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Final Design Report

Adjustable Foot Support for Children with Cerebral Palsy in Low-Income Families

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Abstract

Cerebral palsy (CP) is a lifelong congenital disorder of movement and muscle tone which varies greatly in symptoms and severity among those affected by the disorder. To help address the condition, custom chairs and orthotics are used, but these are often very expensive. To help children with CP in low-income countries, specifically Nicaragua, our group has been tasked with developing an adjustable foot support. This support should be comfortable, affordable, adjustable, and allow for children with CP to better integrate into society. We are working with BLUELab EASE to develop a solution which will work for children in Nicaragua.

Executive Summary

Over the course of this semester, we will be working to design an adjustable foot support for use by children with Cerebral Palsy (CP) in Nicaragua. Our goal is to develop a foot support which is comfortable, adjustable, adaptable to different seating configurations, sustainable, affordable, and allows for children to better integrate into society. CP is a congenital condition which affects movement and muscle tone. Although it does not typically progress over time, the symptoms and severity of the condition vary greatly between cases. Typically, custom made wheelchairs and orthotics are used to help correct and mitigate CP symptoms. However, these can be very expensive, prohibitively so for people in low income countries such as Nicaragua. As such, we will work to develop a prototype of an adjustable foot support by the end of this semester which can be tested in Nicaragua.

Our primary stakeholders include Monica, a teenage girl with Stage 3-4 CP in Nicaragua, and her parents who serve as her main caregivers. Other important stakeholders include BLUELab EASE, a student group at the University of Michigan which works on sustainability projects around the world; FNE International and Salud Para Todos Los Niños (SPTLN), non-profit organizations who work in Central America on issues related to health, education, and housing; Joanna Thielen, an engineering librarian at U of M; and Donn Hilker, a rehabilitation engineer at Michigan Medicine.

From our meetings with stakeholders and review of the existing literature, we developed several benchmarks, stakeholder requirements, and engineering specifications. Some of our most important requirements are that our design must be comfortable, promote proper foot positioning, be made from only materials and manufacturing processes which are readily available in Nicaragua, adjust to different seating arrangements, and be inexpensive.

After considering our design requirements and specifications, we moved forward to concept generation, utilizing brainstorming, design heuristics, and morphological analysis tools to help cover the solution space. After generating over 100 initial concepts, we iterated upon our ideas through convergence and concept analysis strategies and narrowed down our concepts to a final five. A Pugh chart was then created with our design requirements in mind, and we arrived at our alpha concept. Given these considerations, our alpha design was determined to be an attachable seat pad with a height/angle adjustable foot box. The alpha design can attach to various types of chairs for accessibility.

Given our alpha design, we made several iterations of the design after receiving stakeholder feedback, conducting analysis, and creating low, middle, and high fidelity prototypes to analyze each design iteration against our design requirements. We have created a high fidelity prototype which has been tested against our engineering specifications, along with a detailed manufacturing plan for the design. These items will be passed along to BLUELab EASE and FNE International for further testing and iteration to determine the viability of the design for its intended use.

Project Introduction

This semester, we have the privilege of working on a design project that has the potential to create real positive change in the lives of many children in Nicaragua. We will be working to design an adjustable, affordable, and sustainable foot support for children with cerebral palsy (CP). This section will discuss the purpose of the project as well as the intended outcome, the design process that has been employed up to this point, and background information about stakeholders, cerebral palsy, and the scope and context of the project.

Project Description and Intended Outcome

Cerebral Palsy (CP) is a life-long congenital disorder of movement and muscle tone. CP occurs at a rate of approximately 3.6 cases per 1,000 births [1]. In the United States, equipment for people with CP is typically custom-made to suit each person's particular needs as CP does not affect every person in the same way. However, Nicaragua does not have the same resources that are available in the United States. Wheelchairs equipped with a tilt-in-space frame and an adjustable foot support can impose costs of more than 2,800 USD on families of children with CP [2]. In Nicaragua, however, the reported gross national income per capita in 2020 was 1,850 USD [3]. Purchasing customized equipment is not feasible for the overwhelming majority of people in Nicaragua.

To address the above problem, we have been tasked with designing a foot support that can be adjusted to accommodate multiple foot and leg positions, can be used on different types of seats, and can be manufactured using readily available materials in Nicaragua. Most of the children have seats that work for them, however, many of them have seats without a foot support. A foot support would help promote comfort, better posture, and protect the child's feet from dragging on the ground when being wheeled from location to location in their wheelchair. The design must be inexpensive, comfortable, adjustable to accommodate the conditions of multiple children, and must allow children with CP to more easily interact with their community.

Through discussions with stakeholders, we have been able to develop a well-defined problem. We have used benchmarks to gauge the stakeholders' interests in different possible designs and have been given clear constraints by the stakeholders that we must work within. Based on the information we have gathered, we intend to have a fully-functioning prototype developed by the end of the semester.

Design Process

To develop a successful solution to this problem, we have already employed and plan to continue to use a variation of IDEO's design process [4]. The steps in this process go as follows:

1. Frame a question - Understand what the actual need is
2. Gather inspiration - Conduct research, interviews, and observations to better understand the need
3. Generate ideas - Develop a large number of concepts and refine them through iteration
4. Make ideas tangible - Use low-fidelity and high-fidelity prototypes to help determine which concepts would work best
5. Test to learn - Get user feedback on your concepts
6. Share the story - Provide the solution to the stakeholders and share how the solution was developed

At this point in our process, we have worked through steps one and two. We worked through these steps together. When first tasked with this project, the purpose of having a foot support and how it is supposed to be adjustable was unclear. To build a better understanding of the problem, we conducted a literature review of topics related to CP, other foot-related problems, and Nicaragua. We then set up meetings with stakeholders and experts to understand their vision for the project and what we should be thinking about when developing a solution to the problem. Our findings from the literature review and meetings will be detailed throughout this report.

When we move onto steps three and four, we will be employing ideation best practices and using concept generation techniques such as morphological analysis and design heuristics to develop a wide range of possible solutions. We will work as a team to refine these concepts and use low-fidelity prototypes to convey our ideas to one another and to analyze the feasibility of each concept.

Once we come to a consensus on a concept that we want to pursue, we will move into steps five and six. At this point in the process, we plan to be working on a fully-functioning prototype that we can send to Nicaragua to be tested by our stakeholders. If our design proves to be sufficient for their needs, we will send the manufacturing and assembly plans for the design so it can be replicated.

Background Information

Cerebral Palsy Background

Cerebral Palsy (CP) is a life-long congenital disorder of movement and muscle tone, which occurs at a rate of approximately 3.6 cases per 1,000 births, and is caused by damage to a developing brain. It is a non-progressive disorder, meaning the stage that a child is born with is the stage they will be in for the rest of their life. Nonetheless, the symptoms that a child will experience can worsen throughout their lifetime. Symptoms include muscular contractions, tremors, difficulty walking and maintaining balance, skeletal deformation, hip displacement, speech limitations, seizures, and many more. The different types of CP include spastic, ataxic, dyskinetic, hypotonic, and mixed [1]. Spastic CP is the most common type throughout the world and is the type that most of the children we are designing for have. Children with spastic CP have stiff muscles due to brain signals being sent incorrectly throughout the body, resulting in movement that is difficult, jerky, and sometimes impossible [5].

The Gross Motor Function Classification System (GMFCS) categorizes symptoms and severities into five different stages. With Stage I CP, children have limited speed, balance, and coordination, but they are able to walk, run, jump, and climb stairs. With Stage II CP, children are capable of walking in most environments and can climb stairs while holding onto a railing, but they have a more limited ability to run and jump and may have difficulty walking long distances. With Stage III CP, children often use a wheelchair when traveling long distances and use a hand-held mobility device to walk shorter distances. With Stage IV CP, children use powered devices or devices that typically require physical assistance. With Stage V CP, children must use a manual wheelchair in all environments, which requires physical assistance, and have a limited ability to control their arms and legs and maintain good posture [6]. Although CP affects every child differently, the GMFCS provides a sufficient general understanding of the conditions that children we are designing for have. Our design focus is on children that require the use of a wheelchair, or children with Stage III, IV, or V CP.

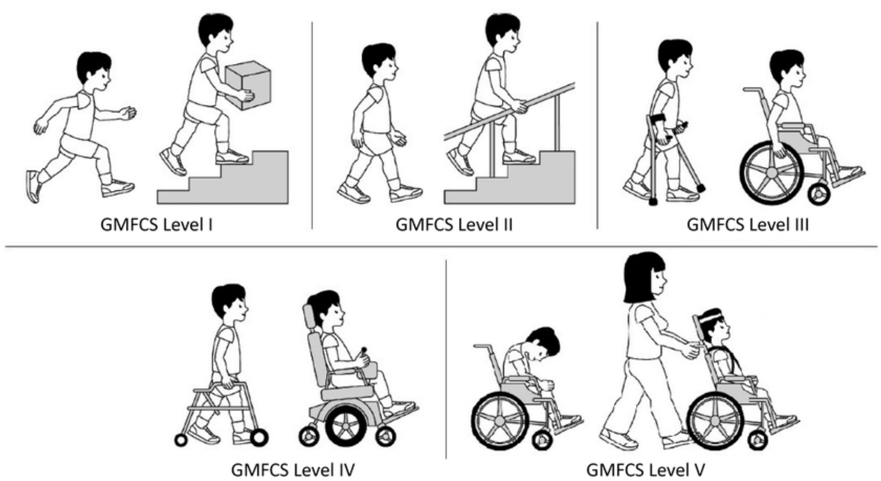


Figure 1. Simplified visual summary of the Gross Motor Function Classification System (GMFCS). In the context of our design problem, our main focus will be on GMFCS levels III, IV, and V due to the children's reliance on wheelchairs and their need for foot support [6].

There are a few ways to remedy CP, such as drug treatments, physical therapy, occupational therapy, speech therapy, and more, but proper treatment depends on the stage [7]. For example, children with Stage V CP typically require surgery to correct their condition. Braces and orthotics, such as ankle-foot orthoses (AFO) and knee-ankle-foot orthoses (KAFO) are often used to correct muscle contractions or prevent bone deformation in children with Stage III or IV CP [8].

Stakeholders and Experts

There are a few major stakeholders involved in this project as well as experts that have provided us insights into the design of medical and assistive equipment. The first major stakeholder is **Monica**, a 13-year-old girl with level 3-4 CP who lives in Nicaragua. She has very little ability to walk and is most often in her wheelchair and other chairs around her house or at school. She currently does not have a foot support on her wheelchair and would benefit immensely from having one. Monica is the main child we will be designing for, however, we hope that our design can be replicated and adapted to be used for other children with CP.

After Monica, her **family and caretakers** are the next stakeholders in this project. Children with CP are often provided with assistance from older family members and caretakers that may help them outside of their home. It is important to recognize that these stakeholders will also be interacting with our design often, meaning we have to ensure that the design works well for them.

BLUELab EASE is a student organization at the University of Michigan that works on sustainability projects all over the world. BLUELab started this project in 2019. The project originally began with designing a back support system to be added to the children's wheelchairs, and a previous ME450 group worked with BLUELab on that project. The need for a foot support was not introduced until this semester when it was discovered that most children did not have foot supports on their chairs. Given that BLUELab started this project, they play a large role facilitating communication between our team and the organizations that work with the children in Nicaragua.

FNE International and Salud Para Todos Los Niños (SPTLN) are the other major stakeholders in this project. FNE is a non-profit organization that partners with communities in Nicaragua, Peru, and the Dominican Republic to improve housing, health, and education. SPTLN is a group of medical professionals who work together with FNE to provide accessible healthcare to children in rural areas. They have offered us insights into the lives of the children and families that we are designing for and have helped us define the problem, giving us direction for the concept generation phase of the project.

One person we have reached out to for assistance with conducting research and performing a literature review of related topics is **Joanna Thielen**. Joanna is an Engineering Librarian in the Duderstadt Center and focuses on the Biomedical Engineering, Mechanical Engineering, and Integrative Systems and Design departments, as well as the University of Michigan Transportation Research Institute. Joanna helped guide our team's research efforts in the University library database, which allowed us to dive deep into all topics related to the project.

Donn Hilker is a Rehabilitation Engineer in the University of Michigan Medicine Rehabilitation Engineering Program. We interviewed Donn to gain a better understanding of what the design process is like for medical orthotic devices. Donn has experience working with children with CP, therefore, he was able to provide us with information on what conditions to be paying attention to when designing our device. We plan to use the information gained from that interview extensively throughout the concept generation phase of the project.

Stakeholder Analysis

Given the stakeholder climate surrounding our design problem, we created a hybrid stakeholder-ecosystem map to analyze the priorities of our stakeholders. Figure 2 displays this stakeholder ecosystem map which, which includes our obvious stakeholders (Monica and others, their family, and our direct collaborators) but more obscure ones as well (craftsman, government, and indirect entities)

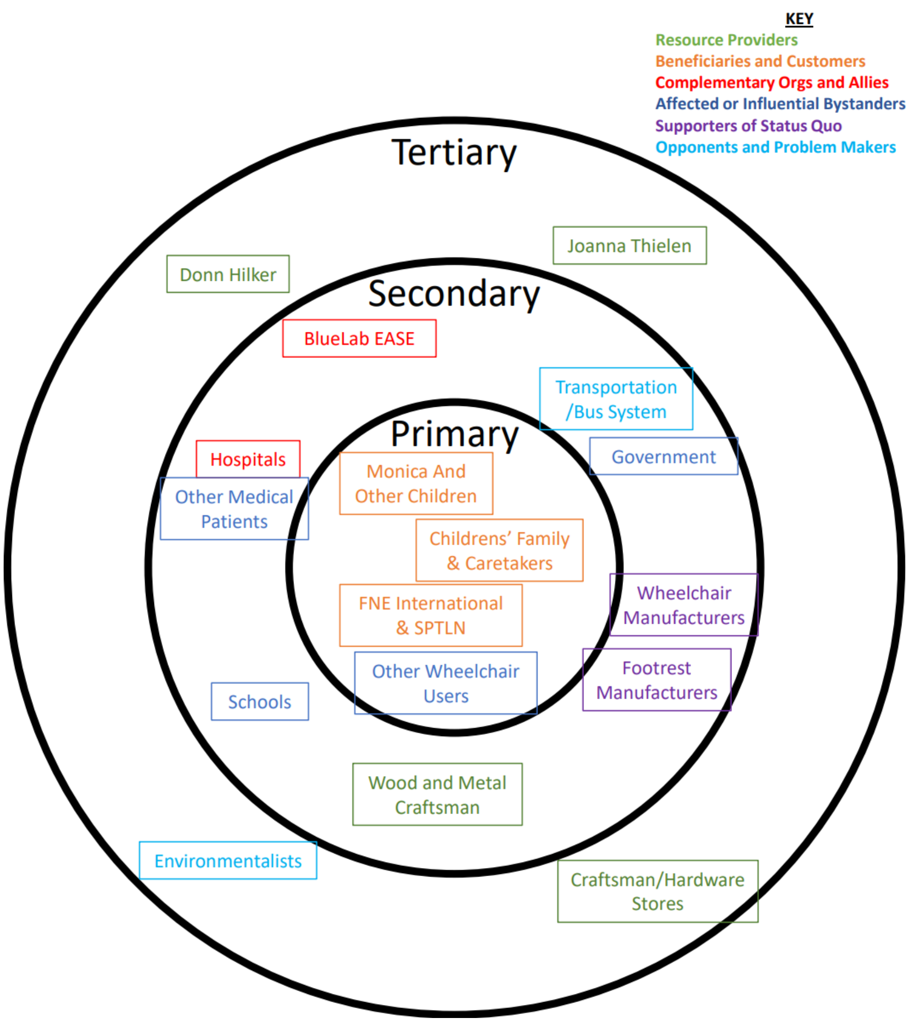


Figure 2. Hybrid stakeholder-ecosystem map for foot support design problem. Groups mentioned closer to the center of the diagram are more deeply involved with the design problem, while groups on the outside may not be directly involved with the design problem but could still affect the outcome of the solution.

