DESIGN OF DURABLE WHEELCHAIR FOOTRESTS

BME Design 200/300

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Abstract

Wheelchair footrest durability is important for the long-term safety and health of users. Depending on the patient, standard equipment may be upgraded to support unique musculoskeletal needs. However, challenges often arise due to the complexity that follows increased adjustability. The footrest components can experience wear or even complete failure due to the significant and repeated forces that occur in users who retain muscular strength but lack control. For this project, wheelchair footrests were designed which feature reinforcements to the frame, a novel locking mechanism, and decreased joint complexity in order to increase durability.

Contents

1. Introduction 5
  1.1 Motivation 5
  1.2 Current devices 5
  1.3 Problem Statement 7
2. Background 7
  2.1 Medical Information Background 7
  2.2 Client Information 7
  2.3 Design Specifications 8
3. Preliminary Designs 8
  3.1 Upper portion/Locking mechanism 8
    3.1.1 Current Pin and Flange 8
    3.1.2 Hole and Pin 9
    3.1.3 Extended Hanger 10
  3.2 Extension Rod and Footplate 10
    3.2.1 Single Footplate 11
    3.2.2 Double Footplate 11
    3.2.3 Crutch Extender 12
4. Preliminary Design Evaluation 12
  4.1 Evaluation of Design Matrix 1 13
  4.2 Evaluation of Design Matrix 2 14
  4.3 Proposed Final Design 15
5. Fabrication and Development Process 16
  5.1 Materials 16
  5.2 Methods 17
    5.2.1 U-Saddle 17
    5.2.2 Footplate 17
    5.2.3 Extended Hanger 18
    5.2.4 Welding 19
  5.3 Final Prototype 20
  5.4 Testing 21
    5.4.1 Static Calculations 22
    5.4.2 SOLIDWORKS Simulation Testing 22
6. Results 22
7. Discussion 25
8. Conclusions 26

9. References 26
10. Appendices 26
Appendix A. Product Design Specifications 26
Appendix B: Project Gantt Chart 28
Appendix C: Materials and cost 28
Appendix D: SOLIDWORKS Models 29
Appendix E: Fabrication Protocols 31
Appendix F: BME Design Funding Proposal 32

1. Introduction

1.1 Motivation

Wheelchairs are amongst the most common assistive devices used worldwide, with 3.6 million people aged 15 and older in the United States alone reporting using a wheelchair to assist with mobility in 2010 [1], [2]. Ideally, each chair and its many components should be highly customized to suit the needs of each patient in terms of size, adjustability, support, and safety. This includes the footrests, which encompass the hangers or bars and their connection to the wheelchair frame and to the footplates. If this structure experiences wear or stress, chipping, torsion of the bar or other elements, or even complete failure, this can pose a safety risk for the patient [3]. Additionally, if the desired footrest configuration is not maintained due to these failures, patient support and comfort may be negatively affected [3]. Ideally, wheelchair footrests should be durable long-term and not necessitate replacement or excessive maintenance before the user is ready to replace the entire chair.

1.2 Current devices

The chair used in this case is the IRIS™ Manual Tilt Wheelchair manufactured by QUICKIE© Wheelchairs. This device features an angle adjustable frame to easily change position in space, prevent sores, and support Mark's frame during prolonged sitting. There are several custom elements to supplement the standard model, including a custom headrest and seat. Because of the patient's specialized musculoskeletal needs for footrest height adjustability and specific foot angle tilt, the IRIS™ chair also features custom 70-degree swing in/out footrest, manufactured by Freedom Design Incorporated. The bi-directional locking mechanism allows the footrests to be rotated in or out and to be secured in place. Additionally, the current device features angle adjustable footplates and a length extension bar. These specifications for these components are set after evaluation by the client's medical team, and are adjusted as muscle strength, spasticity, and tension change over the years.

While the custom footrests provide tailored fit, commercially available products have not proven to be durable long-term. There are multiple points of failure with the current iteration, including the locking mechanism, bolts, and lengthening rod, though each of the patient's past footrests have experienced complete failure of some type. The locking mechanism centers around a switch and spring component which rests on a pin; both the pin and the locking mechanism are visibly worn. This reduces their ability to maintain correct placement. In an attempt to reduce the shock felt by the footrests when the user applies forces at the footplates, the current design also features dynamic gas springs applied to connect the hanger and extension bar. However, given the wear already experienced, they have clearly not been entirely successful. Given the current footrests are only two years old and device replacement is typically possible only every five to eight years, this rate of failure is significant. The client has also reported shearing of bolts and torsion of the extension bar as problems with past models.

Many footrests designs are currently on the market. For example, patent US 6234576 B1 features a swing away, detachable footrest bracket for any wheelchair [4]. One of the key features of this design is the attachment of the footplate by sliding it on a rod extending from the extension bar of the footrest. A pin and bolt secures the footplate to the rod. Presumably the footplate can be removed without removing the entire footrest. However, this design features a spring loaded locking mechanism much like the one causing trouble currently.

A second design allows easy manipulation of the footplate between an upper retracted position and a lowered use position [5]. All that it requires is squeezing a handle. This is an interesting addition because it allows for easier storage as well as a way to possible allow space for a wheelchair lift to access the wheelchair when it is not being used.

A third patent, US 7425010 B2, is attachable using a rotatable socket and a swivel element [6]. This allows the footrest to swivel up or down when it is not locked into place. These three adaptations are interesting ideas that could be used to help us think about possible adaptations in our design.

Figure 1. Quickie IRIS Wheelchair. The user currently has the standard model with additional adaptations including a modified headrest and footrests. Some common points of failure for his past footrests include failure of the locking mechanism, breakage of the footplates, shearing of the connecting bolts, and torsion of the lengthening rod.

Figure 2,3. Current Footrests. The design features a two-pronged hanger which attached to the wheelchair frame via a point of rotation above and a bi-directional locking mechanism below. The hanger is attached to an extension bar, gas-loaded springs, and an angle adjustable footplate.


Figure 4. Breaking of Locking Mechanism Pin


Figure 5. Wear of Locking Mechanism

1.3 Problem Statement

Current wheelchair footrests are not typically built to withstand repeated, significant applied forces and stresses. Footrests which are mass-manufactured and mass-marketed must suit the needs of a wide range of clients, and thus balance adjustability and durability, while keeping costs accessible. As a result, a given footrest which must be highly adjustable to accommodate musculoskeletal needs is not likely to also be highly durable. Especially in cases where patients with retained muscle leg strength experience seizures, have muscle spasticity, or do not generally have movement control, wear occurs in the footrests as forces are applied repeatedly over time. The effects may be exacerbated when feet need to be strapped to the plates, and movement is restricted. This can ultimately lead to failure of key components, thus compromising footrest function and safety. Therefore, a more durable footrest design is needed.

2. Background

2.1 Medical Information Background

Worldwide 17 million people are afflicted with cerebral palsy. Cerebral palsy is a physical disability which affects movement, muscle coordination, and posture. As of this time, it is a permanent and incurable disease caused by brain damage due to an injury during development. This can happen before birth, during birth or after; however, most occur prior to birth. The condition can frequently be accompanied by difficulty with hearing and vision, seizures, and intellectual disabilities. Spastic cerebral palsy is the most common type of Cerebral Palsy where the person has hypertonia - increased muscle tone that causes muscles to be stiff, weak, or tight [7]. The seizures experienced may cause straightening of the legs, as well as jerking motions.

2.2 Client Information

Our client, Andrea Gehling of Avenues to Community, is a case manager for Mark Hindle, the recipient of our product. Mark is a 32 year old male with spastic cerebral palsy and an intellectual disability. Mark uses a wheelchair for transportation, during which his feet are strapped in for safety. Being strapped in helps prevent any injury when the chair is in motion and during his uncontrolled movements. Due to his strength and muscle spasticity along with the forces applied during his seizures, he often breaks the foot rests on his wheelchair.

2.3 Design Specifications

Mark's father and primary caretaker, Chris Hindle, focused on creating the most durable footrest possible while maintaining Mark's safety and comfortability. In the past, Chris has had to replace and fix multiple parts so the goal is to make a device that he will not have to fix or replace. He also mentioned that he would like the device able to accommodate the lift and be intuitive for use by a single caregiver. Ideally, this device would still be adjustable in terms of ankle flexion and length to the footplate. In addition, since this device is a long-term solution, it would ideal for the footrest to be transferable to future wheelchairs since Mark gets a new wheelchair every five to eight years. All of this needs to be accomplished within the budget of $200. Please see the complete Product Design Specifications attached in Appendix A.

3. Preliminary Designs

In order to provide a more specific explanation of different designs we split our preliminary design approach into two areas. The first subgroup of our design was the upper portion which mainly focuses on the locking mechanism. The second subgroup was the extension bar of the footrest along with the footplate. By splitting our design up we were able to come up with multiple designs for each portion and consider combinations from both subgroups to make our final design. This gave us more options and allowed for a more accurate design matrix.

