)	Time to retract (s)
1	7.57	6.42
2	5.85	5.85
3	8.87	5.32
4	5.92	7.09
Avg	7.05	6.17

Figure [9]: Table of times recorded extending and retracting the footplate, and the average of all the trials.

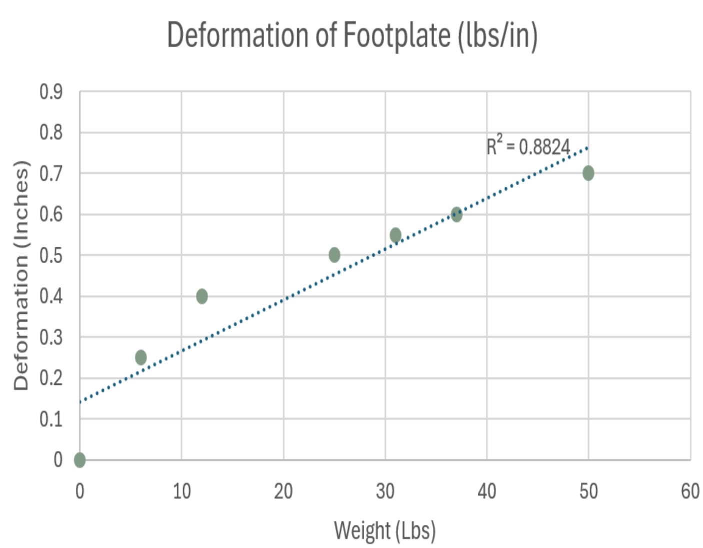

Figure [10]: Graph showing the deformation as weight increases from six to fifty pounds.

In the speed test, the average time taken to fully retract and lock the footrest was 7.05 seconds. The total time to fully extend the footrest was 6.17 seconds, making the combined time to operate the footrest through one cycle 13.22 seconds. One possible reason for the extension being quicker than the retracting is that the force of gravity is working against or in favor of the motion of the footrest. When the footrest is extending, gravity works in favor of the motion of the footplate, accelerating the motion. The opposite occurs when the user is retracting the device, as the weight of the device is pulling itself down, making it more difficult to generate the same speed as retracting the device does.

For the force test, various tests were performed with the following weights added to the footrest: 6 lbs (2.7 kg), 12 lbs (5.4 kg), 25 lbs (11.3 kg), 31 lbs (14.1 kg), 37 lbs (16.8 kg), and 50 lbs (22.7kg). The weight tests having different amounts of weight between them is because of the available weights that were accessible. That being said, the graph follows a linear line of best fit. The greater the weight, the more deflection occurs. On the line of best fit, the R^2 value is 0.88, or 88%, meaning that the plot points follow a linear line for a large majority of the test runs.

VII. Discussion

Strengths

The final footrest prototype is able to completely fold up under the client's wheelchair and out of the way to create maximum space for the client's legs while the footrest is not in use. The design also includes a double footplate that will allow the client to remove his feet from the footrest before pulling it under the wheelchair if he so chooses. The footrest is also easily removable from the sides of the wheelchair as it utilizes the rail and sliders that were originally on the chair.

Weaknesses

The final prototype has a few flaws. The first being a stability issue that was originally not thought through enough while drawing up the criteria of the design matrix. The original featured a bolt on the square piece of metal welded to the legs of the footrest that would be screwed into the slider of the rail on the wheelchair. This was flawed because if the bolt is tightened all the way it the footrest does remain stable but the slider is unable to move down the rail. The second flaw is the type of wheel chosen for the footplate. In the original design the team decided on suitcase wheels in order to have fast and easy pivot ability when directions can change very quickly. The error in this was that the footplate being at an angle made the wheels unable to turn well. An easy fix would simply be to choose a different kind of wheel such as the ball castor wheel. Functioning by a ball and socket design, the ball castor wheel has no edges that would get stuck or cause skidding across the ground as the wheelchair takes quick turns.

VIII. Conclusions

The team was commissioned to make a retractable footrest for a Quickie 700 series wheelchair. The main goal of the project was to create a wheelchair footrest which would accommodate an operator capable of limited movement in their legs. This would be accomplished by fully vacating the leg space of the operator without requiring the use of the legs or feet of the operator. The main focus of the design was to be ease of use, safety, durability, and transportability.