Our stakeholder ecosystem map described in Figure 2 highlights how closely related each group is to our design problem. The diagram also categorizes each stakeholder group (based on color coding), highlighting each stakeholder's relative relationship with the proposed design outcome.

Stakeholder Meetings

While all of our stakeholder meetings provided us with necessary information to move forward with the project, the most important meetings we have had were the meeting with FNE and SPTLN and the meeting with Donn Hilker. The information gathered in those meetings heavily influenced our research efforts and our work to develop requirements and specifications.

In our meeting with FNE and SPTLN, we were able to gather information about specific problems that Monica and other children have with their current chairs, the purpose of a foot support and the problem we are aiming to address, the ways in which our design has to be adjustable, and the materials and manufacturing capabilities available in Nicaragua. They conveyed to us that our main objective is not to address the medical concerns of Monica and her family, but instead to design a foot support that promotes a more comfortable sitting position. Wheelchairs are not meant to be sat in all day, but many of the children with CP in Nicaragua have to sit in their wheelchairs for long periods of time because there are not many other options for them, so the foot support should help make this more comfortable for the children. It would be ideal if the foot support could help keep Monica's legs centered in relation to her body, and this would be especially helpful for children who have more spastic symptoms that force their legs to veer off to the side and cross over one another.

With regards to adjustability, the foot support should be able to work with other children's wheelchairs, not just Monica's, and should also be capable of working with other seats the children may find themselves in, not just wheelchairs. With regards to manufacturability, FNE shared with us that wood, metal, sponges, cloth, vinyl, velcro, and canvas are all readily available materials in Nicaragua. Using these materials would make the design more practical for use in Nicaragua. They also explained that common power tools could be found throughout Nicaragua, and they have a contact who has access to a 3D printer if that was something we were interested in using, but access to that would be harder to come by than other manufacturing techniques.

In our meeting with Donn Hilker, we gathered information about CP in general, learned about the process of designing medical-related devices and what things need to be considered when designing, and he offered suggestions on information to find out from FNE and SPTLN. He shared his process for meeting a patient and understanding what they need help with, and explained to us that once we understand what the need is, the problem becomes a materials and manufacturing issue, especially for our project. Donn, like FNE, emphasized that comfortability is important for children with CP, and explained that children are often uncomfortable because they are not sitting in their chair properly, so if the foot support could help them sit in a more correct position, then they would be much more comfortable. He also made sure that we understood the importance of getting information from the children's caretakers because they would more than likely be the people adjusting any of the equipment we design for her.

Social and Environmental Context

With regards to the social challenges related to this project, the main concern expressed to us by FNE and SPTLN is ensuring that the design can allow the children to more easily interact with their community. This can be translated into a few different social interactions.

One situation explained to us was bringing Monica to the grocery store. It is often difficult for Monica's parents to bring her to the grocery store with them because it is difficult to maneuver her in her wheelchair throughout the town, and the constant movement might cause Monica to be uncomfortable. The foot support that we design should help keep Monica comfortable for longer periods of time in her chair and keep her feet in a secured position above the ground, making it easier for her parents to walk with her throughout the town, and therefore, making it more likely for them to bring her with.

A second scenario described to us by FNE was bringing Monica on the bus. Buses in Nicaragua can be very tightly packed, and while people will stand up to give Monica a seat on the bus, there is often not enough space to bring her wheelchair on the bus. Her wheelchair is typically strapped to the back of the bus for the duration of her ride. Putting Monica in a normal bus seat for an often long and bumpy ride can make her very uncomfortable. If there was a way to have a foot support that can be detached from her wheelchair and used on the bus, the ride would be much more pleasant for Monica. This is something we hope to achieve with our design.

With regards to environmental and sustainability challenges related to this project, the main idea that was shared with us is that our design should use materials that are readily available in Nicaragua. Materials that are readily available include wood, metal, sponges, cloth, vinyl, velcro, and canvas. Ideally, we would be able to design a foot support that uses only these materials. The goal is to develop a prototype, send it to Nicaragua and have it tested on Monica's chair, and if it suits her needs and the needs of other children, then we would be able to send manufacturing and assembly instructions to FNE and SPTLN so that the foot support can be replicated by craftsmen in Nicaragua to be used for other children with CP. The use of these materials and developing a design that can be easily manufactured would make the product cheaper and more sustainable for families in Nicaragua.

Intellectual Property

There are no intellectual property restrictions or non-disclosure agreements which apply to our project. We would own any intellectual property developed as a part of this project.

Inclusivity

Our group holds significant power over our stakeholders in that our work directly impacts the quality of life of our end users. Additionally, because we are engineers, the stakeholders we interact with may be inclined to assume we know best and go along with whatever we suggest. To try and mitigate this, we will be meeting with stakeholders as frequently as possible, and in each meeting, we will be sure to involve our stakeholders in decision making as much as possible.

Ethics

The primary ethical consideration we will have to focus on for this project is to keep the well-being of our end users in mind and paramount in all our design decisions. Ultimately, this aligns with both our personal and professional ethics including the University of Michigan Engineering Honor Code.

Sustainability

For our design problem, we want our design to be sustainable for our stakeholders in Nicaragua. We can examine the definition of sustainability in two ways: how effectively the production and management of the design will be integrated, and how our device will minimize costs and environmental impacts. Our requirements and specifications heavily consider the first definition of sustainability as we are limiting our design to a strict list of materials and production processes available around our target area. Failing to meet these requirements would make our design unsustainable for our users as it would lead to dependence on outside sources. The second definition that we outlined can be readily calculated by conducting an eco-audit on our design. The outcome of the eco-audit can provide insight on the environmental impact of the design, and we plan on conducting an audit on iterations of our alpha design to help guide us toward a sustainable solution.

Library

After reviewing our prior benchmarks and past literature again, after developing our final design concept, we addressed the following key points from literature:

- We utilized a more adjustable foot rest compared to many common footrests, since there is an additional degree of freedom in the knee flexion that is not present in many low-cost footrest solutions
- Our materials are much more accessible and manufacturable than the benchmarked designs, notably in the limited use of welded and/or bent metal tubing, with increased use of common off-the-shelf wood products and metal bars. This enhances the accessibility of the product in areas where industrial equipment is not present.

- Our literature review raised the question of adjustability to support proper posture and musculoskeletal orientation. While our support device does not address all concerns, emphasis on allowing mobility and fine adjustment in the height, width, foot positioning, and knee flexion of the user provides many features that the stakeholders asked for to support the user better
- Standards on wheelchair sizing were used to develop a device that is adjustable within the most common wheelchair sizes, allowing for maximum adaptability. Sizing is also able to be easily changed depending on the user during manufacturing for a custom sizing fit.

Literature Review

This section will discuss our comprehensive literature review of benchmarks, outline existing research and engineering standards, and review our current needs for information from this point forward.

Benchmarks and Existing Solutions

In our research, we came across a few existing devices that perform similar functions as what we are trying to design. These benchmarks provide a good method of refining our problem definition by showcasing the state of the art.

Figure 3. Two-part foldable wheelchair footrests. Provides adjustability for each foot while sacrificing stability compared to a single platform footrest [9].

Figure 3 shows one existing solution: two separate, foldable footrests that are attached to the bottom front of a wheelchair. This design incorporates a degree of adjustability, but at the cost of a single stable platform for resting feet on. The foldability allows for the footrests to be stowed in case of storage or transportation of the wheelchair, and this specific product includes heel loops to help secure the position of the feet.

Figure 4. An integrated one-piece wheelchair footrest. Less adjustability per foot, but provides a secure platform for foot support [10].

A similar existing solution is shown in Figure 4. This wheelchair footrest mounts permanently to the structure of the wheelchair. This, combined with the single-piece design, provides a more structured and rigid surface that provides more support to the user's feet. This is especially useful in the use case of children with cerebral palsy; however, there is no way to address the issue of muscle spasms that may cause the children's legs to pull or push in different directions.

Figure 5. A wheelchair-integrated footrest with supportive sides. This specific product is an attachment meant for traditional wheelchair footrests. The side support that this device offers is relevant to our design due to the need of protecting our user's feet from moving parts of the wheelchair and keeping their body aligned [11].

Figure 5 shows a third existing solution of a wheelchair footrest. This design provides support and stability to the feet and holds them relatively securely in space. This is especially useful for children with muscle spasms or misaligned legs; the box-like design prevents the feet and legs from moving excessively. This sort of support is similar to what Donn Hilker suggested for our project as well, since it prevents the children's feet from moving too far off center.

Figure 6. Two images of Ankle-Foot Orthotics (AFOs). When initially exploring the design problem, the focus was on correcting the user's ankle and feet positions similar to these AFOs. However, after speaking with primary stakeholders, corrective measures were deemed out of the scope of the design problem [8].

The two images in Figure 6 are examples of Ankle-Foot Orthotics (AFOs), which are devices worn on the lower part of the leg that hold the foot/ankle system in place. FNE uses them to treat children who have misalignment in their lower legs; use of these devices helps to prevent the worsening of symptoms and further degeneration of the musculoskeletal system in that specific area. However, while lessons can be learned from these devices, according to FNE, it is not necessary to provide AFO functionality in the final footrest design.

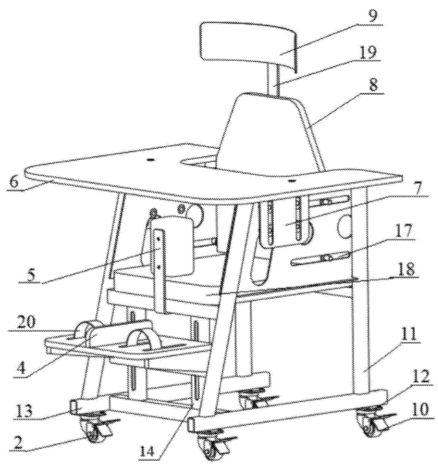


Figure 7A. Patent for device that constrains feet and hips to align ankles to promote alignment of hips and feet [12].

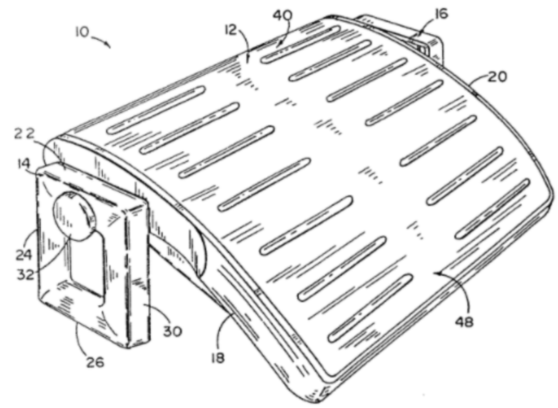


Figure 7B. Patent for footbed that can be adjusted to different angles and heights via a hinge mechanism [13].

We also came across patents for devices that are trying to solve similar problems to the one that we face. Figure 7A shows a chair with an integrated footrest that can be used to constrain the feet in place and promote proper musculoskeletal development in children. This device is ideal for children in lower stages of CP and who may not already have extensive musculoskeletal degradation. Figure 7B shows a patent for a standalone footrest that can be adjusted in both height and angle. This device aligns with our goals of creating a relatively simple footrest, but its standalone nature makes it conflict with our goal of integrating a footrest with existing wheelchairs.

Existing Literature and Research

One of the first sources of information we received was the final report from an ME 450 team last semester who worked on a postural support for chairs for children with CP. While that team tackled a slightly different problem from ours, this report provided a lot of useful background on cerebral palsy that helped us with our initial learning and problem definition [14].

Another piece of literature we used for initial problem understanding was an article on the effects of cerebral palsy on the feet, specifically with regards to children. Since our problem is to create a footrest or similar solution for children with CP, this was an important article in understanding the specifics of the challenges children with CP must face [15].

This article provided a breakdown on how orthotics can be used to help cerebral palsy patients correct musculoskeletal deficiencies. The most relevant type of orthotics described are ankle orthoses. These are the quintessential CP orthoses, and can include types such as dynamic (for walking), solid (for providing knee stability when standing), and hinged (these include a mechanical joint to aid in mobility) [8].

To help identify the types of seats that our design must accommodate, we referenced this web article which outlines typical wheelchair sizes and methods for determining proper wheelchair sizing for users. Although our design is aiming to be compatible with other seating arrangements outside of wheelchairs, this article was helpful in determining our requirements and specifications for the dimensions of our design [16].

Aside from these literature sources described, we have also examined global standards relevant to our design problem. Specifically, the standards we examined were published by the International Organization for Standardization (ISO) and are described in further detail in the next section, "Relevant Engineering Standards".

Relevant Engineering Standards

As part of our literature review process, we examined global health and mobility standards developed by the International Organization for Standardization (ISO) to further our understanding of the design requirements that our foot support should fulfill. We were unable to find specific health and mobility standards pertaining to Nicaragua, our targeted region of interest; however, we have decided to use relevant standards from the ISO to ensure that our design fulfills basic safety and stability requirements for our users.

One relevant series of ISO standards is ISO 7176, which describes design requirements relevant to wheelchairs. These standards outline the testing and determination of mass, size, loading, and stability requirements for wheelchairs along with specifications for electrical wheelchair components. Due to the nature of our project and the limited access of electrical instruments for our users in Nicaragua, our focus when examining these standards omitted analysis of electrical components as they were deemed irrelevant to our design problem. Two standards that we did examine as part of ISO 7176 were ISO 7176-5 and ISO 7176-8, which outlines the determination of mass and dimensions of wheelchairs and the test methods for static and impact loading of wheelchairs respectively.

ISO 7176-5 describes several use cases for manoeuvrability of wheelchairs and the relevant dimensions that wheelchairs must satisfy to satisfy these use cases. One specific use case highlighted in this standard describes changes in the ground elevation, specifically related to ramps. Figure 8 shows three scenarios wheelchair users will encounter during use, and how the dimensions of the wheelchair must satisfy all of these scenarios to ensure smooth and safe travel for the user.

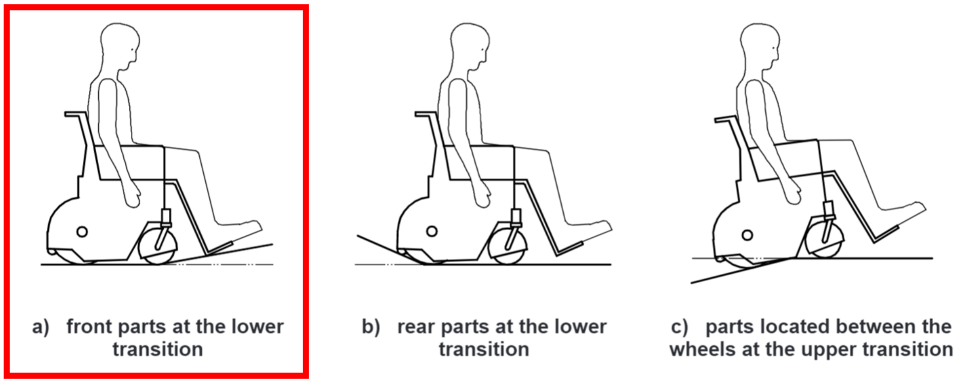


Figure 8. Three different scenarios wheelchair users may encounter during regular use. When focusing on footrest positioning, figure (a) is especially important because collision of the ground and the footrest must be avoided when encountering a ramp as shown. To combat this, sufficient ground clearance between the foot support and the ground must be met to avoid ground collision [17].