3.1 Upper portion/Locking mechanism

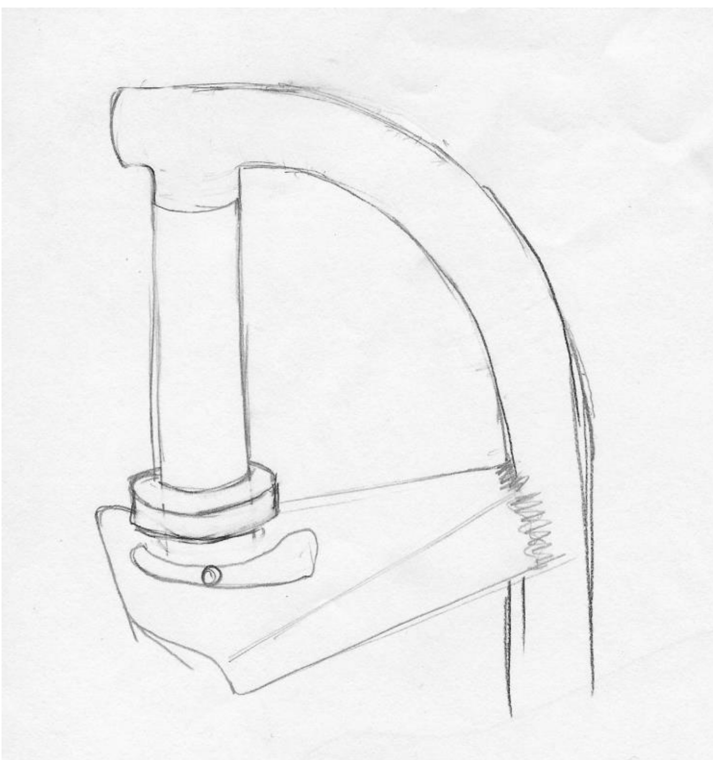


Figure 6. Current Pin and Flange

3.1.1 Current Pin and Flange

The current locking mechanism involves a spring-loaded lock that locks into place when it is pressed against a pin located to the side of the frame of the wheelchair. It is unlocked by a lever attached to the footrest. The top of the foot rest sits into the frame of the wheelchair which provides extra support. Design one does not change any of this. A metal flange is built off of the footrest which contains a locking mechanism. The locking mechanism would then attach the footrest to the wheelchair itself. The flange would deflect a portion of the force that is being placed on the current locking mechanism as well as stabilize the footrest. Both the current locking mechanism as well as the additional locking mechanism would unlock when rotation of the footrest is desired.

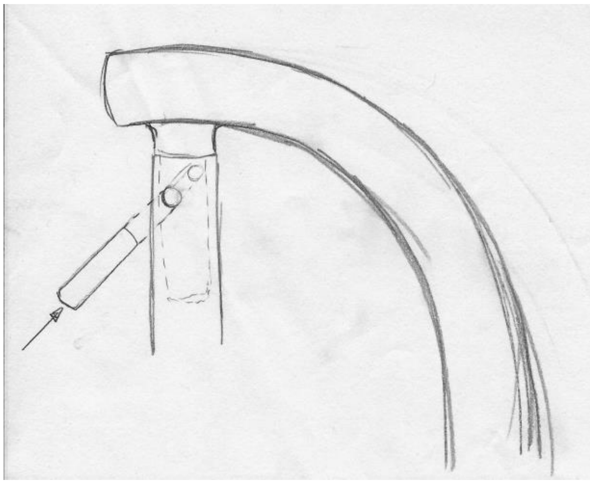


Figure 7. Hole and Pin Sketch

Figure 8. Pin Mechanism

3.1.2 Hole and Pin

This design utilizes the current footrests but bypasses the current locking mechanism. It focuses on the frame of the wheelchair and the footrest extension rod which fits into the frame. A hole is drilled through both the frame of the wheelchair and the footrest extension rod. A pin is then inserted into this hole. The ends of the pin have larger parts than the middle in order to keep the pin in the hole. The ends of the pin can be removed in order to take the pin out. The pin would maintain the position of the footrest extension rod inside of the frame of the wheelchair. This prevents all motion and directs the force entirely on the pin instead of the current locking mechanism. When the pin is removed the footrest extension bar has the ability to rotate freely from its position in the frame of the wheelchair.

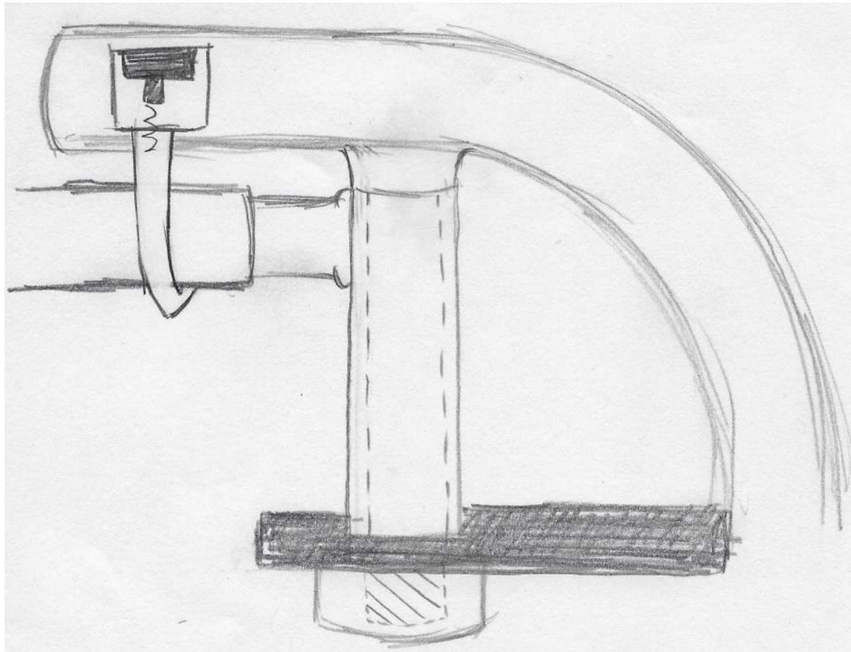


Figure 9. Extended Hanger

3.1.3 Extended Hanger

This design involves the fabrication of completely new footrests. The footrest extension rod is extended to be approximately equal in length to the hollow tube coming off the frame of the wheelchair. This utilizes the stability of the entire hollow tube as opposed to the two to three inches that is currently used. The bottom of the footrest extension rod is threaded and screws into a cap which is also threaded. This would prevent the footrest extension rod from moving up and out of the frame of the wheelchair. The hanger above the footrest extension rod that sits in the frame of the wheelchair would deflect all of the downward vertical force. The hanger of the footrest is extended behind the hollow tube on the frame of the wheelchair. A locking mechanism built off of the hanger attaches to the frame of the wheelchair behind the hollow tube. This would prevent all rotation while it is locked. When rotation is desired the mechanism can be unlocked and the footrest extension bar can freely rotate inside the frame of the wheelchair.

3.2 Extension Rod and Footplate

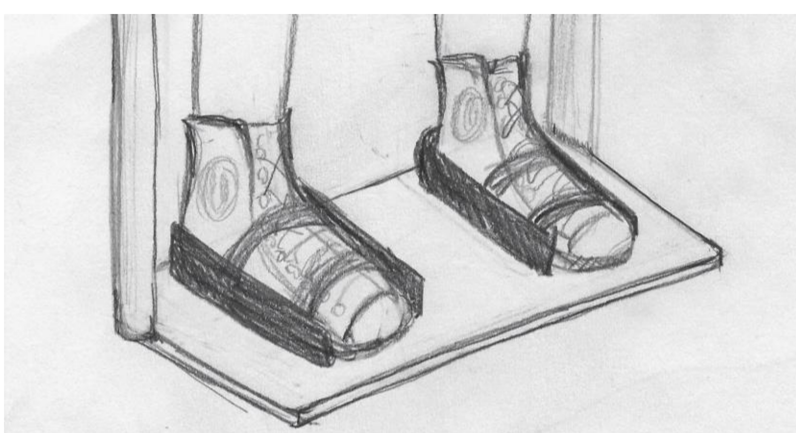


Figure 10. Solid Bar with One Footplate

3.2.1 Single Footplate

This design is one footplate that is connected to the frame of the wheelchair by two solid bars. The footplate is a solid metal plate with bindings on the top that the client's feet are strapped into. The solid footplate reduces the centripetal force of two separate feet moving in different directions by keeping them connected. The solid bar does not contain connecting bolts and thus limits points of failures. Due to the fact that connection points are limited in both the footplate and the extension bar, the design is significantly durable. The footplate cannot be rotated outwards and must be removed completely in order to access the space directly in front of the wheelchair.

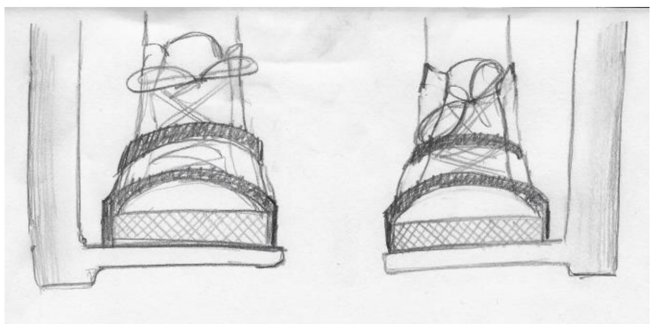


Figure 11. Solid Bar with Two Footplates

3.2.2 Double Footplate

The design shown in Figure 11 is made up of two individual footplates connected to the frame of the wheelchair by solid bars. The footplates contain bindings that the client's feet are strapped into. The individual footplates along with the solid bar are built to sustain forces in all directions. The solid bar does not contain connecting bolts and thus limits points of failures. The individual footplates allow the footrest to be rotated in order to access the space directly in front of the wheelchair.

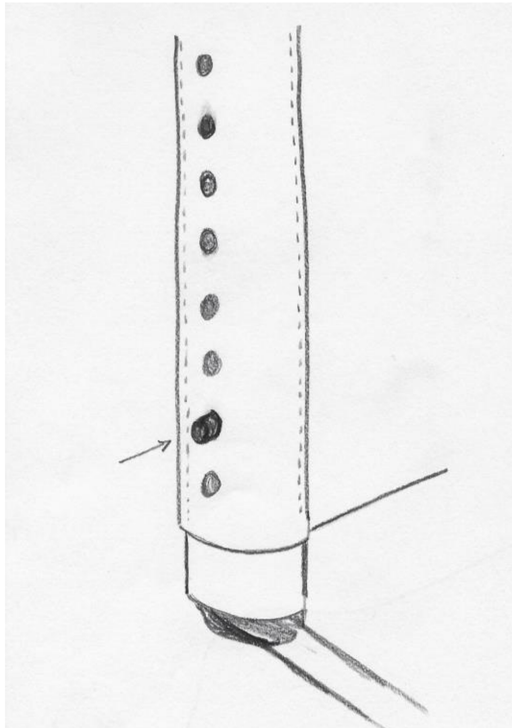


Figure 12. Crutch Extender

3.2.3 Crutch Extender

This design, seen in Figure 12, is an adaptation to the extension bar of the footrest. There are two shafts with one fitting into the other. Holes are drilled through the shafts at fixed intervals. Bolts and wing nuts that fit into these holes allow for the length of the extension bar to be adjusted. This bar can be used with both two footplates or one footplate. This design offers adjustability while reducing durability.