The team determined that a design which could move in multiple axes to allow for a high degree of customization while simultaneously leaving the leg space of the operator completely unimpeded would be the optimal solution. The design chosen was the most versatile option that required minimal amounts of effort by the operator and could be utilized completely electronically. It was decided that an exclusively mechanical option would be more favorable, due to the possibility of electrical failure causing the machinery to cease functioning under inopportune scenarios.

The testing and fabrication stages brought forth several challenges which the team tackled. The initial design had featured several buttons similar to what could be found on a pair of crutches embedded in the telescoping rods. However, this was deemed to be too unwieldy for an operator with limited use of their upper middle body. Another challenge arose in the form of the structural integrity of the footrest. It was determined that adding wheels under the footplates would allow much of the force to be translated through the footplate into the ground, dramatically reducing the strain on the contraption. A seat belt locking mechanism was added onto the rail system to secure the apparatus when fully retracted. In order to make the entire footrest removable, the footrest, cable anchor point, and locking mechanism were all fitted to the rail system to be easily removable and transportable with only use of a screwdriver. If given the chance to work on a similar prototype, the team would elect to make several modifications. Firstly, testing should be done to determine the functionality of the built in rail systems before usage. Any issues with them did not become apparent until later in the project. Secondly, wheels that have an off center axis of rotation should not be used. Due to the axis of rotation of the wheels, the footrest lost valuable turning capabilities and structural support. Thirdly, it would have been preferable to mill out sections of the footplate and rods that are not necessary to structural integrity. This would allow better traction as well as further reducing the weight of the prototype.

For future work on the project, it would be beneficial to find a way to compact the design more for more simplistic transportation logistics. The prototype produced cannot fit inside some smaller carrying cases, and as such is harder to transport by a single person. Furthermore, it would be beneficial to develop a method by which the three separate removable pieces on the rail system could be removed without the use of a device, as issues with the mechanism would be much harder to address if the operator did not have the needed tool at hand. The safety and operator comfort of the design should be improved upon, with methods such as more thoroughly sanding down of edges and adding protective rubber coatings to pieces which may come in contact with the operator. A complete remeasurement of the parts would be valuable, as a better configuration of the parts used would result in a much more functional prototype. Simple things such as re-measuring where certain screw holes and pegs are placed along with adjustment of the angles at which numerous parts are connected would result in a much more functional footrest design. The prototype met most of the requirements set for it, especially in the areas of durability and ease of use, but several key design and part changes could further improve many aspects of the design far beyond what was required of it.

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X. Appendix

A. Product Design Specification

Low-Interference Wheelchair Footrest

Product Design Specification

Sept. 19, 2024

BME 200/300 Lab 301 Design Project

Team Name: Footrest Fanatics

Clients/Advisors : Mr. Dan Dorszynski, Prof. Melissa Skala

Team Members: Elaina Rizzo, Elleana Thom, Yair Ben Shaul, Timothy Mendler

Project Function

Currently on the market, there are no known wheelchairs that allow for users who have remaining function in their legs to maintain use of their feet in everyday life. Use of the feet may include opening doors, putting their feet on the ground for better mobility overall, and picking up objects from the ground. Current footrest models are static in their position and do not allow for modification in position, as well as heavy and are not easily removed for storage. While wheelchair footrests are essential in supporting the user's legs and feet when reclined or tilted, it is vital to design the footrests to be able to allow for greater mobility of the feet should the user need it. The revised footrest should be adaptable to the user's abilities and lifestyle, be easily removable, and have reduced weight while still remaining functional as a traditional footrest when in the original position.