As shown in Figure 8 above, our footrest design should ensure sufficient ground clearance of the footrest should be met to avoid collision with the ground during elevation changes. According to ISO 7176-5, ground clearance should be greater than or equal to 50 mm for lower weight occupants, and 40 mm for middle/upper weight occupants (see Appendix A). Although we currently plan for our footrest to have varying amounts of adjustability related to ground clearance, it is still important to note these critical values to ensure comfort and safety of our users (see “Requirements and Engineering Specifications” for more details).

Aside from use cases for wheelchairs, ISO 7176-5 also describes the optimal angle for foot-leg positioning in the footrest and the footrest position itself. According to this standard, the feet should have a 90° angle to the legs for all occupants to promote healthy ergonomics and comfort (see Appendix A). In the case of our design, we plan to allow feet-leg angle adjustability outside of 90° due to varying positions of our users’ ankles, which is reflected in our requirements and specifications.

While ISO 7176-5 describes the determination of dimensions relative to wheelchairs, ISO 7176-8 provides an overview of testing procedures for static and impact loading of wheelchairs and their components. Appendix B shows loading scenarios for wheelchair footrests in the normal (downward), upward, and impact (horizontal) directions experienced during regular use. These loading conditions encounter different magnitudes of force, and as such require different testing scenarios to determine viability of the footrest. We plan to conduct similar force benchmarking and testing on our design to verify its viability for our users, and have included these considerations in our engineering specifications (see “Requirements and Specifications” for more details).

One final standard relating to wheelchair benchmarking was ISO 7176-19. This standard describes the use of wheeled mobility vehicles on motor vehicles, which was thought to be relevant to our use cases pertaining to taking our footrest design on a bus (see “Use Cases” for more details). FNE International highlighted this use case for our design, though considerations regarding public transportation in Nicaragua are very different from the United States. After examining this standard, we deemed it to be irrelevant to our design purposes, as it relates more to the securement of fully functional wheelchairs and the user to motor vehicles as opposed to specifications of wheelchair components and footrests specifically. It is important to note that this standard describes different belt restraint locations for the wheelchair and that proper contact of the belt restraint and the user’s lower pelvic region (among other contact areas) of the user must be met to ensure proper securement [18]. Although this standard may not be applicable to our current design problem due to the cramped nature of buses in Nicaragua, it is important to note that our design should still allow for this contact to be made for safety purposes.

Aside from examining standards related to commercial wheelchair use, we also examined waterproofing standards provided by ASTM International. The standard D7017-20 provides instructions on different conditions of water exposure and testing strength values for materials exposed to water [19]. Although not all aspects of the standard may be applicable to our design, we will keep them in mind when designing and will likely conduct testing based on procedures described in this standard and materials we intend to use.

Requirements and Engineering Specifications

To create well rounded and detailed, verifiable requirements, this section outlines our requirement generation process, use cases, and requirements and specifications.

Requirements Generation Process

The requirements generation process started first with initial background information research and meetings with major stakeholders to understand broad needs. Feedback, literature, and benchmarks were found and discussed with stakeholders, formed into common day-to-day use cases, and generated into stakeholder requirements and specifications. An overview of this process is shown in Figure 9 below.

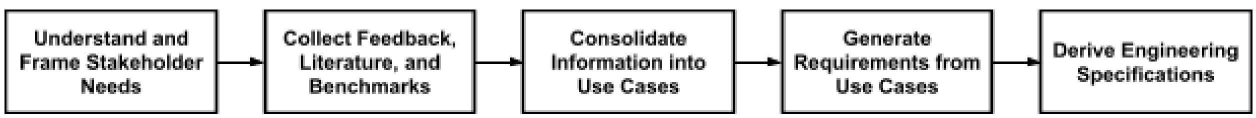


Figure 9. Requirements generation process adapted from the ME 450 Capstone Design Process Framework. Stakeholder needs were developed into various conceptual blocks to derive engineering specifications usable in design [20].

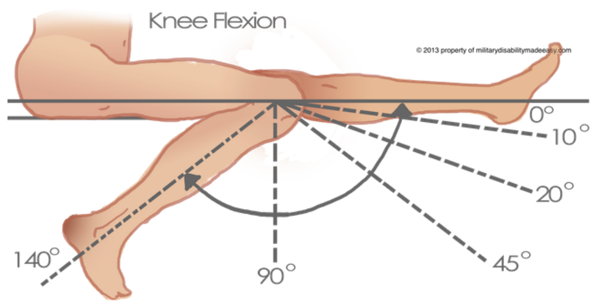
Initial meetings with stakeholders included:

- Donn Hilker, who discussed typical support device considerations for patients with challenges similar to CP.
- Discussions with the BLUELab EASE team regarding the current status and future goals of the BLUEeLab EASE project.
- Meeting with FNE to discuss the children's current state and any updates regarding the project and overall needs.

Upon analysis of our conversations with various stakeholders, it was clear that the approach to developing requirements had to be tailored towards sustainable implementation of a foot support device rather than developing a novel device. The particular challenge, as expressed by FNE, is a lack of advanced manufacturing resources and availability of supplies as typically found in developed countries like the United States. They desire a sustainable design that can be adjusted and used for many children with cerebral palsy in Nicaragua in the future, aside from the two girls we are designing for currently.

Definitions of Joint Angles and Considerations for CP

Designing a footrest for patients specifically with cerebral palsy presents multiple unique considerations. Firstly, due to varying levels of spasticity in the legs, some children have different natural leg and ankle positions based on how their musculoskeletal system has developed. To accomodate for varying spasticities, knee flexion and ankle flexion (dorsiflexion and plantarflexion) are defined in FIgures 10A and 10B below for use in engineering specifications.



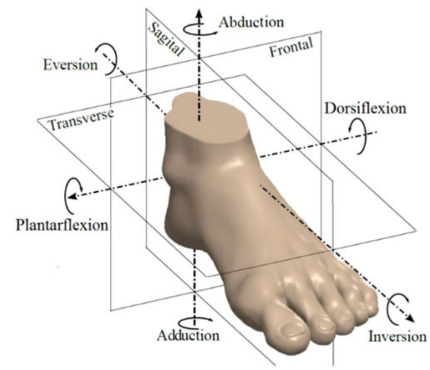


Figure 10A. Knee flexion diagram. Knee flexion angles should be considered when determining range of footrest. End position of the foot can impact knee flexion, muscular strain, and therefore comfort in the chair over time [21].

Figure 10B. Ankle planes of motion. The footrest in our case may focus primarily on adjustability for plantarflexion and dorsiflexion based on images from FNE, however they have indicated this is not needed. Children have widely varying degrees of ankle flexion [22].

Foot and leg deformities, along with abnormal neutral ligament positions, are commonplace. A classic 90-90-90 hip-legs-ankle position, as shown in Figure 11 below, may be uncomfortable or unattainable, so adjustability with condition severity and with child size is required.

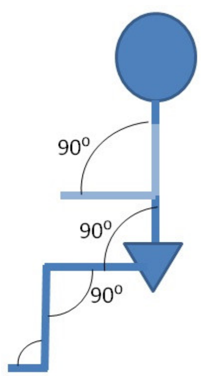


Figure 11. Typical 90-90-90 posture, widely regarded as the de-facto “correct” posture [23]. While correct posture, this is not always the most feasible. For children with musculoskeletal disorders, sitting in their chair all day (12-18 hours in many cases) can be challenging especially if proper cushioning and ergonomic support is not provided [24].

Use Cases

Before developing our requirements and specifications, we felt it was useful to explicitly define our use cases. While some use cases are similar, variations on use cases are included as they have unique challenges that should be addressed. Our primary use cases include foot support usage indoors and outdoors in both a wheelchair and in other (non-wheelchair) chairs in the home.

FNE specified that they want to “get the kids out of isolated environments”. They intend on using the footrest in the market, at school, and during longer distance transport, many times on buses. Additional common challenges FNE/SPTLN disclosed were enabling the children to sit in normal chairs, bus and vehicle transportation, physical strain on young and elderly caretakers, sleeping, and self-esteem issues of the children. Table 1 below specifies the most important use cases based on our stakeholder input and literature research.

Table 1. Primary use cases for adjustable foot supports. Considerations and challenges encompass main points described by FNE, SPTLN, BLUELab EASE, and Donn Hilker.

#	Use cases	Considerations and Challenges
1	**At home in a wheelchair**	Ideally not leaving wheelchair often (1x-2x/day) and are comfortable in one chair all day in one position. Caretakers are many times elderly (difficult to move child). Sometimes children may sleep in wheelchair.
2	**At home in a different (ordinary) chair**	Slippage/sizing of other chairs and lack of proper support. Adjustability between different chairs or a self-supported form for legs and/or lower/upper torso would be ideal.
3	**On the bus in wheelchair**	Buses are very busy and may not be able to put wheelchair inside bus. Wheelchairs (and support) need enough space on bus.
4	**On the bus, not in wheelchair**	Busy, crowded. People may give seat up for girl and caretaker. Would need general support to keep posture. Foot support requires ability to be folded/transported on outside of bus.
5	**In the market**	Navigating crowds and enough rigidity/support to keep foot support positioning. Should be comfortable and durable for varying outdoor environments.
6	**At school (wheelchair or not)**	Being comfortable for a long time and easily adjustable if needed by teachers and caretakers.
7	**Being wheeled around in wheelchair**	Feet shouldn't drag on the ground or hit things while passing, potential rough roads going to school and outside of households. Feet shouldnt slide off either as is dependency with children with CP.
8	**Doorways/steps (ledge going in/out of building)**	3-4" high ledge going in/outside. May be common. Many times goes from dirt surface to tile/stone/concrete and vice versa. May also be this way going between rooms in house

9	**Getting into and out of wheelchair**	Must be rigid enough for child to have support and support should not be in the way of getting in/out of wheelchair. Stakeholders specified that it does not need to assist in getting them out of chair.
10	**Eating**	Must not impact on caretakers ability to feed or children's ability to eat. Ideally usable to sit at a table with family.
11	**Bathroom/Latrine Usage**	Ability to get on/off of a chair and must be easy enough to clean. Many latrines are outdoors.

Requirements and Specifications

The stakeholder requirements were created based on the functional considerations found throughout each of the use cases and considerations listed in Table 1 above. Common themes such as comfort, safety, maintainability, and sustainability were developed into stakeholder requirements along with any directly specified stakeholder needs. Specifications were developed to enable complete fulfillment of each currently defined requirement. Each specification is measurable or verifiable through measurement or usage. Table 2 summarizes relevant requirements and specifications culminated from our stakeholder analysis and research.

Table 2. Requirements and specifications. Status of specifications indicate maturity and confidence in requirement with stakeholder needs, and may indicate that review is required by stakeholders or a decision to include the specification is needed.

Requirement	Specification
Promote comfortable and proper foot and leg positioning.	Feet position shall adjust from 11" to 18" below the seat [16, 17]
	Feet shall not extend outside the width of the seat (Hilker, D., video call, September 28, 2021.)
	Use of the device shall score less than 3 on the Revised-FLACC Observational Pain Tool [25]
	The foot support shall adjust so the knee is extended from 60° - 90° of flexion [21]
	Foot shall be able to move a maximum of 1 inches in each direction with respect to the foot support
Can be used in indoor and outdoor environments	Material shall last at least 3 years without replacement when in use for an average of 16 hours per day (Cipoletti, M., McKenna, S., video call, September 28, 2021.)
	Material shall be resistant to water and UV damage [18]
Sourced via common and affordable materials	Devices shall be made from only common materials in Nicaragua such as wood, metals, canvas, cloth, sponge/foam, common scrap materials, vinyl, and velcro (Cipoletti, M., McKenna, S., video call, September 28, 2021.)

The device shall be manufactured via readily available methods in Nicaragua	All parts shall be manufactured with locally available skills and expertise
The device shall minimize cost	Device shall cost less than 100 USD
The device shall attach to multiple different chairs	Device should be attachable to chairs with widths ranging from 10"-18" [16]
The device should be easy to transport	The device should fit within a 9"x20"x20" box during transport
	Device shall weigh less than 10 lbs (based on broad standards)
The device should be easy and affordable to install and maintain	Maintenance shall require no more than 2 commonly available tools
	Exchanging parts of the device should require no more than 2 commonly available tools and take less than 10 minutes
	The device should take less than 2 minutes to install onto a chair
Device should be safe to use	The device should not plastically deform when subjected to 200 lbs in the direction parallel to the user's legs or 50 lbs in any direction perpendicular to the user's legs [26]

While all requirements are critical to the success of the final design, the stakeholders emphasized specified requirements. Important requirements include that the foot support must be:

a) comfortable,
b) sourced with common, readily available materials and manufacturing methods
c) should be easy to maintain and transport.

Firstly, the requirement for comfort was derived from the fact that the end-user will likely sit in the chair all day when not sleeping, and at times may even end up sleeping in the chair. Many chairs that children have in Nicaragua currently are improperly sized, do not provide the correct amount or type of support, and some do not currently have footrests. Comfort in the scope of this project can be mainly controlled by encouraging proper and comfortable foot positioning so that excess pressure is not applied to the legs and feet, causing pressure sores. The stakeholders continued to emphasise that they want feet secured into the foot support, so the feet are required to be relatively fixed, with only small movements allowed for comfort considerations. Usage on wheelchairs and normal chairs was desired. Additionally, creative usage of comfortable and hygienic materials so that pain ranked on the comparative pain scale is tolerable (less than three).

Due to the project location in a low-income country, resources and advanced manufacturing skills commonly used in the United States are not available. Therefore, many solutions developed in the United States are too costly and unsustainable for use in Nicaragua. Material availability is much more limited and manufacturing capabilities are fairly basic, on the level of a home shop. The use of locally available materials was included as an engineering specification, and manufacturing methods were limited to any local skilled and unskilled labor, based on FNE feedback. This typically includes metal and wood workers and limited 3D printing, but no advanced machining. Due to low per-capita income, cost was limited to $55, comparable to a lower-cost footrest in the United States. This cost is up for review by stakeholders since they have more knowledge of current financial situations in-country.

Lastly, the maintainability and transportability of the device itself are of high importance. Many children are taken care of by grandparents and working parents. The foot support must be easy to adjust and minimize any heavy lifting or excess maintenance required by elderly caretakers. It also must be easy to fix with limited numbers of tools due to resource constraints and to make the design practical. The ergonomics of transporting the device are equally factored in, and a 9”x9”x24” maximum folded size and a maximum weight of 10 lbf was specified in case the device needs to be removed during transportation on a bus or other situations.

All other requirements and specifications are necessary for a sound and safe design. Mechanical failure will be prevented by designing the support to typical weight ranges of 200 lbs and lateral strength is required to sustain 50 lbs load in case of impacts or foot movement. Since the device should last a long time especially in a low-income country, resistance to UV and water degradation is required. Degradation may impact usability and require a new foot support in the near future, which is clearly unacceptable.

Problem Analysis

The primary engineering fundamentals and challenges that we anticipate can be divided into three categories: structural design, safety and comfort, and manufacturing and materials. These three areas, while not fully unique, represent a wide array of considerations which will drive our design. In general, we do not anticipate the need for any special equipment, technical assistance, or logistics in order to overcome our major problems. The only exception to this is a better understanding of the logistics surrounding material acquisition and manufacturing in Nicaragua so that our solution can be fully locally sourced and made.