4. Preliminary Design Evaluation

The design areas were broken up into two main categories. The first category is the upper hanger and it involves the connection from the footrest to the wheelchair and the mechanism that prevents rotation of the footrest. The second is the lower hanger and footplate, which involves the lengthening rod and footplate. Separating the ideas allowed the designs to be evaluated based on the function of each aspect, and for the importance of each area to be accounted for.

Table 1: Design Matrix 1- Upper Hanger.

Criteria	Weight	Design 1- Current pin & flange		Design 2- Hole & Pin		Design 3- Extended Hanger	
Durability	25	4	20	2	10	5	25
Safety	20	5	20	4	16	5	20
Cost	15	4	12	5	15	3	9

Range of Motion	15	5	15	4	12	4	12
Ease of use	10	3	6	3	6	3	6
Transferable (to future chairs)	10	3	6	2	4	4	8
Ease of fabrication	5	4	4	5	5	3	3
Total	100	83		68		83	

4.1 Evaluation of Design Matrix 1

Durability is the category of most importance given that the product is expected to withstand multiple years of use. The Extended Hanger design is scored the highest because it provided the most stability and was the strongest of the three designs. The design would eliminate the necessity of the existing pin locking mechanism which has failed in the past. This pre-existing pin failure is the reason that design 1 was scored lower than design 3. The Hole and Pin design is scored the lowest due to the pin not being strong enough to support the forces applied to it.

Safety is weighted second as the product cannot cause the user any harm. Design 2 is scored the lowest because the structural integrity of the pin is not guaranteed. If the pin did fail, the footrest could detach completely from the chair and injure the client. The flange in design 1 and the threaded cap and locking mechanism in design 3 prevent vertical and side-to-side movement that could cause injury to the client.

Cost is ranked high because the budget is $100 and the materials required are expensive. Design 2 is scored the highest due to its simplicity. The only purchase that would need to be made for the Hole and Pin design is the pin. Design 1 is also relatively inexpensive as a result of using the existing locking mechanism. The Extended Hanger design proves to be the most expensive as it requires the most materials to be purchased.

Range of motion is an important category for the client. The footrest must be able to swing to the side to allow access to the lift required to move the user in and out of his chair. All of the designs allow this motion however only the Current Pin and Flange design allow for the footrest to be locked in its outward position.

Ease of use is a category that must be taken into consideration. The client has multiple caregivers when at his care center away from home, so the design of the locking mechanism must be intuitive for the caregivers. All of the designs scored low in this category because they are all slightly more complicated than the current locking mechanism.

The footrests should be made transferable to other chairs. The client gets a new wheelchair every 5-8 years and taking that the footrests are expected to last longer than that into consideration during designing, the footrests need to function on other wheelchairs. The Current Pin and Flange design as well as the Hole and Pin design are scored poorly because they both involve making modifications to the chair. In order to make these designs transferable, the client would have to make the modifications to his chair himself. The Extended Hanger design does not require any additional attachments to the chair which is why it received the highest score.

Finally, ease of fabrication must be considered when scoring the designs. The Hole and Pin design is the most simple design to manufacture because it would only involve drilling a hole through the wheelchair and finding a pin. The Current Pin and Flange design is a close second due to the fact that the only fabrication needed is to attach the flange to the wheelchair. The Extended Hanger design is much more complicated in that the hanger would have to be completely fabricated from scratch and it would involve welding and more complex machinery.

Table 2: Design Matrix 2- Lower Hanger and Footplate

Criteria	Weight	Design 1- Solid Bar, 1 Footplate		Design 2- Solid Bar, 2 Footplates		Design 3- Crutch, 2 Footplates	
Durability	20	5	20	5	20	4	16
Safety	20	5	20	5	20	5	20
Cost	15	4	12	5	15	3	9
Comfort	15	3	9	4	12	5	15
Ease of use	10	3	6	5	10	4	8
Adjustability	10	1	2	1	2	4	8
Removability	5	4	4	5	5	5	5
Ease of fabrication	5	5	5	4	4	3	3
Total	100	78		88		84	

4.2 Evaluation of Design Matrix 2

Durability is the most important category for the lower portion of the design because the user's feet will be strapped in but still applying lots of force directly onto the footplates. Design 3 was scored slightly lower due to possibly wearing down sooner due to the more complex and adjustable parts with the crutch design.

Safety is once again a major concern for the final design of the footrest. All of the designs are weighted equally safe due to their durability, lack of complexity, and low risk of failure.

Cost, as mentioned before, is a consideration that must be made due to the low budget that has been provided. The two-footplate scored the higher than the single footplate because two footplates are sold more frequently than a single footplate. The crutch design scored lowest because of the additional complexity and cost of the crutch mechanism.

The client spends most of his time in his chair so the final design must fit his comforts and needs. The crutch design is scored the highest as a result of its adjustability. The length adjustability allows for ensured comfort over time. As needs for longer or shorter footrests changes over the years, the length of the rods can be changed accordingly. The single footplate design means that the feet need to be strapped to one plate limiting the comfort for each foot. Two footplates would provide comfort individualized to each foot.

The lower hanger design, like the upper hanger design, must be easy to use and relatively intuitive. The single plate design is scored the lowest due to the fact that the caretaker would have to completely remove the footrest in order to access the user's lift. The crutch design is the most complex however it maintains the swing-away function so it is easier to use. Finally, the two footplate design is the easiest to use because it is the most similar to the existing footrests.

Adjustability is a category that needs to be considered based on the changing of the client's needs over time. The solid bar designs are not adjustable which is why they are scored very low. The crutch design allows for lengthening and shortening of the rods.

Removability is important for transportation needs. The footrests are removed when the user travels to limit the amount of space the chair occupies. All of the designs are removable however the single footplate design is more difficult to remove due to its geometry.

Once again, ease of fabrication must be factored into the final design decision. Fabricating the crutch design would be very difficult due to the complexity and machining necessary. The single footplate design would be the easiest as it would involve the least fabrication and the two-footplate design would be slightly more difficult.

4.3 Proposed Final Design

The final design ideas resulted in two options based on what had been presented by the client: the flange and pin design or the extended hanger. Each of these upper hanger options, could be paired with fused footplates. If it had been possible to modify the existing footrests or obtain access to spare parts, the design would have augmented these existing structures to utilize the current pin and flange design with the solid bar and two footplates. However, had the client would prefer that the current equipment remain unaltered, or spare parts were proved unavailable, the frame would need be manufactured from scratch. In this scenario, the design would feature the extended hanger, a solid bar, and two footplates.

The team determined that permanent alterations to the user's existing footrests or chair was not an acceptable solution, should the modifications prove unsuccessful. Separate spare footrests or footrest parts were not available within the current budget. Therefore, the extended hanger design was chosen.

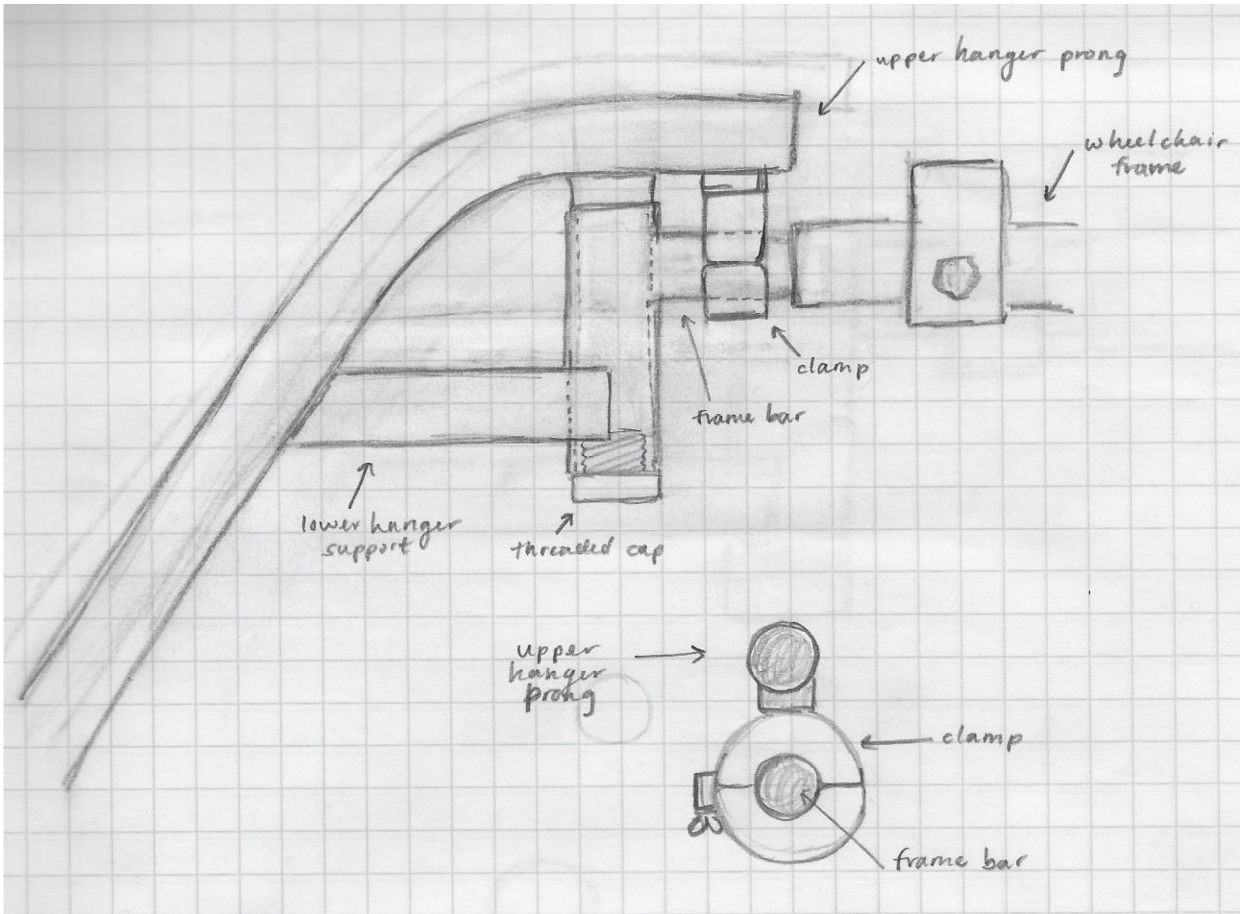


Figure 13. Sketch of proposed design for "Extended Hanger". The extended hanger is so named because the prong of the upper hanger extends past the current length to allow for the clamp to secure around the wheelchair frame below and prevent rotational motion. The drop-down bar and cap, and the lower hanger support bar are also shown.