Client requirements

- Has the ability to be removed for translation to another wheelchair or be stored
- Provide the function of a traditional wheelchair footrest
- Total weight of less than 5 pounds
- Has the ability to move with the rest of the wheelchair during reclining

Design requirements

1. **Physical and Operational Characteristics**
    a. **Performance requirements**

    The wheelchair footrest will have a lifespan of 3 to 5 years, equal to the lifespan of the average wheelchair base [1]. The client must be able to retract and extend the footrest a minimum of 3 to 4 times per day, for everyday that the wheelchair is in use. The product must not have a total weight exceeding 5 pounds. The footrest should be able to retract to the extent where the client may reach an area of 0.762 m x 0.305 m around the wheelchair with no restricted movement.

    b. **Safety**

    The footrest extension should not take up much room in order to prevent the inability of the user to exit through doorways of an area safely and efficiently. The footrest should easily swing to the right of the wheelchair for the user's ease of movement from wheelchair to car, bed, chair, etc. All wiring of the extension should be safely stowed to prevent injury to the user as well as damage to the product from climate effects. If the footrest requires a battery proper labeling must be applied to make it known the mechanism is battery powered.[2] Material used in the footpads should be anti-slip to mitigate risk of a fall, in addition to this the material needs to be sturdy enough to withstand the load applied by the user's legs while avoiding materials that can be sharp or cause pinching.[3]

    c. **Accuracy and Reliability**

    The footrest needs to be able to attach to the user's wheelchair for as long as the wheelchair itself lasts. Speed of the footrest from "in use" to "stowed" must be accurate and efficiently timed. If battery powered -

battery must be able to last the entirety of the day before needing a charge. The footrest must be able to withstand the weight of the user's legs without breaking or degradation to the mechanism.

d. **Life in Service**

The footrest will be used both indoors and outdoors, therefore the mechanism will need to be weatherproof with an emphasis on water resistance due to wiring in the motor. Throughout the product's life span it will need to be unharmed in the removal process from the wheelchair. The footrest is also required to be easily condensable for most efficient transportation and last the entirety of the wheelchair's lifespan (3-5 years)[1]

e. **Shelf Life**

Storage climate conditions are not harmful to the product. The footrest should be able to be stowed or folded for long periods of time without wear or degradation to the materials of the footrest or the mechanism and electrical system. Batteries will need to be stored in a safe, dry, and neutral temperature environment. All attachments, brackets, braces, or hinges must be able to withstand constant motion throughout the day without losing stability over time.

f. **Operating Environment**

The footrest will be exposed to both indoor and outdoor environments. The footrest must be able to withstand all weather conditions and range of temperatures in the Midwest including, water, ice, snow, rock, mud, uneven ground, cold and hot conditions and wide humidity ranges. The footrest must have proper clearance in order to account for these things and consideration of all safety and environmental concerns while deciding the materials that will be used in the project. While the footrest is being stored it must also be able to withstand less frequent use in areas where problems may arise, such as; hinges, braces, or brackets.

g. **Ergonomics**

The ergonomics of wheelchair footrests are incredibly important to consider, as most people bound to wheelchairs will spend a great deal of time utilizing them every day. There are four main components to the overall ergonomics of the footrest. Firstly, it must be safe for all users, meaning that it should not be able to pinch, cut, or hurt the user in any other way. Secondly, it needs to be the proper height both above the ground and below the seat level of the wheelchair. There is no universal height for footrests, so it is best to make them to customer specifications. The only requirement is that they maintain proper ground clearance, or about 0.05 meters [4]. The third is that it can withstand the full weight of the human legs for extended periods of time, or about 33% of your body weight. This means that they should be able to withstand (on average) 250 N of force. The fourth is that the footrest is comfortable, meaning that it should be longer than the average human foot (0.269 meters) and should have a good deal of traction [5].

h. **Size**

The footrest should be large enough to fully support the average human foot length (0.269 meters) and should be at least as wide as the average human's hip width (98.70 cm) so that their feet may sit comfortably straight out in front of their body [6]. The footrest should also be able to easily fit through door frames, the standard width of which is about 91.44 cm in the U.S. [7]. In order to decrease the size of the wheelchair footrest during storage, it would be beneficial to make the individual parts hinged or be able to collapse in on themselves. Preferably, the overall dimensions of the collapsed attachment should be no more than 35.56 cm x 45.72 cm [8], which is the average size of a drawstring bag. If the device was needed to be larger, it could be made to be smaller than 48.26 cm x 33.02 cm x 17.78 cm [9], which is a standard size for a backpack. By these standards being met, the footrest would be quite easy to store and transport.