Our design must be structurally sound. As put forth in our final requirement and associated specification, our design must be able to withstand significant loads without deforming or moving much, and any failures of the device must be easy to address as put forth in our specification about maintenance. This consideration will drive the geometry of our design as well as the material choices we make. From our knowledge of the mechanical behavior of materials, we know that deflection is dependent on the load applied, the elastic modulus of the material used, and the geometry of the device. In our design, we will be able to tailor these properties to ensure minimal deflection or structural failure. This consideration is also related to our requirement that the device must be easy to transport as this is closely tied to the geometry of the solution. In this area, we expect the primary challenge to be designing a device which is strong enough to withstand the loads we might expect while being small enough to be easily transported. To address this challenge, we plan to leverage our knowledge of statics to do hand calculations to find an optimal configuration to allow our design to be both strong and portable.

Additionally, our design must be safe and comfortable for the end user. This is reflected in our specifications regarding foot positioning, adjustability, and safe use. In this area, our design will be driven by factors which allow us to place the user's feet in the optimal position and adjust to reflect changes in this optimum. In this area, we foresee our primary challenges to be the adjustability of the foot support and its ability to adapt to a variety of different users and seating arrangements. To overcome these challenges, we intend to employ ideation best practices and thorough prototyping and testing to ensure our solution works properly in all the expected use cases.

Finally, our design must use only materials and manufacturing processes which are affordable and readily available in Nicaragua. In order for our solution to be affordable and sustainable, it must be produced entirely in Nicaragua so that the users are not dependent on external or international sources. This is reflected in our specifications related to materials, manufacturing, and cost. The primary challenge we anticipate in this area is understanding what resources are available in Nicaragua and limiting ourselves to only those materials and processes as the resources available to us in Michigan are different. To overcome this challenge, we plan to repeatedly meet with stakeholders who are either in Nicaragua or who frequently travel there to ensure that we understand what is available. We also plan to be very strict during concept development and evaluation and pursue only ideas which could be made from the materials and processes our stakeholders tell us about. As such, our design will be driven by the materials and manufacturing information given to us by our stakeholders.

In addition to the engineering considerations explained above, some of the challenges that we expect to face include a lack of access to our end users, ensuring that our solution is low cost, and testing our prototypes in a representative environment. Because our end users are in Nicaragua, we cannot physically visit and observe their conditions or speak with them. This also means our understanding of what the environment our end users are in is limited. To mitigate this, we plan to meet with members of FNE and SPTLN frequently as they directly meet and work with the children in Nicaragua we are designing for. For testing, we plan to emulate the environment that they describe to the best of our ability. We foresee ensuring a low cost solution to be an obstacle as it places a significant constraint on the materials and tools we are able to use to create our final design. To address this, we plan to stick very closely to our cost specification and use only materials which are affordable and readily available in Nicaragua.

Concept Generation

In order to develop our alpha concept, we employed individual brainstorming, then morphological analysis, and finally design heuristics before converging to a single design. The result of our brainstorming, morphological analysis, and design heuristics was more than 100 initial ideas which we then developed and narrowed down in three phases before using a Pugh chart to determine a final alpha concept. Figure 12 outlines this process.

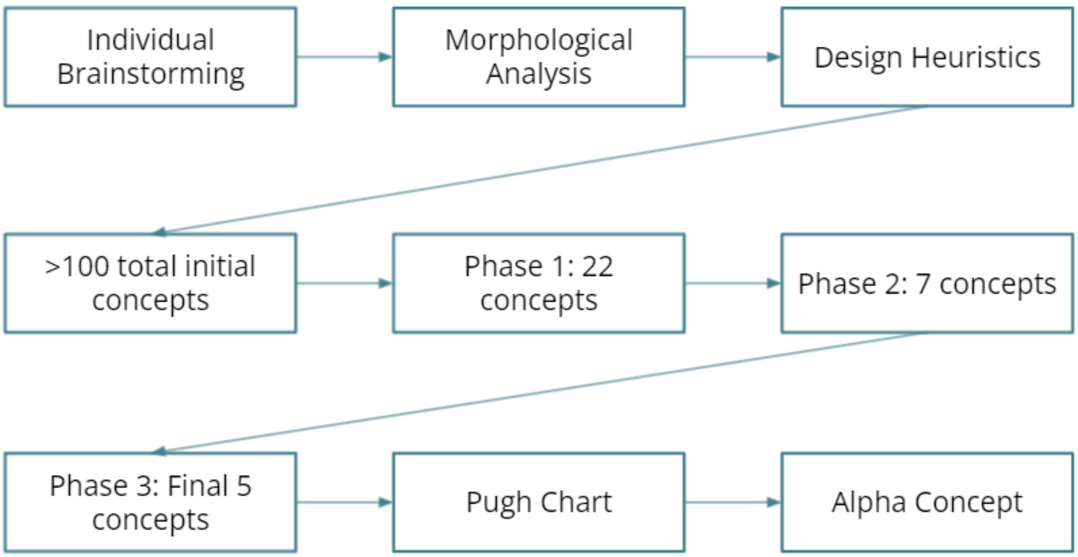


Figure 12 . An outline of the process we used to generate our alpha concept.

Brainstorming

The first step we took to generate concepts was brainstorming. We began with individual brainstorming before coming together to review the ideas generated. While brainstorming, we were each sure to defer judgement on any concept and encourage wild ideas even if they would obviously not be feasible. These non feasible ideas helped to spur further individual thought, even though they were quickly removed during phase I of our concept selection. During individual brainstorming, each of us generated between 10 and 25 unique ideas, although there was some overlap between our ideas. Several of these concepts are shown in Appendix C. The concepts generated vary in completeness in addition to being unique; some ideas represent full solutions while others are simply ways to perform one of the functions a final device will have to. Figures 13 A-C show a few different ideas generated through brainstorming to highlight the divergent thinking we practiced at this step.

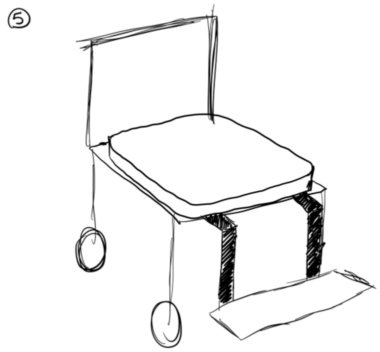


Figure 13A. Idea 52: Detachable seat with foot support. A seat pad is attached to a foot support board and can be placed on any chair.

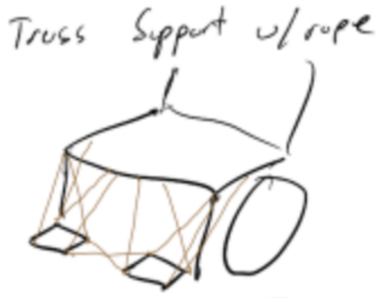


Figure 13B. Idea 17: Rope truss. A truss made of rope is used to hold a pad or pads on which the user's feet rest. The device can adjust by changing the length of rope used.

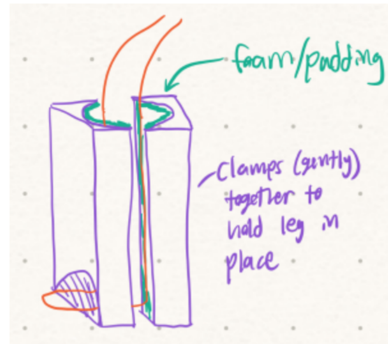


Figure 13C. Idea 76: "Massage chair" gripping footrest. Two sets of rigid clamps lined with foam or other padding would gently hold the user's legs in place.

In addition to simply being unique, these ideas highlight the varying levels of feasibility and completeness in our initial brainstorming concepts. For example, the rope truss was later deemed infeasible as it would likely not be strong or stable enough and would be significantly more complex to make and adjust. The "massage chair" gripping footrest, while more feasible, represents an incomplete solution as features like adjustability and connection to a chair are not clear.

Morphological Analysis

After performing individual brainstorming, we used morphological analysis to generate more ideas. We chose to utilize this technique as we felt any viable solution would have to fulfill three primary subfunctions: adapting to different chairs, adjusting the height of the foot support, and supporting the user's feet. Since these subfunctions were clear and easily defined, we felt morphological analysis would be a helpful and appropriate strategy to use. Table 7 in Appendix C shows the morphological chart we used with each subfunction and associated concepts. In the table, each concept is labelled with an uppercase letter, lowercase letter, or number to make it easier to keep track of the combinations used as complete ideas. In theory, the chart we used could produce 120 unique complete designs. One such concept is shown in Figure 14.

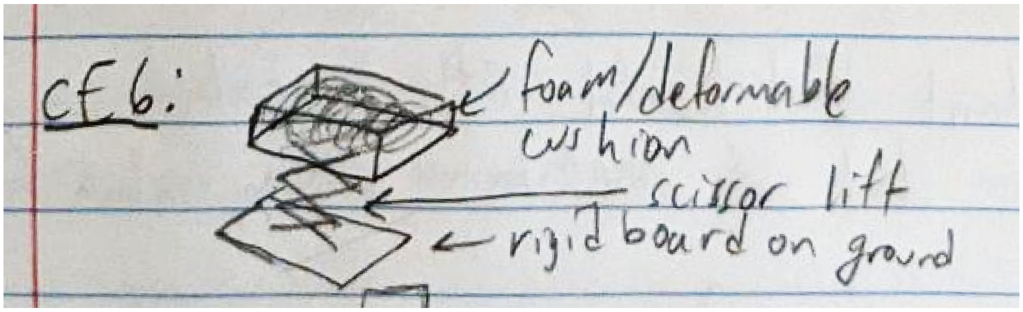


Figure 14. Morphological Analysis combination cE6: a deformable board with a rigid base for supporting the user’s feet (concept 6) with no direct attachment to the chair (concept c) that uses a scissor lift to adjust height (concept E).

Design Heuristics

After individual brainstorming and morphological analysis, we used design heuristics to further diverge and generate more concepts. We chose to use design heuristics as this is a technique many of us have experience and are comfortable with, and design heuristics tend to be effective when beginning with a set of existing ideas like we were. We chose to practice design heuristics individually while in a group so that we could generate concepts more quickly while also allowing for collaboration as needed. Some of the cards we used include Card 62: Stack, Card 15: Attach product to user, Card 7: Align components around center, Card 61: Slide, Card 42: Make components, attachable/detachable, and Card 74: Use repurposed or recycled material. Sketches of several concepts generated using design heuristics cards are included in Appendix C. Figures 15A and 15B show two examples of concepts generated using these cards.

Card 15: Attach Product to User

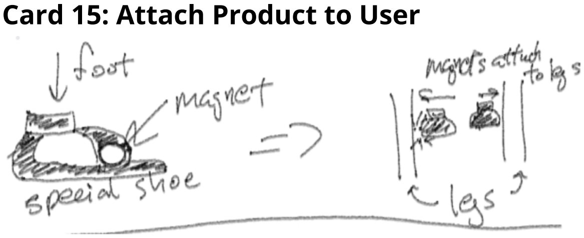


Figure 15A. Idea 109: Magnetic shoe. The user would place their feet inside a pair of magnetic shoes to keep them in the proper position.

Card 74: Use repurposed or recycled material

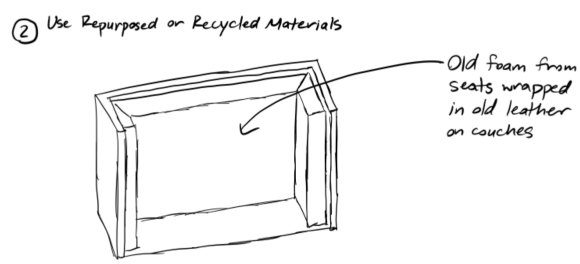


Figure 15B. Idea 104: Foot support made of repurposed or recycled material. This concept reflects a standard “boxed in” foot support made of different materials.

Some of the concepts generated using design heuristics represent a small change from an initial idea on which the concept is based, as shown in Figure 15B. At this stage, we were still committed to divergent thinking, so even more complex designs like Idea 109 shown in Figure 15A were still considered.

Social Context in Concept Generation

Throughout our concept generation, the context in which we were designing was considered, primarily in the form of our use cases and requirements. Every idea generated was made with at least a subset of the requirements in mind. Not every idea addressed everything in the end user's environment, particularly during brainstorming when wild ideas were encouraged. During brainstorming specifically, the full context of the problem was held secondary to the functional requirements of the device; at that stage we wanted to encourage wild and divergent ideas even if they would be clearly infeasible in the context we are designing for.

Concept Analysis

When analyzing our design concepts, we divided our selection process into three phases as shown in Figure 12 . In this section, we outline our convergence process for analyzing our designs and how we managed to consolidate our dozens of designs into one final design.

Phase 1/2/3 Convergence

To select a final Alpha design concept, multiple phases of convergence, iteration, and co-evolution of design concepts were performed. Prior to performing convergence activities, a FAST (Function Analysis System Technique) diagram was created. We used the FAST diagram as a tool to understand the root problems we need to solve and understand what aspects of design are important. Throughout the convergence process, we analyzed our stakeholder use cases and requirements, while allowing room to iterate and improve the quality of designs as they passed to a later phase.

We consolidated 112 concepts from the divergence concept development stage, and narrowed them down to 22 concepts in Phase 1. This included eliminating unfeasible ideas, consolidating similar concepts, and improving upon designs by combining them with other design concepts to create higher quality ideas. Even if an idea could not fulfill specific requirements, we included them due to the potential to iterate and use multiple ideas to fulfill requirements. We then performed Phase 2 to converge to seven potential alpha concepts, primarily by combining and developing designs to better fulfill our requirements and address the functions in our FAST diagram. To achieve a list of five unique ideas, the seven concepts from phase two were discussed heavily with the group, again using our FAST diagram, requirements, past stakeholder research and use cases. Throughout each phase of concept analysis, the group used engineering intuition and information from stakeholders, bouncing ideas and concerns off each other in both technical and social context aspects to fully understand the potentials and drawbacks of each design.

FAST Diagram

Our FAST diagram outlining our high and low-level functions is shown below in Figure 16. This was used throughout concept analysis to evaluate functionality of our designs and iterate concepts into higher-quality ideas.