5. Fabrication and Development Process

5.1 Materials

The single pronged hanger is made up by a 2024 alloy aluminum rod. Originally, aluminum was chosen to match the current wheelchair frame in case welding needed to occur to fuse these components. It also has a Young's modulus of 73 GPa which means it is reasonably stiff. The price of aluminum rod was comparable to that of the stainless-steel rod also considered, so this was not a limiting factor. Ultimately, aluminum was chosen as a lightweight, durable metal which would be compatible with existing hardware. The drop-down bar and, U-Saddle, and footplate are aluminum as well, allowing the entire structure to be TIG welded together.

At the advice of shop staff, a ¼-20 x 2.5 in. stainless steel screw was chosen to connect the cap and drop down bar. As the cap in the main component currently preventing vertical movement, the cap and screw will bear a large portion of the force. This piece should be able to withstand a reasonable amount of force, but in case of deformation or wear occur over time, the screw is a standard piece which is easily replaceable. Additionally, a 3/4 inch rubber grommet was provided by the shop to ensure a snug fit between the cap on the drop down bar and the wheelchair as well as to absorb some of the vertical forces.

5.2 Methods

5.2.1 U-Saddle

The U saddle is fashioned from a ½'' thick aluminum plate. First the outline, a 2.53'' by 1.65'' rectangle, can be cut out using a bandsaw. This is not to large that it will be an inconvenience, but allows room for the hole in the middle and the open portion which straddles the bar. Next a smaller square is cut out of the bottom half so the u saddle can straddle the frame of the wheelchair. The square is cut .385'' in from the long side of the piece and is .88'' x .88''. Finally a hole, 1'' in diameter, is drilled with its center .83'' from the short side opposite the cut out square and .83'' from the long side. Finally, the edges are filed to ensure they are dull.


Figure 14. U-Saddle

5.2.2 Footplate

The Footplate is first cut out of a large aluminum block of scrap metal and is cut to 9.264''x 6.015'' x .5''. It is cut to desired length and width using a bandsaw. It is brought down to the desired thickness using an Octa-Mill. A finish pass is done on both sides using an Octa-Mill in order to ensure that it is smooth. A 1'' diameter hole is drilled in the bottom left/right corner with its center 1.366'' from the long side and 1.4470'' from the short side. Finally, all edges are filed to ensure they are dull.

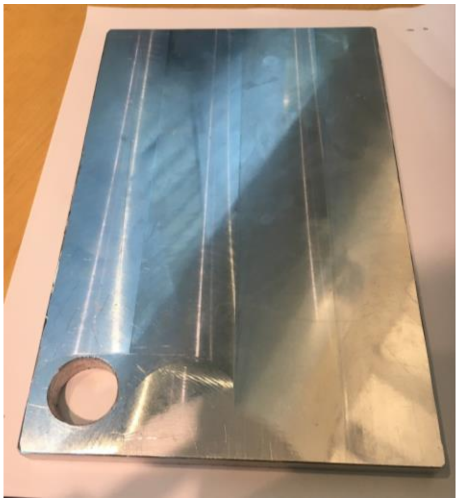


Figure 15. Footplate

5.2.3 Extended Hanger

The drop bar and cap are made from 2024 Aluminum rod. The rod is placed in the lathe where a hole is drilled into the bottom of the rod 1” in depth using a ¼” drill. The hole is threaded using a ¼-20 tap and the edges are filed.

Figure 16. Drop down rod

The cap is fashioned from a 1” rod and is cut to length 1.5” using a miter saw. A hole is drilled through the bottom of the rod and a countersink of 0.161” deep is added to ensure that the screw lies flush with the cap.

Figure 17. Cap with screw

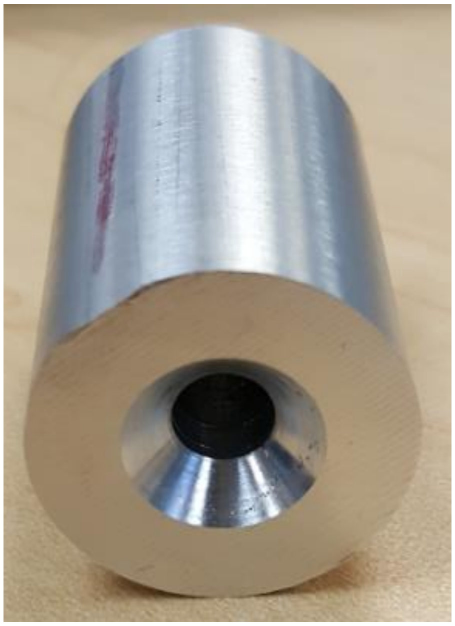


Figure 18. Cap

The rod itself also required a 70 degree bend. A 12 ton hydraulic pipe bender was used to hand crank the pipe to the appropriate angle ending with a 68 degree bend that can be seen in figure 19.

Figure 19. Bent rod

5.2.4 Welding

The aluminum rods were first heated with a propane torch and scratched with a wire brush to prep them for welding. The drop down bar was also ground down with a belt sander to provide more surface area for a larger weld. Each joint was then welded using tig welding specific for aluminum including using AC current, 4043 filler, and pure Argon gas. Below there is an image of the weld between the footplate and the hanging rod shown in figure 20.

Figure 20. Weld between footplate and bar

5.3 Final Prototype

Figure 21. Final Prototype. The final extended hanger design features a hanger bar which extends further past the bent segment than the current footrests, a "U-Saddle" piece which prevents rotational motion by dropping down over the wheelchair frame bar, and a drop-down bar and cap which prevent

vertical movement when tightened. The footplate is welded to the hanger, as is the U-saddle and the drop-down bar.


Figures 22, 23. Final Footrest Prototype.

The extended hanger originally called for a hook or a clamp which would be attached to the extended upper hanger prong and be secured onto the wheelchair frame. In order to avoid modifications to the user's existing chair, the team researched solutions which would not require welding on the lower bar. Several clamps and hooks were considered, in particular a circular KF25 vacuum clamp. However, concerns about the ultimate strength of the small pins and points of rotation found in these clamps eliminated them as a feasible solution. Instead, the design now features a piece dubbed the "U-saddle" which drops down over the wheelchair frame as suggested by Dr. Rogers to prevent rotational movement and to keep the point of contact far from the site of applied loads. The piece was manufactured from half inch thick aluminum plating to match the hanger rod, and is securely TIG welded in place.

Based on advisor feedback the team decided to plan for the possible failure of design components over time when designing. We recognize that the design failing is not ideal for our client; however, if the piece most likely to fail were easily replaceable, this solution would still be an improvement from the current device. We also kept in mind that any failure needs to be simple to fix for a single caregiver. Implementing a replaceable screw in the cap of the drop down bar accomplished this because the screw will have to sustain substantial vertical forces from the applied loads on the footplates. Should the screw threads wear over time, the ¼ 20 x 2.5 inch machine screw is easily replaced for low cost.

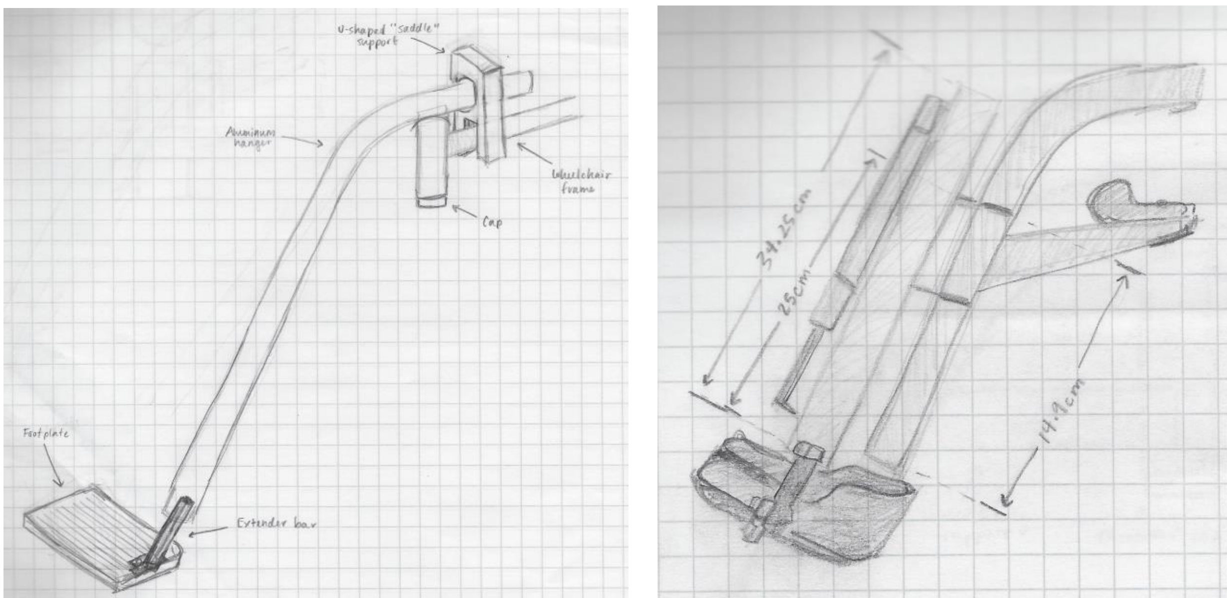
The connections (between the U- saddle and bent rod, the connection between the rod and the footplate, and the connection between the drop down bar and upper hanger) are all now TIG welded to decrease the complexity at connections. Ultimately, in order to keep the client's budget intact and due to the long arrival time of footplates, it was decided to create one aluminum footplate as a prototype for the client. See Future Work for additional comments.