i. **Weight**

The client will need to be able to lift, store, and reattach the footrest with minimal exertion, thus the design must be lightweight while also maintaining structural integrity. Standard wheelchair footrests with various compositions range in weight from 3-10 pounds. The aim for this product is to reduce the amount of work required for removal and installation of the footrest, thus the team aims to have the design weigh in on the lower end of this range, with 3-5 pounds being the target.

j. **Materials**

The client has specified that they have no particular allergies to materials that may be used in the footrest. As the footrest will be subjected to all sorts of weather conditions and terrain, it would be best to use a material that is not capable of rusting and is easy to clean. All mechanization (motors, winch systems, hinges, locks, cables, rail systems, etc.) should be able to withstand these conditions. As there is a weight requirement given by the client of 5 pounds, the structure would preferably be made out of a lightweight material that is also sturdy enough to withstand the 250 N or force required. Aluminum is an appealing material choice due to its low price and low weight, paired with decent strength and durability. Steel is a more sturdy, albeit more expensive and heavy choice of material for the structure. A combination of the two in the overall design depending on parts should be researched. The other main material will be utilized on the footrests, which will likely be a rubber or resin material for its higher degree of friction and comfort for the operator's feet.

k. **Aesthetics, Appearance, and Finish**

Due to our product's design being specialized for our client, any cosmetic/aesthetic choices are made to his preferences. When asked about cosmetics during our meeting, the client stated that he has no preferences as long as the design is reasonable and that he encourages us to be creative with the aesthetics of the products. This leaves a high degree of freedom for our design in regard to aesthetics. Since there are no preferences from the client, the aesthetics of the footrest will probably be simple and emphasize durability over eye-catching designs. Due to the wheelchair being subjected to outdoor conditions and contact with different materials, the finish of any metal parts should offer rust resistance, and parts that may make contact with the client or surroundings should have textures and finishes that are relatively resistant to abrasion, yet not uncomfortable to make contact with.

2. **Production Characteristics**

a. **Quantity**

The client has not expressed a desire to create multiple units of the footrest but has mentioned that he has several backup wheelchairs. If he is satisfied with the completed design it is reasonable to assume that a few more units could be made for his backup wheelchairs. The client is open to the possibility of mass production but stressed that the product is mainly meant for his own personal needs and use.

b. **Target Product Cost**

While there are few other detachable footrests for wheelchairs that are sold separately, the ones that are usually range from $35 to $60 dollars. Most of those are not automatic and require work on the part of the operator to move them. In the event that an automatic footrest is designed, it is likely to cost a deal more than the manual ones, likely in the range of $80 - $120. As the prototype will likely cost more than any units of the final product that might be mass produced, it is expected to cost not more than $200 dollars to produce.

3. **Miscellaneous**
   a. **Standards and Specifications**

ISO 7176: This standard outlines the specifications in which wheelchairs are tested and the requirements they must meet. Parts 1 [10] and 2 [11] outline the requirements for static and dynamic movement of the wheelchair as a whole. The product must not obstruct the movement of the wheelchair in any way in order to meet this. Part 14 [12] outlines the testing standards to all electrical systems that are a part of the wheelchair. If battery powered or rechargeable, the product must be tested in accordance with this section.

CFR890.3920: The FDA classification of a wheelchair is a class I medical device. This regulation is in reference to wheelchair accessories that have the intention to meet the specific needs of the user. Because the product is not intended for use as a protective restraint, it is exempt from the premarket notification procedures [13], as well as the good manufacturing practice requirements, subject to limitations.

If the product has the intention for mass manufacturing, it will be important to keep billing and insurance standards in mind, such as Medicare Insurance [14]. The footrest needs to be up to date on electric wheelchair regulations in the state of Wisconsin.

   b. **Customer**

During our initial meeting, the client mentioned several preferences for the design of his footrest. Notably, he stated that he prefers designs that feature two separate footrests, one for each leg, as opposed to a single piece. However, he is still open to any design as long as it meets his needs. The client has expressed interest in designs that are less bulky, referring to previous designs. He also said that in the case we design a single-piece design, he would prefer it to swing to the right when stored. The client has mentioned that he disliked how loud the previous design was, so any motorized designs should be evaluated for noise. Additionally, the client informed the group that he likes unique designs that "think outside the box" and innovate, since many footrests on the market are similar.