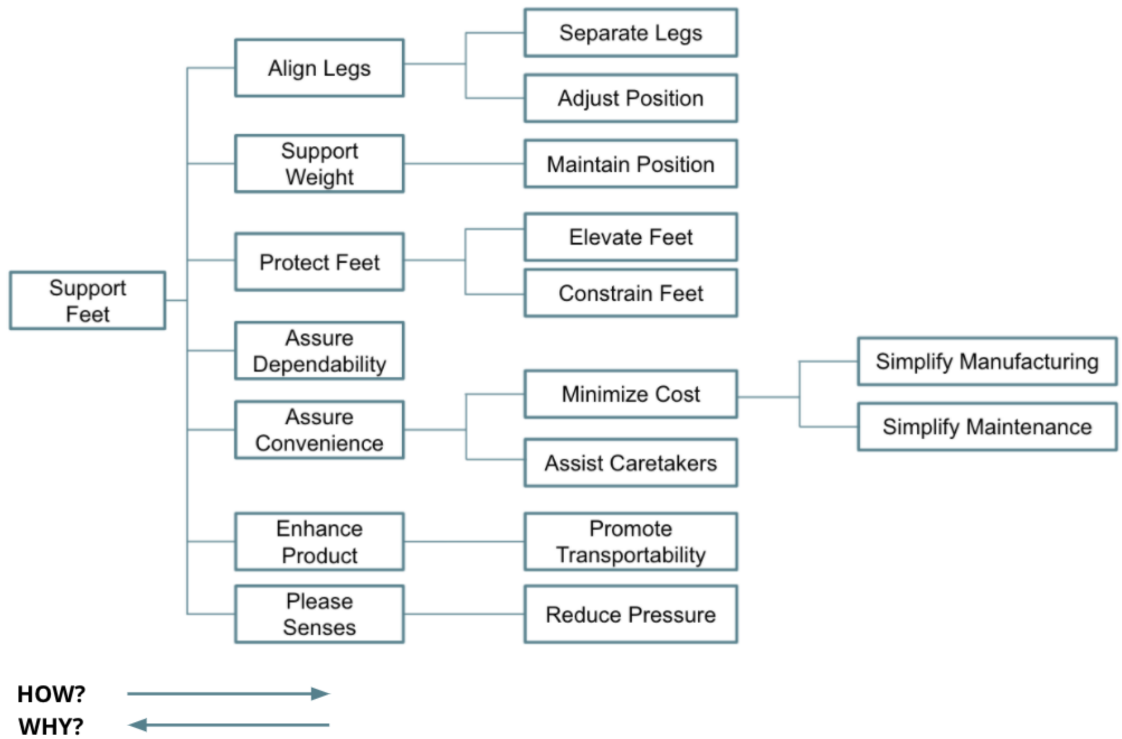


Figure 17. FAST (Function Analysis System Technique) Diagram outlining the functional decomposition of the adjustable foot support device. Moving to the right, overarching functions are broken down into Main Primary Functions (second column from left). Functions are further broken down to explain "how" the device would satisfy a function from a functional perspective, eliminating considerations of "form". Moving to the left, the chart explains "why" we need a specific function.

Phase 1

Phase 1 of concept selection narrowed our original 112 design concepts to 22 viable concepts. The primary considerations for Phase 1 were eliminating unfeasible ideas and removing any duplicate concepts that may have appeared as a result of individual brainstorming. Since this was the first convergent step after the initial concept generation, the elimination of unfeasible ideas was especially important and served to dispose of a significant number of concepts immediately. After this first cut, each concept was judged on whether a more fleshed-out version would be able to fulfill our requirements and the functional needs given in our FAST diagram.

A number of similar concepts were identified. Table 3 below outlines various similar concepts.

Table 3. A select variety of similar concepts consolidated from Phase 1 convergence. For the sake of clarity, one representative picture was selected that encompasses similar ideas in a group. Not all idea groups are shown, however the major concept groups are shown.

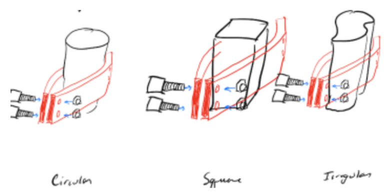
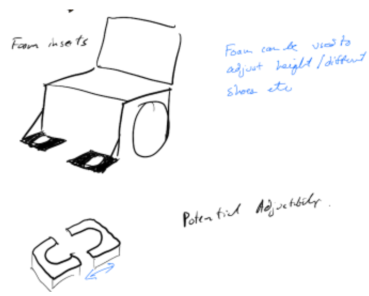
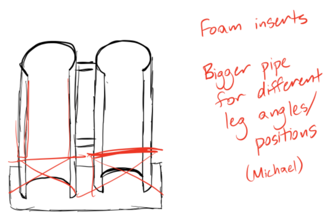
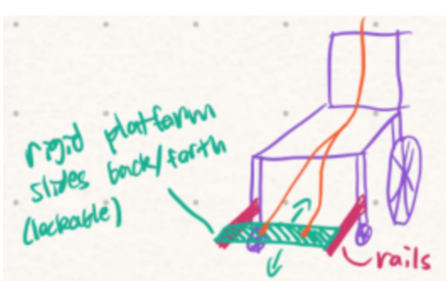
Concept Group	Picture	Short Description
Elastic Clamp		Elastic region metal clamp (metal bends around the chair attachment).
Foam Inserts		Foam foot "insert" to insert feet into that conforms like orthotics or shoe inserts.
AFO-Type Support Device		Hard "AFO" type device that holds legs and feet in position/angle but is supported and immobilized by chair. Can use half PVC Pipes for legs.
Rocking Roller Device		Foot support that is similar to a foam roller but with a round section that can be placed on ground for varying feet positions and possibly heights. Latches onto the chair.
Tray table		Wooden tray table similar to the example construction, connects to legs.

Table 3 Continued

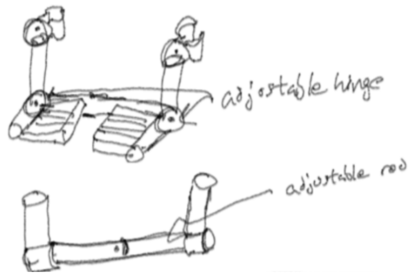
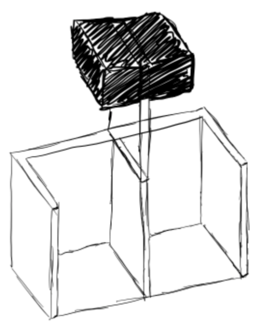
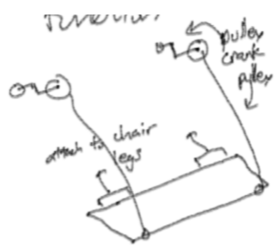
Concept Group	Picture	Short Description
Telescoping rods with footrests		Telescoping rods that attach to chair legs. Joints allow for angle adjustability. Feet could be boxed in.
Straight slot support		Slots that allow a flat plank to adjust up and down. Does not have to be adjustable for individual feet, could be that backboard that adjusts. Slot adjustability is the key idea.
Box footrest attaching to seat		Platform which has the footrest attached as shown. Platform attaches to the chair seat for securement. Boxes in person's feet but has a divider in the middle to keep feet separate for better posture and has a pommel to keep legs separated at the knee.
Strap support holder		Rod that has built in holes for straps that hold legs and feet in place, leads to a telescoping platform. Pommel can be added to the clip.
Detachable seat with foot support (VS - 5)		Seat with a foot support that can be detached and placed onto different seats. Seatbelt potentially could be added and the device can strap to seat for safety.

Table 3 Continued

Concept Group	Picture	Short Description
Adjustable rod support		Simple rod foot support with pitch adjustment. Adjustability in pitch and length allows scalability for multiple children.
Pulley footrest		"Design Heuristic: Substitute way of achieving function" Pulley mechanism to adjust height/angle of footrest

Phase 2

Phase 2 of concept selection brought our 22 concepts from Phase 1 down to seven concepts. For this phase, we relied heavily on our requirements and FAST diagram to narrow down our concepts further. Primary discriminating requirements used at this stage were manufacturability in Nicaragua and durability over a long period of use. After eliminating concepts that met the fewest requirements, we grouped concepts together based on their overall design and the main functions that they performed, and incorporated any concepts that were not full designs. Once these main groups were set, we combined different aspects of concepts within groups to end up with one enhanced concept for each group, which gave us a total of seven concepts.

Phase 3

Phase 3 of our selection process reduced our seven initial concepts down to five. This was done by combining existing ideas and by ensuring fulfillment of requirements and desired function via the FAST diagram. We then refined the more viable concepts by adding more detailed sketches and elements of the design. These final five concepts were then used for our final concept selection via a Pugh chart.

Our final five concepts are shown below in Figures 18 -21 .

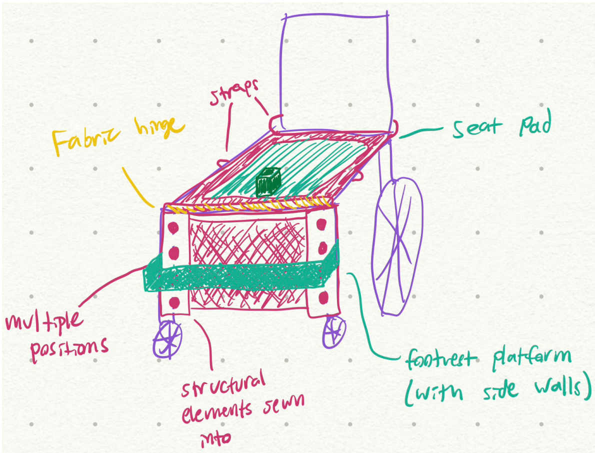


Figure 18. Concept #1: "Pillowcase" seat liner footrest

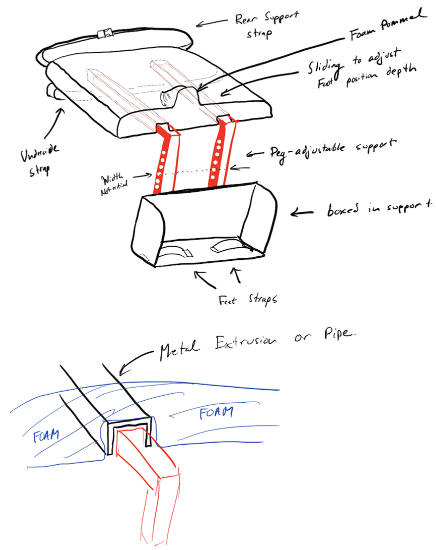


Figure 19. Concept #2: Seat-supported foot support

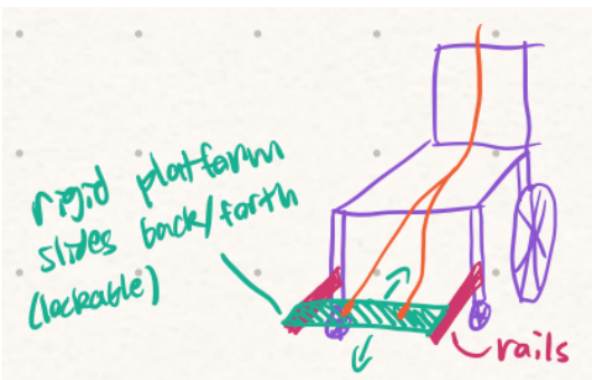


Figure 20. Concept #3: Tray Table

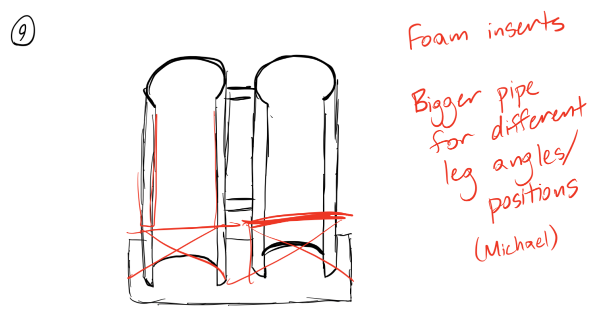


Figure 21. Concept #4: Tubular Support Footrest

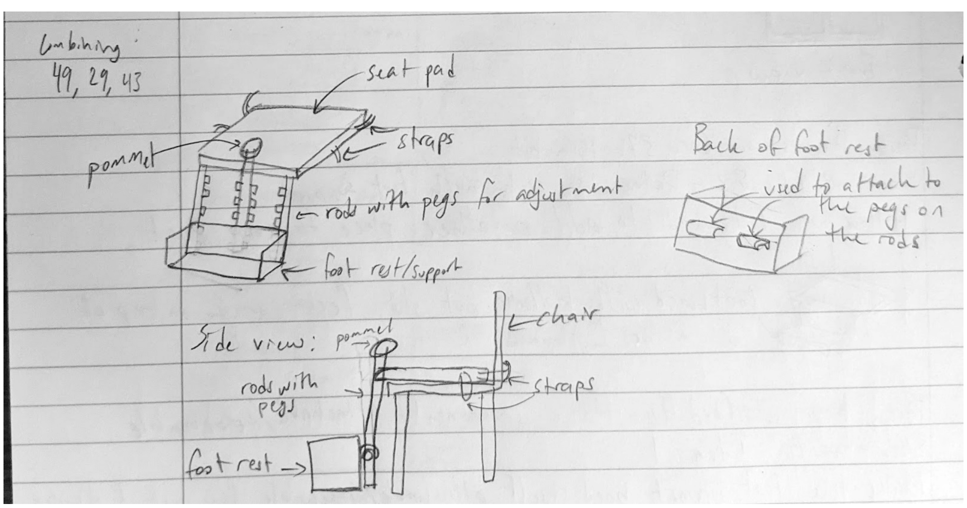


Figure 22. Concept #5: Box footrest with "ladder" adjustability

For Phase 3, we took our seven concepts from Phase 2 and compared them again to our requirements and FAST diagram to pick the best five concepts that fulfilled those needs. We also combined a few of the concepts. After that, we refined the concepts themselves and added more detail:

- Concept #1 (“Pillowcase” seat liner footrest) was chosen because it fit our requirements’ needs of durability, ease of use, and manufacturability in Nicaragua. The one-piece design allows for the footrest to be taken off of a wheelchair and put onto a normal seat, which contributed to our stakeholders’ expressed want of flexibility and a greater ability for the user to participate in social activities. It also provides easy height adjustability for the user.
- Concept #2 (Seat-supported foot support**)** had many of the same advantages as Concept #1, but had the added feature of being more compact and rigid. Those factors are important in transportation and in withstanding the everyday loads the footrest will be under.
- Concept #3 (Tray Table) had the advantage of durability and easy adjustability, but doesn’t fulfill other requirements like easy maintainability or attaching to multiple chairs.
- Concept #4 (Tubular Support Footrest) constrains the legs well and can be designed to be comfortable. It also had the potential to be able to be attached to multiple chairs beyond the patient’s wheelchair, although that would need to be added to the existing concept.
- Concept #5 (Box footrest with “ladder”) has a box foot support to constrain the movement of the patient’s feet and an easy adjustable “ladder”-based adjustment system. It fulfills our requirements of being easily adjustable and able to be attached to other chairs, but has the risk of being not as durable as the other options and is potentially not manufacturable with the resources available to our stakeholders in Nicaragua.

Reflection

Working through the concept generation selection process virtually had its advantages and disadvantages. We started our concept generation process with individual brainstorming sessions. We gave everyone time to develop a minimum of ten concepts on their own and then came together to share our ideas. Each of us explained our concepts to the group and we took note of suggestions given by other team members for later ideation sessions. After developing a large number of concepts, we all used design heuristics to iterate on the concepts we had already developed. Using the design heuristics for our last ideation session helped us exhaust the design solution space.

The virtual concept selection process proved to be more difficult than the virtual concept generation process. For an in-person concept selection process, we would have been able to use Post-It notes to write down our concepts and categorize them based on their style and function. This would have made the process quicker as it would be easier to visualize. Virtually, however, we had to use a spreadsheet to organize our concepts, which took time to set up and was a tedious process. It also took longer to go through each concept as we could not have them all in front of us at the same time. In the future, we would work through the concept selection process in person to make it quicker and more productive.

Preliminary Alpha Design

The alpha design concept was decided based on our Pugh chart decision matrix results, which was heavily reliant on how well we felt the design satisfied our given stakeholder requirements. Since the key goal is to make a sustainable (affordable, manufacturable, and environmentally friendly) foot support, special care was taken to evaluate the social context in which our alpha design would be used. We considered comfort considerations, caretaker needs, affordability/practicality in material selection, manufacturability in Nicaragua, maintainability, and many other needs during deliberation. The Pugh chart in Table 4 below outlines the scoring results of our deliberation for each design concept with respect to each requirement.

Table 4. Pugh decision matrix for alpha design selection. Design sensitivity gives a weight (1-3) for each requirement based on how much the requirement is anticipated to affect design changes. Scores of -1, 0, or 1, were given to a concept based on how well it satisfies a requirement based on the baseline.