5.4 Testing

A literature search was performed in order to estimate a physiologically accurate force which theoretically could be applied by the user at the footplates, as we do not have access to quantifiable strength evaluation data for the user. With their feet strapped into the footrests and lying flat against the footplates, the maximum force able to be applied with the legs in the scenario would be to press straight down on the plates. The average male is capable of applying an average maximum force of 2913.3 N with this leg press motion [8]. Leg extension and flexion movements were also considered, though as these were less than those applied during leg press, a force of approximately 3000 N became the benchmark for all theoretical calculations [9]. Due to his condition of spastic cerebral palsy, it is unlikely the user would be able to apply the full force calculated. However, as we are unable to calculate the exact degree of muscle strength, the team proceeded with the healthy control data as an approximation.

5.4.1 Static Calculations

First, the team performed static calculations to determine how much of the force applied at the footplates by the user would be transmitted to each component. This was compared to the geometry of the current device.



Figures 24, 25. Comparison of current and previous footrest geometry. Sketches of the current prototype (left) and the professional models (right) show the changes in geometry. In the current design, the lower hanger prong was eliminated entirely and the point of rotation was moved from the pin and locking mechanism to the drop-down bar and U-saddle. This places the point of rotation further from the footplates, where forces are applied by the user's feet.

5.4.2 SOLIDWORKS Simulation Testing

During the design development process and during testing, various SOLIDWORKS models were prepared. These include: an assembly of the entire footrests, an assembly of the cap and drop-down bar alone, and individual models of each component. The aluminum rod, stainless steel screw, and aluminum U-saddle were tested by applying scaled static forces appropriate for their distance from the forces applied at the footplate. The theoretical strength of the weld was also evaluated at each fused connection point: the footplate to the hanger, the drop-down bar to the hanger, and the U-saddle to the hanger. Segments of aluminum rod were compared to aluminum tube to justify material choice.

6. Results

The static calculations comparing the geometry of the previous and new footrests designs yielded a decrease in the forces felt at the connection point in each case by a factor of 3.8. This was accomplished by moving the U-saddle further from the footplate and the applied load than the position of the current locking mechanism. The robust geometry of the U-saddle compared to that of a single pin, also improves the likely durability of this component.

As expected, the aluminum U-saddle and rod did not experience significant strain or deformation during SOLIDWORKS Simulation testing. Under axial deformation testing of a six inch sample of aluminum rod of one inch diameter, the calculated maximum deformation was 1.0731e-9m. For comparison, this calculation was run with aluminum tube which had also been considered for the hanger. This produced a maximum deformation of 1.07964e-9m. The slight decrease in strength is not significant for the purposes of this project, however the fabrication plan influenced our choice of rod over tubing.

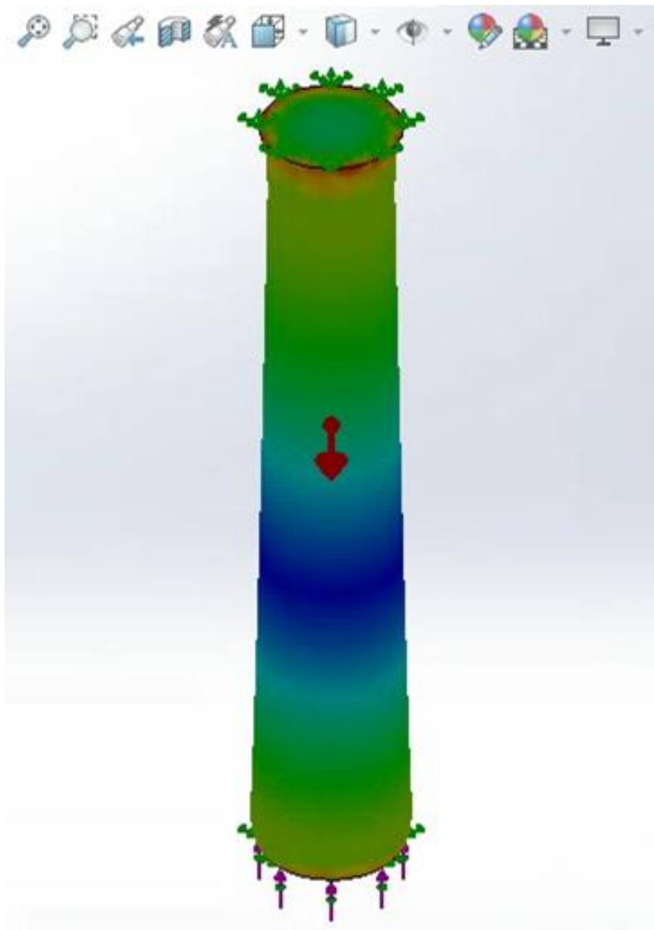


Figure 26. Static Deformation of Aluminum Rod. A static, axial load was applied to a six inch segment of 2024 alloy aluminum rod to test for maximum deformation. Aluminum tubing was also tested for comparison. The rod and the tube experienced a maximum deformation of 1.0731e-9m and 1.07964e-9m, respectively.

The static calculations demonstrated that the screw in the cap and drop bar would experience the majority of the load that that would result from the downward force on the footplate; this made the screw the most likely point of failure. To ensure that the screw would not fail, the screw was modeled in SolidWorks and tested for fatigue. The forces were applied to the threads to accurately demonstrate the function of the screw. The results of test showed that while the screw did undergo some deformation over the course of 1000 trials, the deformation was not enough to cause failure.

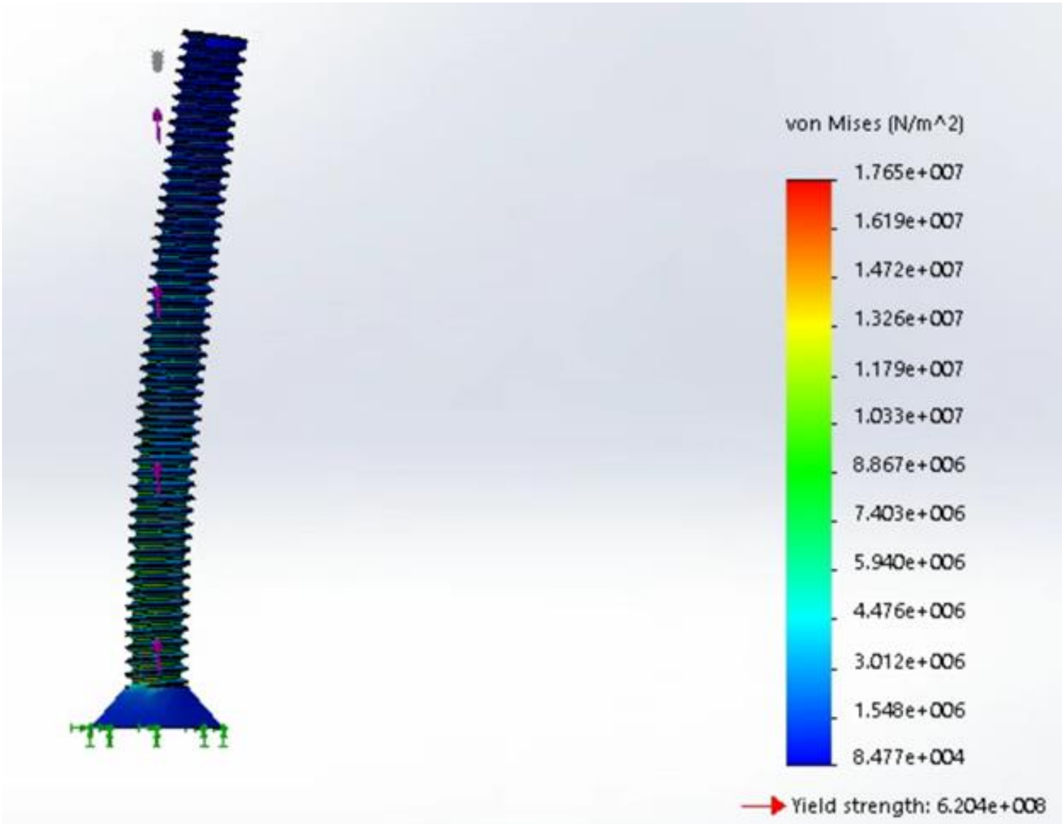


Figure 27. Static force test of ¼ 20 machine screw.

To test the theoretical strength of the welded connections, the fused connections were modeled in SOLIDWORKS and assembled using TIG weld. According to the COE Student Shop professionals, the weld should be very strong if done correctly. In fact, the metal surrounding the weld would be more likely to fail due to heating effects during the TIG welding process. As expected, the welded connections did not exhibit significant deformation or strain. For example, the yield strength of the weld connection between the aluminum rod and the U-saddle was calculated to be $7.583e^7$ N/m^2. The other connections were similarly strong, and did not exhibit significant deformation.