c. **Patient-related concerns**

This device is designed specifically for the needs and abilities of our client, but it is possible that others can benefit from it as well. If we intend to mass produce this device, our design should take into account a patient's degree of mobility in their lower extremities and how well they can use their arms to operate the functions of the device. The device should offer some adjustability to fit the patient's feet under different circumstances. The device should also be removable and storable while being able to fit wheelchairs of different sizes and models than our client's for it to be available to patients.

d. **Competition**

Most commercial wheelchairs have footrests custom to the brand and model of wheelchair, however there are models of removable and modular footrests. The model from Fold-&-Go [15] highlights a foldable design, but only works with certain models of wheelchair, and is priced at $129.99. The standard footrests that are not retractable have an average price of around $50 [16]. Comprehensive research into foldable wheelchairs can be found [17], which highlights the folding of the entire wheelchair, making the device unusable while folded. The team's product intends to fold independently from the rest of the wheelchair to maintain usability.

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B. Design Criteria Description

Category	Weight	Description/Reasoning
Ease of Use	25	The client's ability to operate the footrest and retract or detract the mechanism when the footrest is in out of operation.
Client Comfort	20	The client's ability to operate the device using the least amount of mobility as possible to prevent injury or discomfort. It is also about the general comfort of the client and how the legs feel when the footrest is in use.
Safety	20	The client's ability to use the footrest with minimal to no threat of pinching from joints that are not hidden or injury due to electronics or wiring.
Compactability	15	The ability for the footrest to fully fold up and not be an obstacle or hindrance to the client while not in operation.
Cost	10	The cost of materials that will be implemented or used during the manufacturing of the footrest.
Ease of Fabrication	10	The team's ability to design, manufacture, and test the product in the timeframe of one semester during BME 200/300 with the skillset of the members.

C. Material Cost Table

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Cost Each	Total	Link
All Individual Purchased Parts										
Aluminum Telescoping Rods - 1.0" x 0.110"	Square Aluminum Rods	Alcobra Metals	SKU: AQT1.00F	Alcobra metals	SKU: AQT1.00F	10/21/2024	24"	$11.81	$11.81	Link
Aluminum Telescoping Rods - 1.25" x 0.110"	Square Aluminum Rods	Alcobra metals	SKU: AQT1.25F	Alcobra metals	SKU: AQT1.25F	10/21/2024	24"	$16.14	$16.14	Link
Aluminum Telescoping Rods - 1.5" x 0.110"	Square Aluminum Rods	Alcobra Metals	SKU: AQT1.50F	Alcobra metals	SKU: AQT1.50F	10/21/2024	24"	$19.70	$19.70	Link
Carbon Steel Cables - Item 54DR93	Carbon Steel Cables	PRIME-LINE	GD 52183	Grainger	54DR93	10/21/2024	1	$8.48	$8.48	Link
Aluminum Swage Sleeves - 5/32" - Item 54DR93	Swage Sleeves	DAYTON	2VJZ2	Grainger	2VJZ2	10/21/2024	1	$7.17	$7.17	Link
2" L-Shaped Castor Wheels	Castor Wheels	LEE TEAM RISE	B0C64ZB1G3	Amazon	B0C64ZB1G3	10/21/2024	1	$18.99	$18.99	Link
12" x 12" x 1/4" Metal Plate - Aluminium	Aluminum Plate	Wendt Maker Space	N/A	Wendt Maker Space	N/A	11/8/2024	1	$30.00	$30.00	N/A
3/4" x 36" x 1/8" Flat Bar - Aluminium	Aluminum Flat Bar	Wendt Maker Space	N/A	Wendt Maker Space	N/A	11/8/2024	1	$5.00	$5.00	N/A
¼" Flat Bolts and Nuts	Assorted Nuts and Bolts	ECB Shops	N/A	ECB Shops	N/A	11/26/2024	8	$0.10	$0.80	N/A
2Pcs Seat Belt Cover	Seat Belt Buckle	QYDHOUZHE	QYD-KOU01	Amazon	B0C1TB5CG8	11/12/2024	1	$6.50	$6.50	Link
								TOTAL:	**$124.59**	

D. Quickie Q700M Series Side Rail Parts Sheet