		Concept				
Requirement	**Design Sensitivity**	**[Baseline] 1**	**2**	**3**	**4**	**5**
Promote comfortable and proper foot and leg positioning.	3	0	0	-1	1	0
Can be used in indoor and outdoor environments	1	0	1	1	1	0
Sourced via common and affordable materials	3	0	0	0	-1	0
The device shall be manufactured via readily available methods in Nicaragua	3	0	1	1	0	0
The device shall minimize cost	2	0	0	1	-1	-1
The device shall attach to multiple different chairs	2	0	0	-1	0	0
The device should be easy to transport	2	0	-1	0	-1	-1
The device should be easy and affordable to install and maintain	3	0	1	1	1	0
Device should be safe to use	1	0	1	1	1	0
	Summed Scores	**0**	**6**	**5**	**1**	**-4**

To develop a well-developed design, the Pugh chart proved useful for design selection by evaluating each design with respect to a baseline. It also served as an excellent tool to guide group discussion of how well each concept could potentially satisfy requirements. Concepts were evaluated between each other and how they emphasize certain requirements. For example, concept four scored well for positioning and comfort, and usability indoors and outdoors, however, due to concerns of PVC not being readily available or affordable, and not being easy to transport, the score was brought down.

The leading design (concept two) and second leading design (concept three) scored fairly similarly. Both appeared readily manufacturable and able to be made more safe, as well as were easier to install and maintain. Concept three was not believed to be as comfortable as the baseline. Attachability, while easy if implemented correctly, scored lower since this design was not as easily adaptable to multiple chair structures as the baseline, which is strapped on a chair.

Concept two ultimately scored highest due to a variety of reasons. It was deemed better to use outdoors due to better materials than the baseline, which extensively uses canvas. Foam padding can be covered with vinyl or another material, and is more easily replaceable than a stitched canvas design. Concept two uses multiple larger pieces of material that do not require significant labor, making the concept more manufacturable and accessible than the baseline. We also believed that it could be made safer to use since it consists of a more rigid structure than the baseline, and was more easily adaptable in form and between chairs than most concepts.

In selecting design concept two, we did not solely rely on the Pugh chart for our decision, however the concept was the highest scoring design. Extensive use of engineering intuition and discussion guided by formulating the FAST diagram, Pugh chart, and reviewing our requirements and stakeholder goals prompted us to believe concept two had the highest probability of providing safe, sustainable, and functional foot support for the children we are designing to.

Considerations and Discussion on Pugh Chart Methodology

Based on feedback and looking back on the concept analysis process, we took note of a few points that could improve the use of decision making tools.

1. Usage of a higher range of weights that emphasize certain requirements, rather than weighting requirements based on their impact on design, would be more accurate and better reflect our needs.
2. After stakeholder review of our final design, they agree with our decision based on the options, however we received more information that impacts multiple assumptions made during concept scoring. This would potentially impact final concept scores (for example, PVC pipe is available in Nicaragua, and we were overconstraining our designs to generally exclude plastics)

3. Sensitivities for concepts could be weighted 1, 3, or 9 to emphasize a true advantage over another concept, and provide a wider range of potential scores to better compare designs.
4. We noticed after feedback, that some weights and/or scores did not appropriately reflect the true intent of the Pugh chart. While the Pugh chart was still very useful in understanding relative advantages between designs, it could be improved significantly.

We propose a revised Pugh chart incorporating feedback in Table 5 below. When reconsidering sensitivities and scores, we hid the weights and scores to reduce the amount of bias when deciding concept scores, since we had previously selected a score. Concept two was still the resulting winner of the five designs.

Table 5. Revised Pugh chart from Table 4, based on suggestions for feedback. While a decision has been made for which concept to use, this is an additional exercise to understand design concepts and provide for further ideation when iterating the alpha concept.

		Concept				
Requirement	**Sensitivity**	***Baseline*** **1**	**2**	**3**	**4**	**5**
Promote comfortable and proper foot and leg positioning.	**9**	0	**1**	-1	1	**1**
Can be used in indoor and outdoor environments	**1**	0	1	1	1	**1**
Sourced via common and affordable materials	**9**	0	0	0	0	0
The device shall be manufactured via readily available methods in Nicaragua	**9**	0	1	1	**1**	0
The device shall minimize cost	**3**	0	0	1	0	-1
The device shall attach to multiple different chairs	**9**	0	1	-1	0	1
The device should be easy to transport	**3**	0	-1	0	-1	-1
The device should be easy and affordable to install and maintain	**3**	0	1	0	1	0
Device should be safe to use	**9**	0	1	0	1	1
	Summed Scores	**0**	**37**	**-5**	**28**	**22**

Alpha Concept Details

Concept two, our selected Alpha design concept, is shown in an updated detailed sketch in Figure 23 below. Note the adjustability possibilities and flexibility in the foot support tube positions within/around the padded seat. The support device can be placed on any chair seat (wheelchair or regular chair). This eliminated the need to attach to a wide variety of chair structures, a primary technical concern that influences the stability of the device.

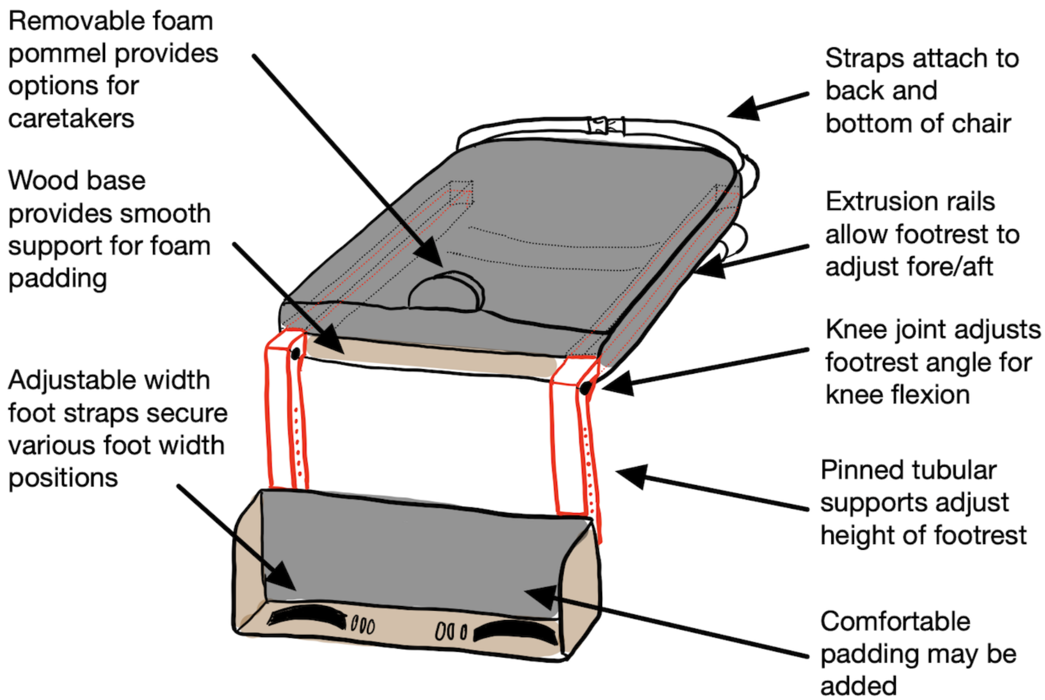


Figure 23. Updated alpha concept drawing. A wider rail base underneath the chair reduces pressure points for the seated child and a wooden base provides better, flat support for the foam. Additional adjustability was provided for the foot straps so they can move to different foot positions/widths.

This alpha concept can be easily adapted to different wheelchairs and other chair sizes depending on the need. The seat is constructed primarily of foam with the potential for a wooden rigid base to mount foot support extrusion rails below (instead of embedded inside the foam, which may prove uncomfortable). During manufacturing for a specific child, the seat size can be manufactured to fit the chairs that the child will be sitting in most of the time. This manufacturing can be performed with common tools (i.e. saws) and would require minimal effort by the manufacturer. The primary advantage to this design is the easy installation onto any chair with a big enough seat, so that the device can be used wherever the child may need to sit. Two straps, around the bottom and back of the chair, secure the device quickly. Figure 24 below shows the attachment method onto a wheelchair and common outdoor chairs and bus seats/dining chairs.

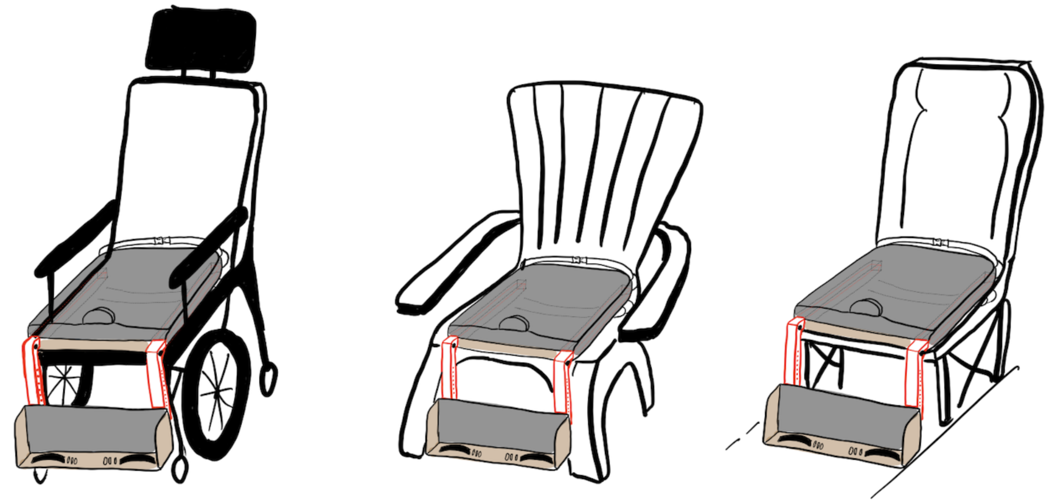
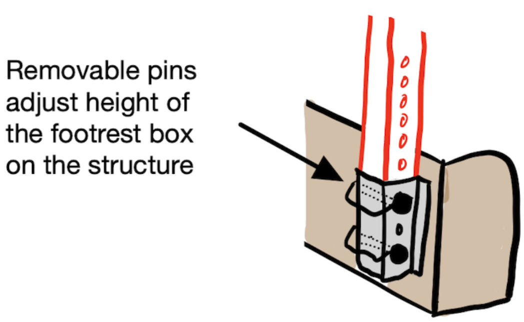
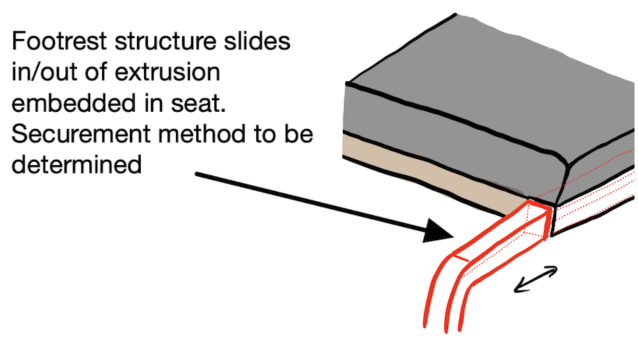


Figure 24. Conceptualized alpha design on various chair types: Wheelchair (left), outdoor chair (center), and bus seat or comparable sized dining chair (right). The foot support seat straps around the bottom and backrest of each chair for secure attachment.

To provide adjustability for foot and leg positions, extrusions are inset into a seat that allow a foot support device with one or two tubular supports to slide. This sliding motion allows fore/aft adjustability of the feet position. Vertical feet positioning is achieved via hole patterns drilled into the tubular supports, adjusted via pins or a similar device. This allows fine tuning of the seat for the caretaker and adjustability between patients, allowing ease of scalability. The tubular support structure will incorporate a mechanism for knee flexion adjustment, likely near the corner of the tube structure. This feature needs additional concept generation but is feasible based on discussions amongst the group and with stakeholders.





Figures 25A (left) and 25B (right). Adjustability components of the alpha concept. Figure 25A is the adjustable pin mechanism to vary the footrest height while locking it in place. Figure 25B shows the sliding action of the footrest tubular structure that accommodates for different limb lengths. Final securement method for the sliding action needs to be determined in the future.

The foot support itself is a boxed structure with adjustable foot straps to prevent dangerous movement of the legs and secure the feet in place, a common issue amongst children with CP. This will prevent dragging of the feet and caretakers being required to fix feet position throughout the day. The boxed structure is attached to the tubular structure via pins, and is angled to provide knee flexion via the knee-flexion adjustment mechanism under development. A comfortable padded surface can be used for the footrest.

Potential drawbacks to this design include positioning of the extrusions within the foam padding, which may be uncomfortable. Clever placement of the extrusion is needed to eliminate the possibility of seat padding wear and to reduce potential pressure points as discussed with our stakeholders when presenting this concept. As mentioned above, knee flexion adjustability must be incorporated. There exists potential to provide additional adjustability in ankle flexion as well as rotation of the foot support about the Z axis (as if one leg is pushed more forward than another). These additional degrees of freedom are not required by the stakeholders but will be incorporated provided our initial requirements are still satisfied. Table 6 below shows a SWOT + Challenges assessment of our design, briefly summarizing the discussion above.

Table 6. Summary SWOTC (SWOT + Challenges) assessment of the Alpha concept.

Strengths	● Can be easily adapted to different size wheelchairs and other chairs ● Keeps child's feet secured ● Easy to install ● Avoids installation on widely varying chair structures, which enables better scalability
Weaknesses	● Somewhat lunky, may be difficult to transport. Could add straps to carry like a backpack ● More involved manufacturing process due to extrusions underneath seat ● Current design iteration does not easily allow for knee flexion
Opportunities	● Adjustability can be increased ● Design can be simplified for ease of manufacturing
Threats	● Extrusions underneath seat may cause it to become uncomfortable if foam compresses too much
Challenges	● Durability and testing durability ● Ensuring any knee flexion component remains cheap and accessible

Potential Alpha Design Iterations

Moving forward with our Alpha design, we will use the significant amount of feedback from peer reviews, stakeholder engagement, consultations with instructors, and our team's internal discussions to improve the design. The next stage in concept development is technical design and engineering analysis to implement our described functionality and ensure that it is feasible, safe, and comfortable for the children we are designing to.

Feedback for Iteration

We consulted with our stakeholders FNE, SPTLN, and BLUELab EASE to review our top five designs as well as our proposed alpha concept. After discussion and questioning, they agreed that the alpha concept we chose would be the most viable concept for adjustability, safety, and ease of use. Through our discussion, multiple points were brought up which were also mirrored by peer feedback and internal discussions earlier. Some key considerations are outlined below.

1. One challenge they perceived about making an adjustable foot support was that there was a lack of consistency on the lower attachments of most wheelchairs in use. They agreed that our alpha design was a great way to get around this challenge by not requiring attachment to a lower structure on the chair.
2. They noted that the device securement around the bottom and back of the chair seems safe.
3. Stakeholders were curious if, since our design incorporates a seat, if this could be adapted to a lower torso support device as well, since the seat is a crucial part of the child's support regimen. This may be outside the scope of our project but could easily be implemented in the future as a low-cost improvement of our design, since it required only remanufacturing of the seat with additional torso support considerations.
4. They expressed concern regarding children sitting on the foam, and compressing into a hard tube underneath the seat. We proposed multiple solutions: relocate the tubes to the sides of the seat, where pressure is lower, using a single tube inline with the center of the chair, or mounting the foot support tubing below a hard bottom of the seat. The updated design shown in Figure 23 above shows how we could relocate tubes to the sides of the seat, where pressure would be lower.
5. They like having the feet boxed in and strapped in, since this aids the caretakers. They emphasized that the straps should be adjustable for different foot positions, which we believe we can implement.
6. Knee flexion mechanisms may not need to support much weight since lower extremities are typically very light for children with CP. We feel that we should still design to our specified load case. It is useful to note that knee flexion could provide the ability to move the foot support out of the way when moving the child on/off a chair, as the caretakers currently do with existing foot supports.