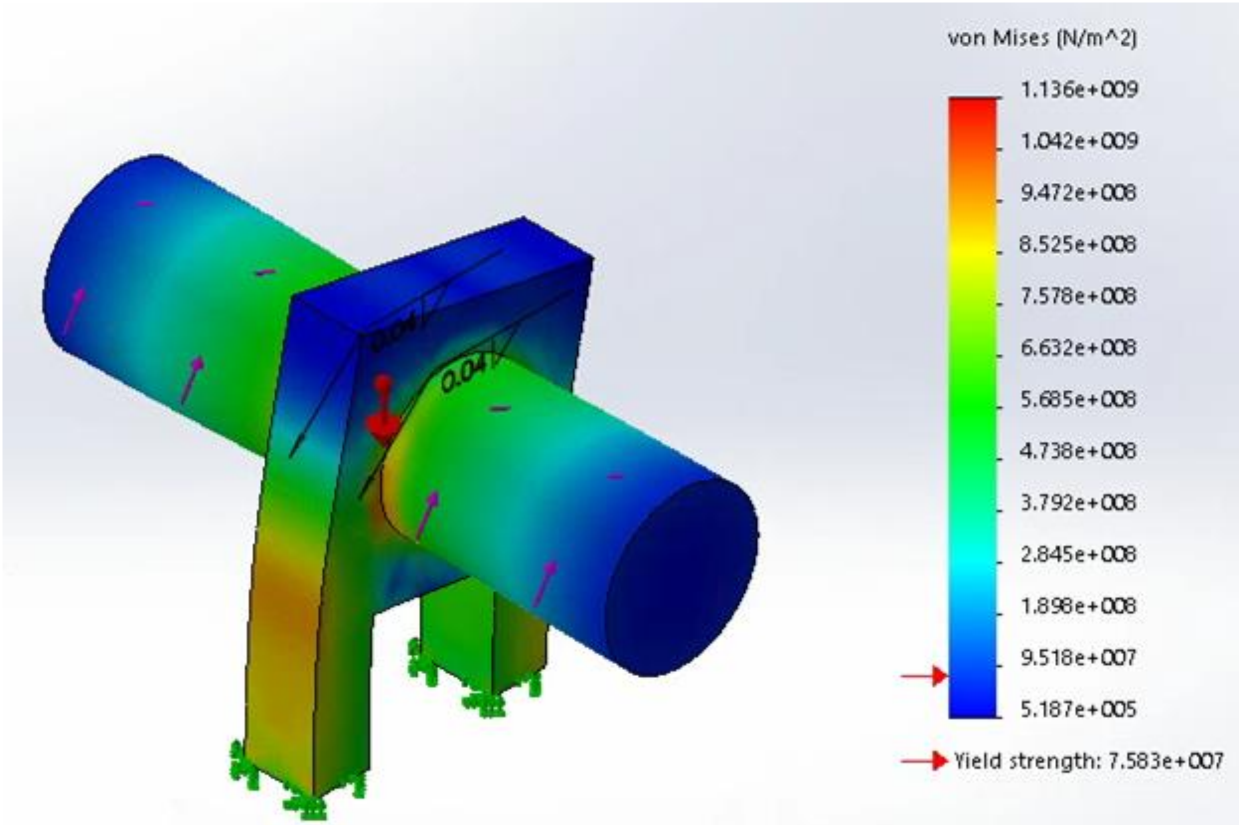


Figure 28. Stress test of U-saddle and aluminum rod. The connections between the rod and the U-saddle were fused with welded assembly and subjected to axial loading, while the feet of the U-saddle were held fixed. The maximum yield strength was found to be $7.583e^{7}$ N/m^{2}.

Due to the complicated geometry of the footrest as a whole the best way to test the strengths of the actual weld was through human forces. First the team clamped the footrest to stabilize it and then applied similar forces to the footplate that the user will apply. This allowed a preliminary test of the weld strength between the footplate and the extension bar. For the U saddle and drop down bar welds we applied force by pulling/pushing and seeing if the weld held up. All three welds withstood the mechanical tests the team applied.

7. Discussion

Most ethical considerations for this design center around the health and safety of the user. The prototype made meets the medical needs of the user in terms of the specific flexion angle and the length for his footplates. The footrests are safe for the client and his caregiver because there are no jagged edges on the prototype and the materials are durable. The final geometry of the prototype should be compatible with his wheelchair due to taking the measurements and dimensions of the connecting pieces of his wheelchair in person. The other ethical consideration is cost to the consumer. This team only spent $84 on aluminum rod, and the rest of the components were donated by the student shop. The cost to manufacture a single footrest is calculated to be $127.81 as projected in Appendix C, which is less than buying a new footrest, and under the budget of $200.

8. Conclusions

It is estimated that 65 million people worldwide have a disability which requires the use of a wheelchair [10]. The client is one of the many with a wheelchair that does not completely suit his needs. We aim to provide the client with durable, long lasting footrests that will accommodate his needs by limiting the number of connection points and adding reinforcements.

There is still a lot of work to be done in terms of testing. So far, the design has been tested by each component ideally in Solidworks but not together as an ensemble. Additionally, physiological fatigue testing with cyclic loading needs to be done. However, with the tests completed so far, the forces applied to load bearing components compared to the geometry of original footrests is reduced by a factor of 3.8 as well as no parts failing under the ideal tests. Together, this gives the impression that eliminating the current locking mechanism, simplifying connections, and adding reinforcements did improve the possible durability of the footrest. The prototype also needs to be tested to ensure it fits on the current wheelchair and determine the ease of rotating and detaching the prototype by a single caregiver. In terms of additional fabrication, a pin could be added to the U-Saddle to further prevent stress on the cap. Also, the foot cradle and straps the client uses would have to be transferred to the new footrest or fashioned for him. Client feedback and testing would be tremendously helpful before creating a second footrest.

9. References

[1] World Health Organization (2008). Concept note: World Report on Disability and Rehabilitation [Online]. Available: http://www.who.int/disabilities/publications/ dar_world_report_concept_note.pdf
[2] M.W. Brault, "Americans With Disabilities: 2010," in Current Population Reports, Washington, DC, U.S. Census Bureau, 2012, pp. 70-131.
[3] R. P. Gaal, N. Rebholtz, R. D. Hotchkiss and P. F. Pfaelzer. Wheelchair rider injuries: Causes and consequences for wheelchair design and selection. Journal of Rehabilitation Research and Development 34(1), pp. 58-71. 1997. Available: http://search.proquest.com.ezproxy.library.wisc.edu/docview/215296901?accountid=465.
[4] D. E. Fleigle, "Universal Wheelchair Footrest Bracket Assembly," U.S Patent 6234576 B1, May 22, 2001.
[5] W. H. Broyles, D.F. Boone, "Wheelchair Footrest Retractor," U.S Patent 6880845 B1, April 19, 2005.
[6] V. Harris, "Swing Away Detachable Footrests," U.S patent 3857606 B2, September 16, 2008.
[7] K.A. Stern. *Definition of Cerebral Palsy* [online]. Available:http://www.cerebralpalsy.org/about-cerebral-palsy/definition
[8] J. Ivanovic, M. Dopsaj. "Reliability of force–time curve characteristics during maximal isometric leg press in differently trained high-level athletes," Measure., vol. 46, no. 7, pp. 2146-2154, Aug., 2013.
[9] M. Hagen, et. al. "Reliability of isometric subtalar pronator and supinator strength testing," J. Foot Ankle Res, vol. 8, no. 15, Aug., 2015.
[10] "Fact Sheet on Wheelchairs," *World Health Organization* , pp. 1–4, Oct. 2010.

10. Appendices

Appendix A. Product Design Specifications

Product Design Specifications:
Design of Durable Wheelchair Foot Rests

Client: Andrea Gehling, Avenues to Community

Advisor: Dr. Jeremy Rogers

Team: Rachel Craven-Team Leader
Allie Hadyka- BWIG
Makayla Kiersten- BSAC
Kobe Schmitz- Communicator
Shannon Sullivan- BPAG

Function: Our client at Avenues to Community works with Mark, a 32 year old man with cerebral palsy and an intellectual disability. Mark uses a wheelchair for transportation while in their community. Due to his spasticity he often kicks his legs, so for safety reasons his feet must be strapped in during transport. As a result, he often breaks the foot rests on his wheelchair. A more durable foot rest design is needed for his use.

Client Requirements: New wheelchair footrests must be suitable for the safety needs of Mark and function without breaking.

Design Requirements:

1. Physical and Operational Characteristics
    a. *Performance Requirements:* Must withstand maximum forces during leg kicks due to spasticity from the user, a 32 year old male with cerebral palsy.
    b. *Safety*: Must safely support and secure the user's legs during wheelchair use, particularly transport. Must prevent injuries such as circulation, restriction, or bruising. Must be able to swing or remove out of the way in order for a lift to be used.
    c. *Accuracy and Reliability*: Must never break during use.
    d. *Shelf Life:* Our goal is for our product to work for Mark's lifetime use
    e. *Operating Environment:* Our product will be used in coordination with an existing wheelchair.
    f. *Ergonomics*: Foot rests should be comfortable for the user of the wheelchair, keep his ankle at the correct flexion, as well as be easy to use for his support staff.
    g. *Size*: Should not increase the current amount of space that his wheelchair currently encompasses.
    h. *Weight:* not an important factor, must be light enough to be removed by Chris, no more than 15 lbs.
    i. *Materials:* Materials should be as durable as possible without compromising safety, adjustability, and weight.
    j. *Aesthetics, Appearance, and Finish*: Aesthetics are not a main concern, but the product should look professional.
2. Production Characteristics
    a. *Quantity*: At least one set of functioning footrests.
    b. *Target Product Cost*: As affordable as can be for the family of the user, staying within our design budget of $200.
3. Miscellaneous
    a. Patient Related Concerns:
        i. Footrests should allow the wheelchair to have easy accessibility and removability
        ii. The footrests should be completely safe for the patient.
        iii. Must be intuitive and simple in nature
    b. *Competition:* Composite footrests vs metal footrests; swingaway or elevating, removable or fastened, and footplates