7. Sustainability of foam materials can be considered in greater detail, since there may be large varieties of foam (i.e. densities, type of material, etc.) that could influence environmental impact and comfort.
8. Multiple people noted that a layering strategy could be implemented for the foam padding, to increase comfort and reduce pressure points, as well as aid in replaceability.

More concept development is required for knee flexion and for comfort considerations with the foot support rails embedded or under the seat. Adjustability of the foot rest appears well developed and feasible based on our *Engineering Analysis* section. A continued emphasis on ergonomics and safety for the children and their caretakers is required.

Design Iteration and Prototyping

To develop our alpha design into our initial final design, we created multiple prototypes to better understand aspects of our design. Figure 26 shows the iterative process we used. Throughout this process, we focused on our design's ability to adjust position, maintain position, reduce pressure on the user, and simplify manufacturing.

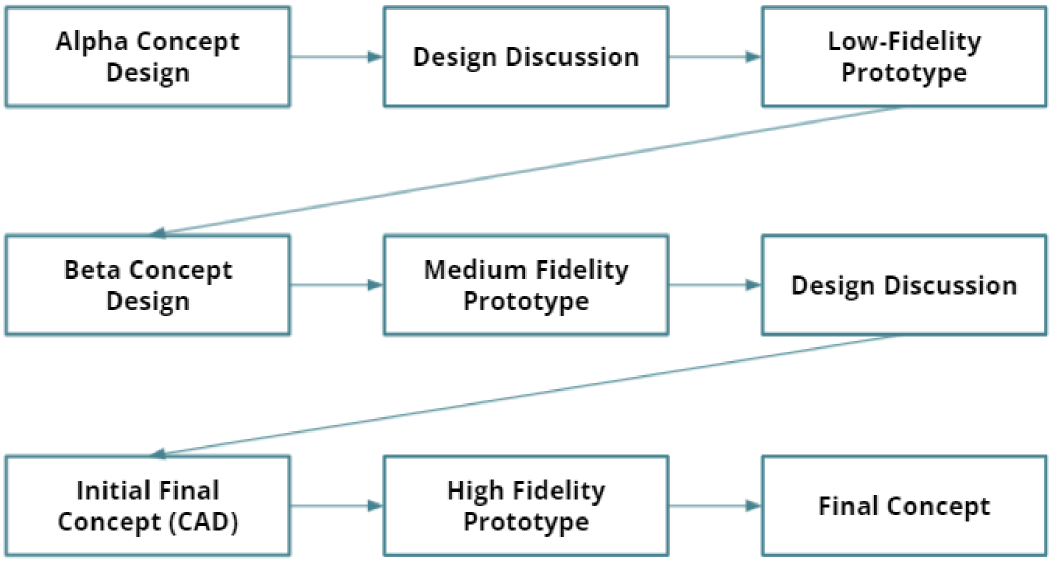


Figure 26. The process we used to iterate on our alpha concept.

Our primary concerns with our alpha concept were the lack of a mechanism to allow for knee flexion and the comfort of the final device given the location of the extrusions going through the depth of the seat. To better understand how we might incorporate knee flexion in our design, we developed a small scale low fidelity prototype using K'Nex as shown in Figure 27 We then developed a full scale low fidelity prototype out of cardboard to further understand this part of the design and how it would interface with the rest of our alpha concept. This is shown in Figure 28

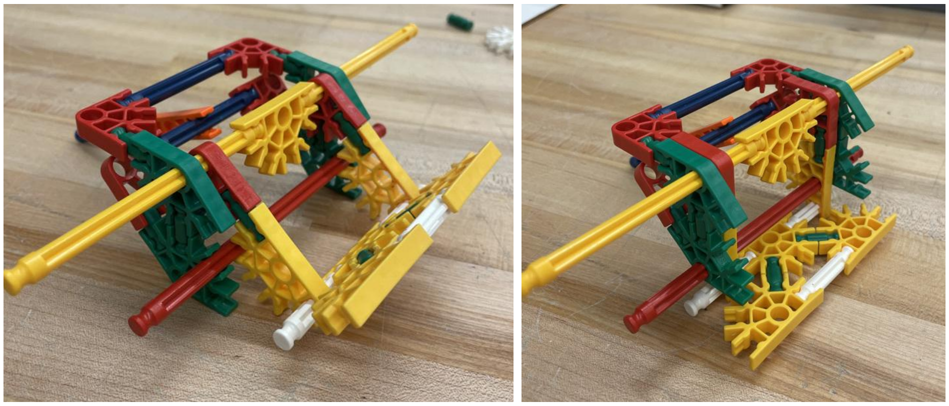


Figure 27. A small scale low fidelity prototype made from K'Nex of the knee flexion component of our design.

Figure 28. A full scale low fidelity prototype made from cardboard to help us understand how knee flexion would interface with the rest of our alpha concept.

From this model, we noticed that there could be an issue with the rod we would use for adjusting the knee flexion angle interfering with the user's legs. As a result, we decided to split this rod into two separate pins with one on either side, although this would likely make aligning the legs relative to each other more difficult. Additionally, we noticed that having the extrusions on top of the seat would cause the device to be uncomfortable as those rails would interfere with the user's hip. To correct this, we decided to move those extrusions beneath a rigid wooden board with foam on top. This would provide a level platform for the user to sit comfortably on.

With these changes in mind, we developed a medium fidelity prototype of our beta design. From this prototype we also wanted to better understand the connection between the footbox and the adjustable legs of our device as we had not yet prototyped that interface as well as how our device would be manufactured and what materials we might use. Figure 29 shows the medium fidelity prototype we developed. We did not choose to include foam padding in this prototype as we felt we had a good understanding of how that would be incorporated into the design.

Figure 29. The full scale medium fidelity prototype of our beta design.

We made this prototype fully out of plywood using a drill press, hand drill, band saw, table saw, and some sandpaper. In making this, we realized that wood would be sufficiently strong and easy to manufacture for our final design. During manufacturing, we learned that several holes would need to be match drilled to ensure alignment between the sides of the device. To match drill, we stacked identical pieces (in this case, our knee flexion joints) and drilled through both at once on the drill press, ensuring that the holes line up in the same way on both parts. We also learned that while wood would be a good material choice, plywood or compressed wood should be avoided as it tends to split when screws are drilled into it. This can be mitigated by drilling pilot holes for the screws, however. Additionally, we decided to change the shape of the knee flexion plates on the sides of the device to not have any curves to make manufacturing easier while retaining functionality.

The primary change we identified between this prototype and the final design would be to reduce the height of the extrusions running through the depth of the seat to reduce the height the user is elevated by. For this prototype, these rails were approximately 1.5 inches tall; however, we would like to reduce this to about 0.5 inches for our final design. We considered not having rails going through the depth of the seat and instead having only a joint at the front, but ultimately we did not move forward with this due to concerns with the strength of that joint and stability of the overall device. Additionally, for our final design, we plan to add foam to the seat pad and foot box to make the device comfortable, and we plan to return to using a single long rod for adjustment as we believe this would make alignment easier and it is clear from the prototype that it would not interfere with the user's legs. We are still considering what configuration of adjustment pins would make changing positions easiest, however.

Initial Final Design

After prototyping, we were able to make final design and material decisions for our initial final design. Our initial final design is shown below in Figure 30.

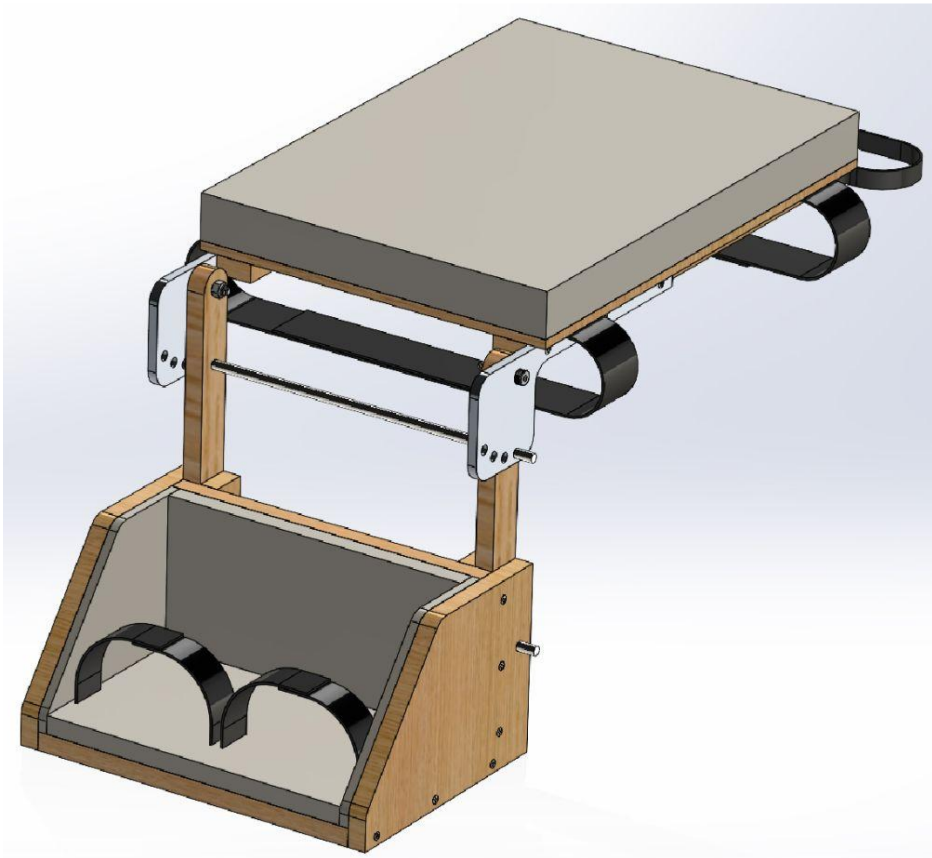


Figure 30. CAD model of our initial final design, made using Solidworks.

The main structural components of our design will be made using oak wood and steel. The other main materials include foam, velcro, and vinyl. Vinyl covers for the foam are not shown in Figure 30. The main fasteners we will use include steel rods for adjustable components, shoulder bolts for rotational joints, nuts, bolts, M3 wood screws, and wood glue for the main structural components. The rest of this section will highlight specific design components in more detail.

Detailed Design Solution

Our initial final design can be broken down into three main subassemblies. These subassemblies include the seat, the knee flexion joint, and the footrest.

Seat

The seat in our design will be made to rest on top of any seat that Monica may find herself in and will have the same dimensions as her wheelchair seat. The seat will be manufactured using a ¼” board and two ½” x 1” wooden rails underneath the seat, which are used to anchor the knee flexion brackets. The board and wooden rails will be fastened together using the M3 wood screws and wood glue. Figure 31 below shows the main structure of the seat.

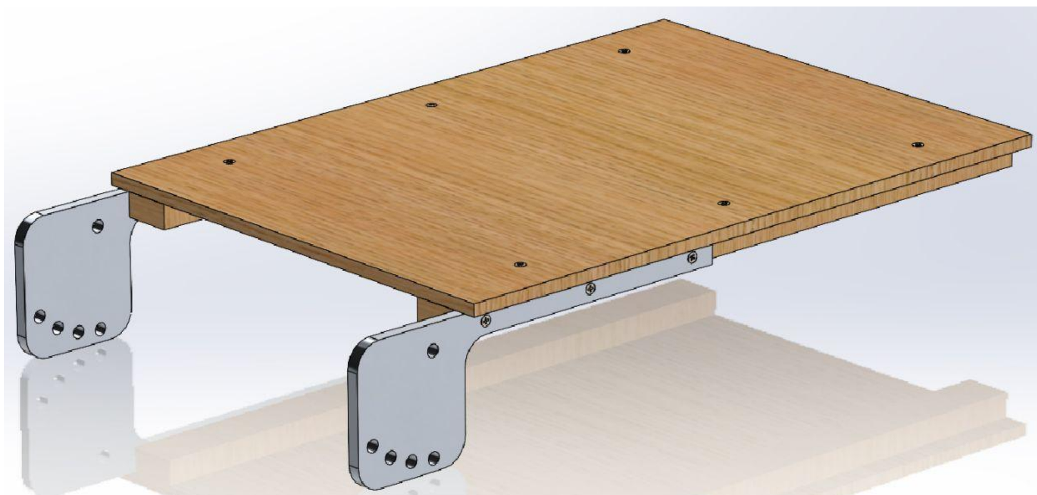


Figure 31. Main seat structure.

The seat also needs to be secured to the chair that the device is used on. This is achieved by three different velcro straps as well as the knee flexion bracket. There is a velcro strap placed toward the front of the seat and one toward the back of the seat which wrap underneath the chair that the device is being used on to prevent the seat from rotating side to side. A third velcro strap is attached to the very back of the seat and wraps around the back of the chair to prevent the seat from sliding forward off the chair it is being used on. The knee flexion bracket also helps to prevent the seat from sliding back and forth as it is pressed up against the front edge of the chair it is being used on. Figure 32 shows the underside of the seat.

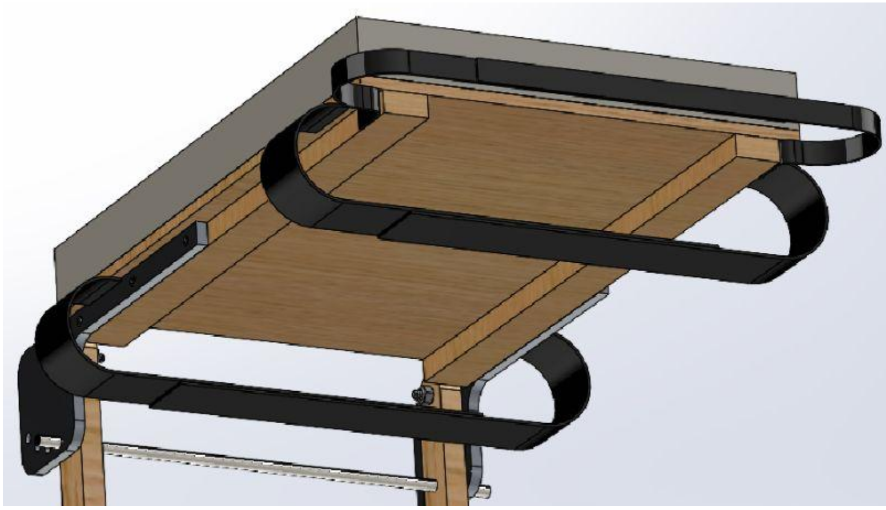


Figure 32. Underside of the seat. Three velcro straps are used to secure the seat to the chair it is being used on.

With these three velcro straps and the knee flexion bracket, all six degrees of freedom (translational motion in the three coordinate axes and rotational motion in the three coordinate planes) are constrained.

Knee Flexion Joint

The knee flexion joint is used to raise and lower the footrest. The footrest will be manufactured out of steel for added strength because it will be taking the highest load of all components on the device. The bracket will be fastened to the wooden rails of the seat using nuts and bolts. The knee flexion bracket is shown below in Figure 33.