Appendix B: Project Gantt Chart

	September			October					November				December		
Task	12	19	26	3	10	17	24	31	7	14	21	28	5	12	19
Project R&D															
Preliminary Research	X	X	X												
Brainstorming		X	X	X	X			X							
Choose Design						X	X	X	X						
Order Materials										X					
Fabrication										X	X	X			
Testing										X	X	X	X		
Product Revision													X		
Final Product													X		
Deliverables															
Progress Reports	X	X	X	X	X	X	X	X	X	X	X	X	n/a	n/a	
Preliminary Presentation				X	X										
Preliminary Deliverables					X	X									
Final Deliverables												X	X	X	
Poster												X	X		
Meetings															
Advisor	X	X	X	X	X	X	X	X	X	X		X	X	X	X
Client				X				X							
Team		X	X		X	X		X	X	X	X	X	X	X	
Website															
Update	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Key: colored cells=projected timeline; X= task completed														

Appendix C: Materials and cost

Item	Quantity	Cost	Manufacturer; Part Number	URL
Aluminum Metal Rod (1 in Diameter)	6 linear ft	$84.00	Grainger; Part #: 2AVB7	Found at: https://www.grainger.com/product/2AVC5 and on MDS Madison

Estimated costs of donated parts:

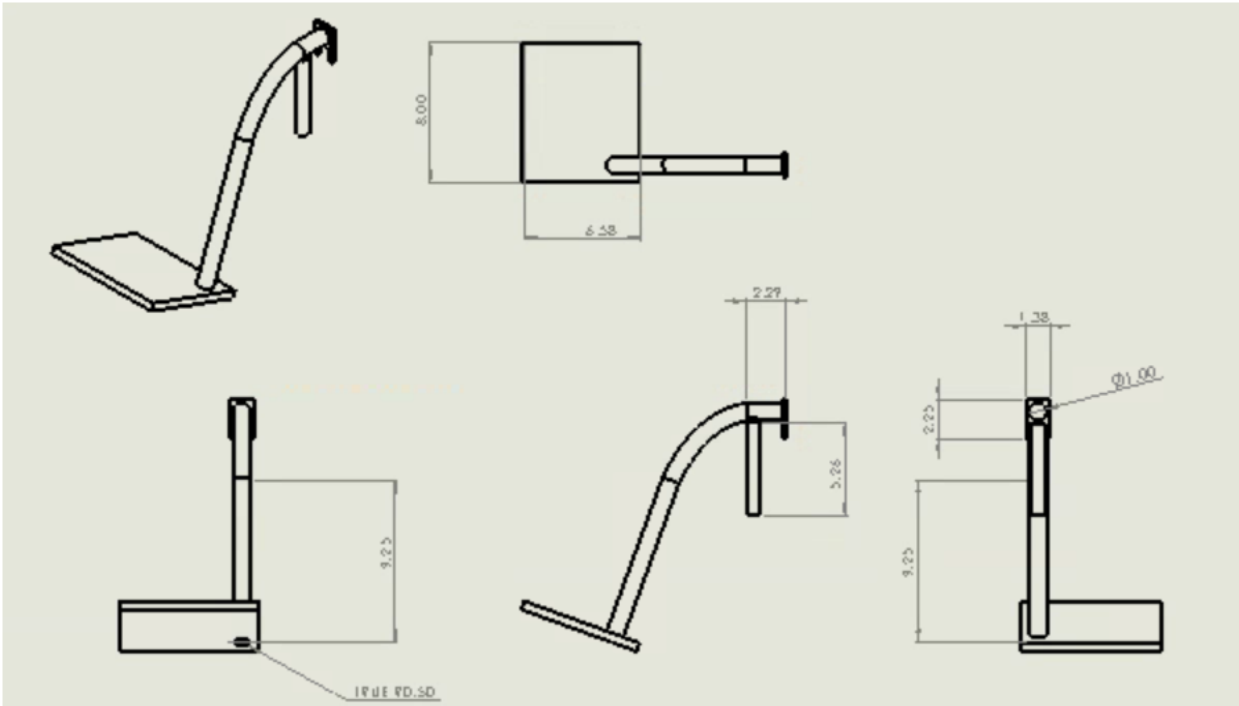
Item	Quantity	Cost	Manufacturer, Part Number	URL

Aluminum Flat Bar	½” x 4” x 12”	$20.74	Remington Industries; Aluminum Flat Bar, 1/2" x 4", 6061 General Purpose Plate, 12" Length, T6511 Mill Stock	Found at: http://www.remingtonindustries.com/raw-materials/aluminum-flat-bar-1-2-x-4-6061-general-purpose-plate-12-length-t6511-mill-stock/?utm_medium=googleshopping&utm_source=bc
¼ 20 x 2.5 inch screw	1 screw	$0.33	Albany County Fasteners; 11610102	Found at: http://www.albanycountyfasteners.com/Phillips-Truss-Head-Machine-Screw-Stainless-1-4-20-p/11610000.htm?1=1&CartID=0
Aluminum for the footplates	½” x 8” x 12”	$22.74	N/a; 1/2" X 8" X 12" ALUMINUM 6061 FLAT BAR SOLID T6511 New Mill Stock Plate .50"	http://www.ebay.com/itm/like/360916525803?lpid=82&chn=ps&ul_noapp=true
Total		Scrap metal and screw= $43.81		Total projected cost for 1 footplate = $127.81

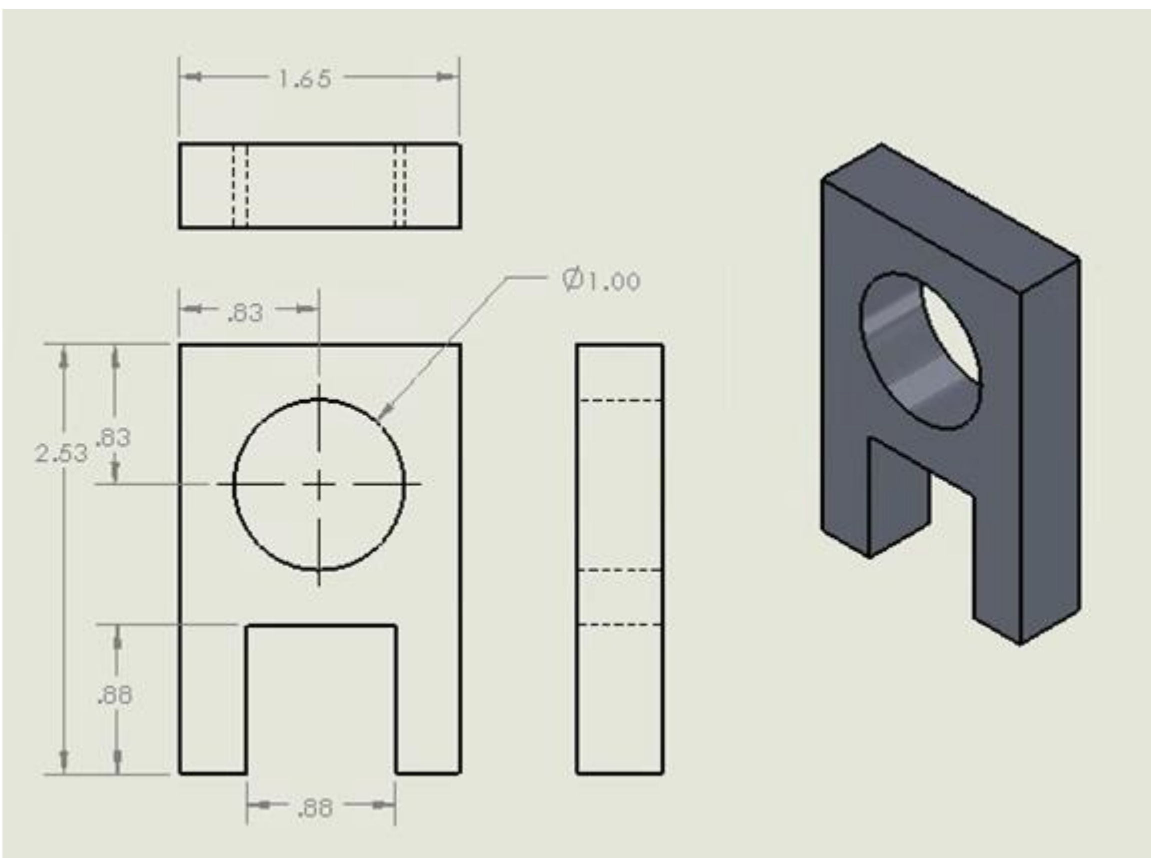
*note shipping costs are not included

Appendix D: SOLIDWORKS Models

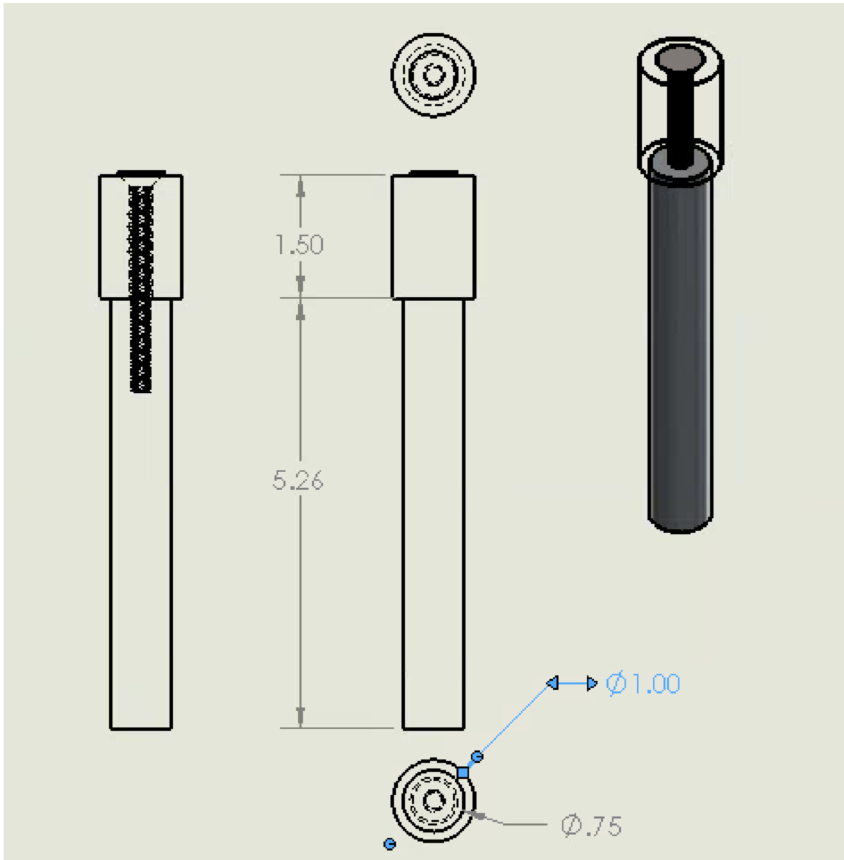
Footrest Assembly



U-Saddle



Drop-down Bar and Cap



Appendix E: Fabrication Protocols

U Clamp:

1. Bandsaw
    a. Cut rectangular outline (2.53''x 1.65'') using straight edge
    b. Make two straight cuts parallel to 2.53'' side .385'' from respective long ends of rectangle
    c. Using diagonal cutting technique, cut out square portion in bottom middle (.88''x.88'')
    d. File down uneven ridges on top of cut out portion
    e. Mark hole in middle of "top part of square" (.83'' down long side of rectangle from top, .83'' from short side of rectangle)
    f. File edges
2. Mill
    a. Machine flats on long side with end mill (allows piece to fit properly in a vice) using 1'' parallels
    b. Using ½'' center drill in drill chuck center drill at marked point (1.d)
    c. Apply oil regularly throughout the rest of the process
    d. Drill through piece using ½'' drill bit in drill chuck
    e. Drill through piece using ¾'' drill bit in ½'' collet
    f. Drill through piece using 1'' drill bit in 1/2'' collet
    g. File edges

Footplate:
1. Bandsaw
    a. Cut aluminum block to desired thickness, length, and width

2. Mill
    a. Mark center of hole an inch from edge
    b. Using Octa-Mill flatten both faces and bring down to desired thickness
    c. Apply frequent oil
    d. Repeat steps b-f in section 2 of U clamp protocol (hole is drilled 1.366’’ from the long side and 1.4470’’ from the short side)
    e. File edges and hole

Cap:
1. Bandsaw
    a. Cut rod to desired 1.5 inches
2. Lathe
    a. Drill 17/64 through hole in center of cap
    b. Use 82 degree countersink until screw lays flat

Drop down bar:
1. Bandsaw
    c. Cut rod to 6 inch
2. Lathe
    d. Drill ¼” inch hole in center rod 1 inch into the piece
    e. Tap the hole for ¼-20 thread size
3. Mill
    a. End mill opposite end with 1 inch diameter bit to final length of 5.7 inch from bottom of saddle to end of the rod.

Hanger rod:
1. The rod is heated with warm running water
2. The pipe is inserted into a 12 ton hydraulic pipe bender
3. The pipe bender was hand cranked to bend the pipe to the appropriate angle, continually checked with a protractor

Appendix F: BME Design Funding Proposal

BME Design Funding Proposal

Team: Durable Wheelchair Footrests
BME Design 200/300

Kobe Schmitz; Rachel Craven; Makayla Kiersten; Shannon Sullivan; Allie Hadyka

Project Summary:

Our client at Avenues to Community works with Mark, a 32 year old man with cerebral palsy and an intellectual disability. Mark uses a wheelchair for transportation while in their community. Due to his spasticity he often kicks his legs, so for safety reasons his feet must be strapped in during transport. As a result, he often breaks the foot rests on his wheelchair. A more durable foot rest design is needed for his use.

Funding:

Our client has some funding through their case management organization, Avenues to Community. The organization has approved a $100 budget. Our client is unable to provide more than 100 dollars.

Materials:

Item	Quantity	Cost	Manufacturer; Part Number	URL
Aluminum Metal Rod (1 in Diameter)	6 linear ft	82	Grainger; Part #: 2AVB7	Found at: https://www.grainger.com/product/2AVC5 and on MDS Madison
Clamps (KF25)	2	25.5	Best Value Vacs; KF25-CLAMP	http://www.bestvaluevacs.com/kf-25-clamp.html
ELR Aluminum Footplate 22 -30"	2	66.00	Southwest Medical- 883157	https://www.southwestmedical.com/replacement-parts/sunrise-medical/quickie-p222-se/seating-and-positioning/hangers-and-footplates/manual-elrs/elr-aluminum-footplate
TOTAL	$199.56			
	-$100		Funding from Client	
Total Requested	$100			

*note shipping costs not included

Utility of Materials:

The metal bar is used to mimic the existing bar and hanger, extending the footplates to their necessary length as well as support the user's feet. In our design however, the bar will be used to additionally extend the upper hanger prong and replace the locking mechanism support against the wheelchair frame. The clamps will be used to lock the footrests to the frame of the wheelchair via the upper hanger. This will serve to prevent rotation and add stability. The footplate will replace Mark's existing footplates, and will be welded directly to our rod.

Summary of Milestones:

Project Gantt Chart:

	September			October					November				December		
Task	12	19	26	3	10	17	24	31	7	14	21	28	5	12	19
Project R&D															
Preliminary Research	X	X	X												
Brainstorming		X	X	X	X			X							
Choose Design						X	X	X							
Order Materials															
Fabrication															
Testing															
Product Revision															
Final Product															
Deliverables															
Progress Reports	X	X	X	X	X	X	X	X							
Preliminary Presentation				X	X										
Preliminary Deliverables					X	X									
Final Deliverables															
Poster															
Meetings															
Advisor	X	X	X	X	X	X	X	X							
Client				X				X							
Team		X	X		X	X		X							
Website															
Update	X	X	X	X	X	X	X	X							
	Key: colored cells=projected timeline; X= task completed														

Several of the group members are in the process of obtaining relevant shop training, which we hope to have completed within approximately 2 weeks, or by the time materials would be shipped. This would enable fabrication to occur during the last two weeks of November, with testing beginning as parts are finished. According to our project timeline, this testing should be begun by the week of November 14th, and absolutely completed by the first week of December. This timeline would allow project completion by the first week of December.

Current Design

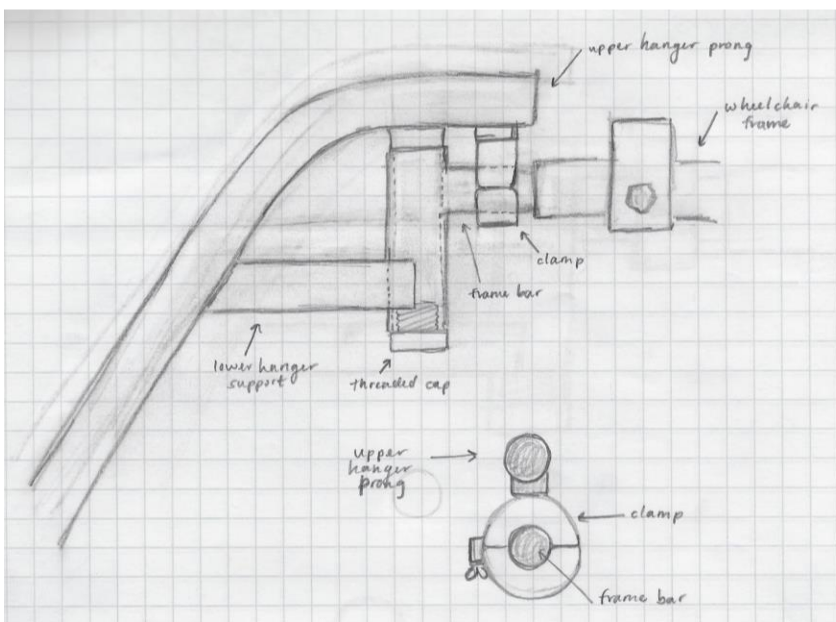


Image 1: Upper hanger. The upper portion of the footrest is shown, hanging off the wheelchair frame piece. Below, a side view section is shown to illustrate the configuration of the clamp.

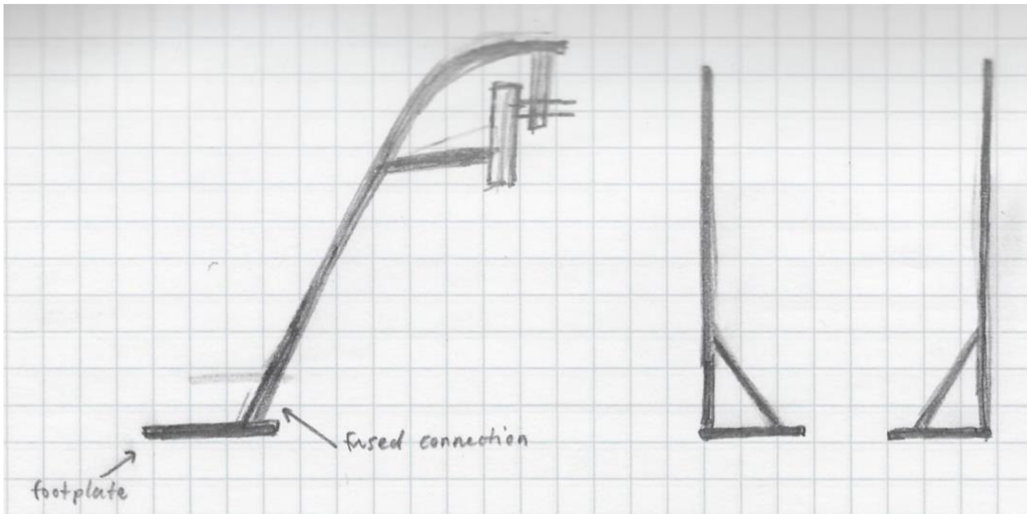


Image 2: Entire Hanger and Footplate. The outline of the footrest frame is shown from the side and the front to illustrate connection to the section shown above, and proposed reinforcements for the lower bar to footplate connection.

Image 3: SolidWorks Model of footrest rod only.