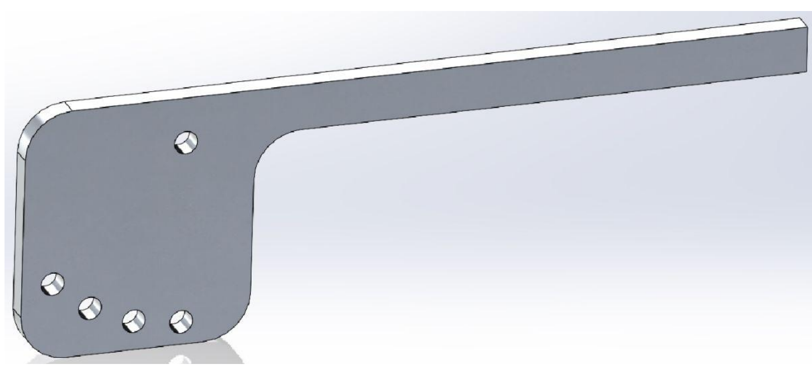


Figure 33. Steel knee flexion bracket. The top hole is for the rotational joint and the four holes at the bottom are for angle adjustment.

The bracket was designed with a fillet at the neck of the bracket to alleviate some of the stress at that section of the bracket. The three outer corners were also designed with fillets for safety purposes. The footrest will be fastened to the bracket at the top hole using shoulder bolts, which will allow the footrest to rotate freely. The four holes at the bottom of the bracket are all located 2” away from the top hole and are spaced out 15° apart from one another. These holes allow Monica's caretakers to change the angle between the seat and the footrest to be 90°, 105°, 120°, or 135°. A single steel rod is used to hold the footrest in position at one of the different angles. Figure 34 below shows the footrest raised to its highest angle.

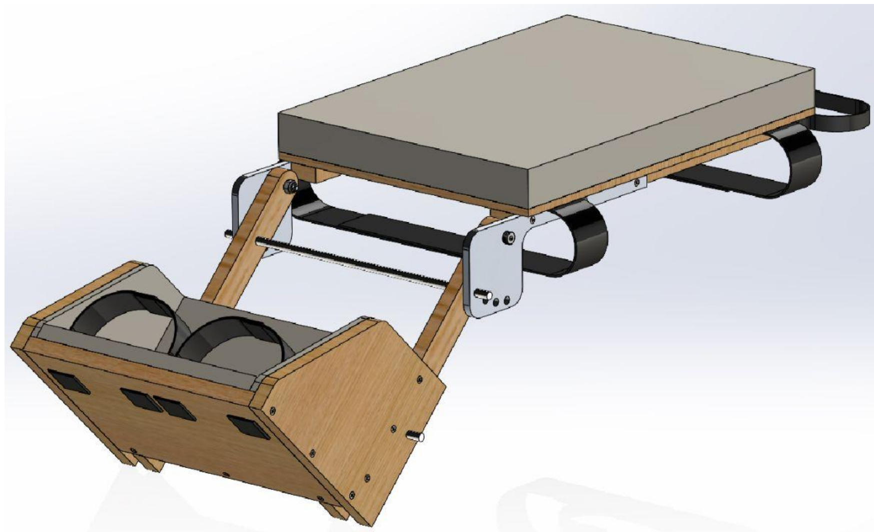


Figure 34. Footrest raised to its highest point with a 135° angle between it and the seat.

Footrest

From our first meeting with FNE, it was conveyed to us that a "boxed-in" style footrest would be desirable as it can contain Monica's feet and keep her in a comfortable seating position. The footrest will be made of ½" wood planks that are fastened together using M3 wood screws and wood glue. The inside will be lined with foam to ensure Monica's comfort and the foam will be wrapped in vinyl to protect it from water. There will also be two velcro straps to anchor her feet in place to help maintain her seating position. Figure 35 shows the inside of the footrest.

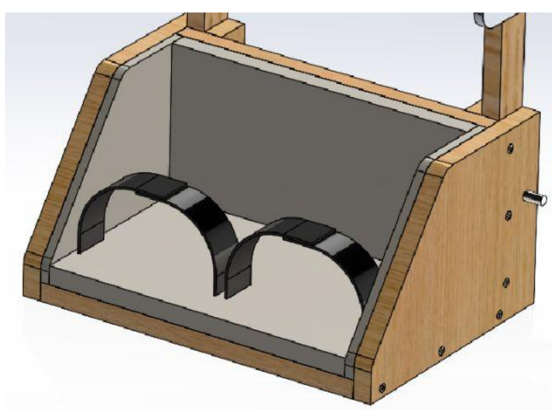


Figure 35. Inside of the footrest. The foam on the bottom and back of the footrest is ½" thick and the foam on the sides of the footrest is ¼" thick.

The height of the footrest can be adjusted by removing the steel rod that is holding the footrest in place. There are multiple holes spaced out ¾" apart for different footrest heights. A single steel rod is used for this adjustable component because it is not something that will have to be changed often. The back of the footrest is shown in Figure 36 to depict how the height of the footrest can be adjusted.

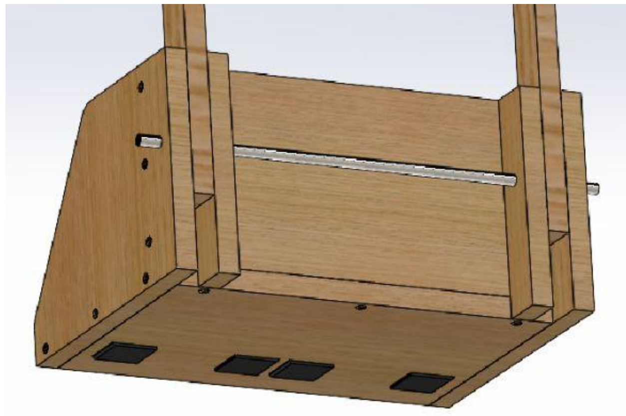


Figure 36. Back of footrest with removable steel rod in place to maintain height.

Final Design Solution

After further discussing our initial final design, we decided to make a few changes to the design to use more readily available materials, decrease weight, and increase the strength of critical components. Our most updated iteration of our design is shown below in Figure 37.

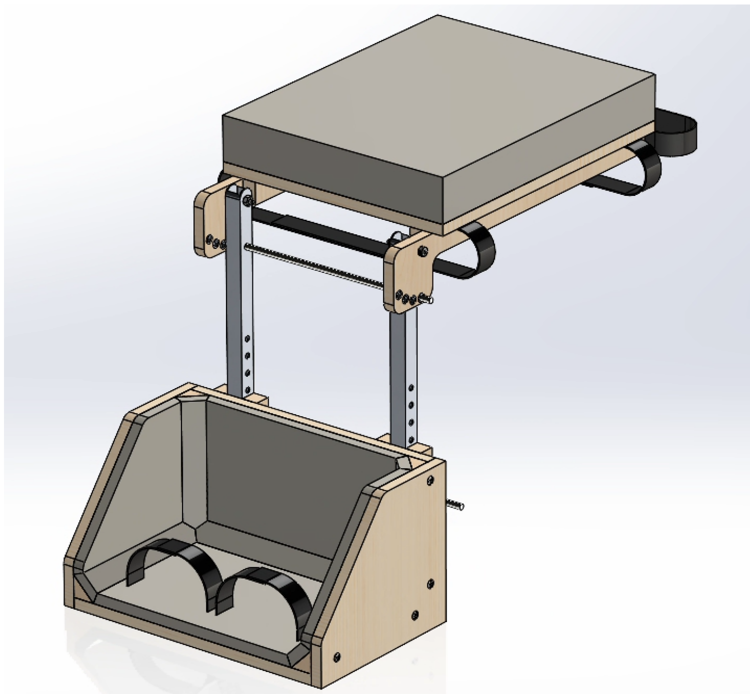


Figure 37. CAD model of our final design solution, made using Solidworks.

We decided to change the main structural components of our design to be made of maple wood, plywood, and aluminum tube stock. We plan to still use foam and vinyl for comfort, and velcro for the straps underneath the seat and in the foot rest, and a strap with a plastic buckle for the back of the seat. Vinyl covers for the foam are not shown in Figure 37.

Detailed Design Solution

Our final design still has the same main subassemblies. These include the seat, the knee flexion joint, and the foot rest.

Seat

Functionally, the seat is still the same. We are using a wood board that will be mounted on top of the wooden rails and the knee flexion joint. However, we increased the thickness of the board to ½" for added strength as ¼" would have deflected too much over time. We are also using plywood for the seat as opposed to solid oak wood because the increased thickness allows for it, and this would allow for a cheaper and lighter design. The seat will be fastened to the wooden rails and knee flexion joint using wood glue and #8x1" wood screws. The new seat is shown below in Figure 38.

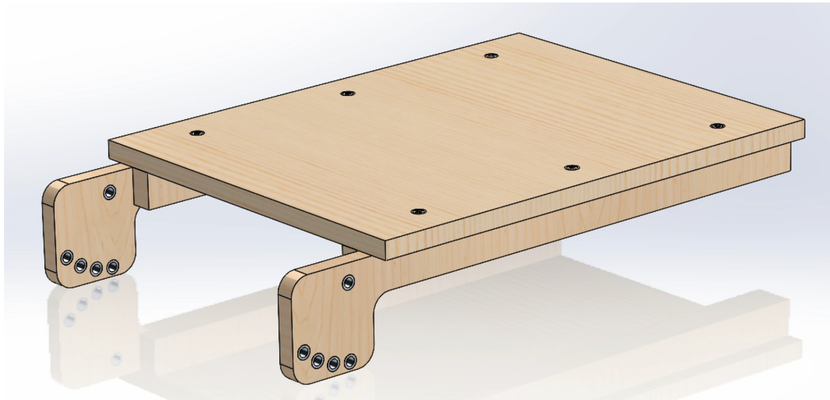


Figure 38. Final seat structure.

Similar to the initial final design, we will still be using three straps to secure the seat to the child's chair. We will still be using velcro straps underneath the seat because it is easier to get a tighter fit underneath the seat with the velcro. We will be using a fabric strap with a plastic buckle for the third strap that will wrap around the back of the seat because it is easier to clip and unclip the buckle in this position. The seat straps are shown in Figure 39A. The plastic buckle on the back strap is not shown in the CAD model, but there is a picture of what will be used in Figure 39B.

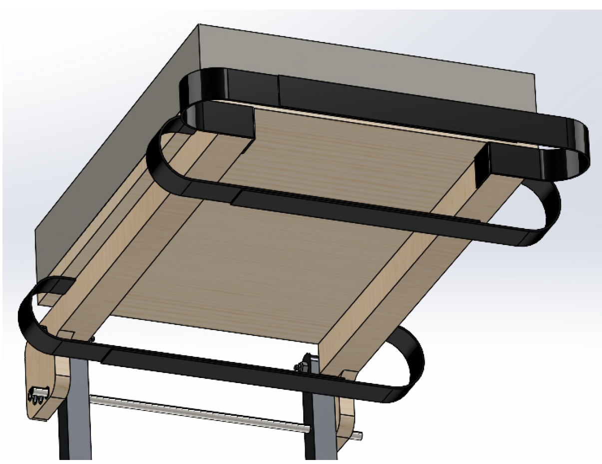


Figure 39A. Underside of the seat with two velcro straps underneath the seat and a fabric strap around the back of the seat.

Figure 39B. Plastic buckles that will be used on the strap that wraps around the back of the seat.

Knee Flexion Joint

The most critical change between our initial final design and our most recent final design is the knee flexion joint. We decided to use one solid piece of maple wood to combine the wooden rails underneath the seat and the knee flexion bracket. While testing our first prototype, we noticed that having these components be two separate pieces would be detrimental to the strength of our foot support. By using one piece of a hardwood like maple, there are less moving pieces and the bracket will still be strong enough for the amount of stress that it will experience. The new combined wooden rail and knee flexion bracket are shown below in Figure 40.

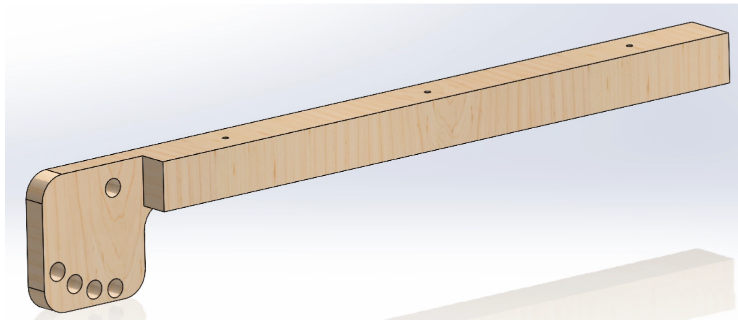


Figure 40. New knee flexion joint, made from one solid piece of maple wood.

The new knee flexion joint still has the same holes to allow for the same angle adjustments. The inside face of the angle adjustment part will be cut down so as not to have too much material in the middle of the seat where Monica's legs will be. We will also be press fitting aluminum bushings into the holes to minimize the metal on wood contact in our design.

Foot Rest

There were multiple changes made to the foot rest. We originally planned to use solid oak wood planks for the sides of the foot rest so that the planks would not split when we screw into the sides of them to put all the pieces together. Now, we plan to use plywood for the sides of the foot rest, and to ensure that we do not split the wood when putting the foot rest together, we will be using 1”x1” right triangular pieces made from maple wood and fasten the plywood sides to those pieces. One of the triangular pieces is shown in Figure 41A and the new foot rest with these triangular pieces implemented is shown in Figure 41B.

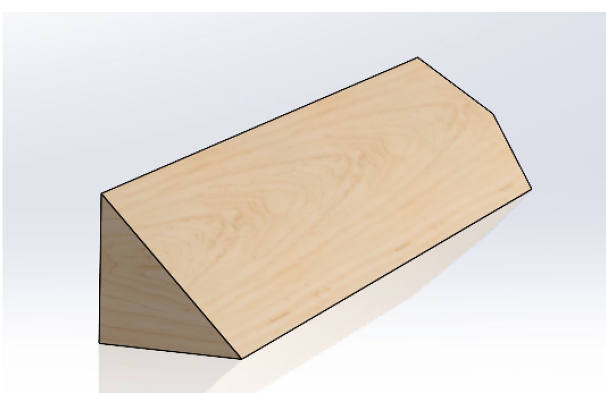


Figure 41A. Triangular piece of solid maple wood to fasten the bottom and left side of the foot rest.

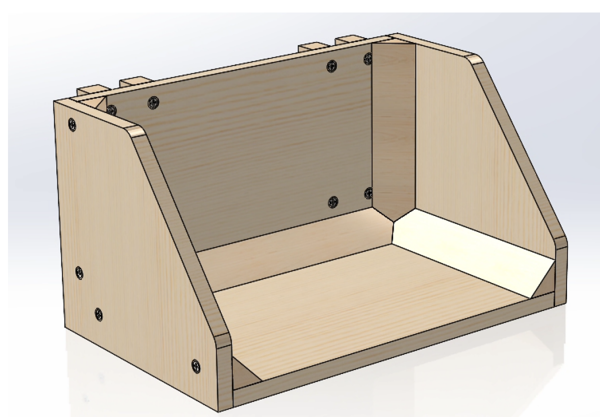


Figure 41B. New foot rest made of plywood with triangular anchors made of maple wood along the inside corners of the foot rest.

The other major change to the foot rest is how we attach it to the seat. Instead of using solid wood to hold the seat and foot rest together, we will be using ¾"x¾" aluminum tube stock. This change was made because we noticed with all the holes going into the specific piece, press fitting too many bushings into the wood may cause the wood to split. Using aluminum, we do not have to worry about press fitting bushings as we are not concerned about the metal on wood contact, we still maintain our lightweight design, and it is still strong enough to hold the loads that will be experienced by these pieces. The new foot rest to seat attachment is shown below in Figure 42.

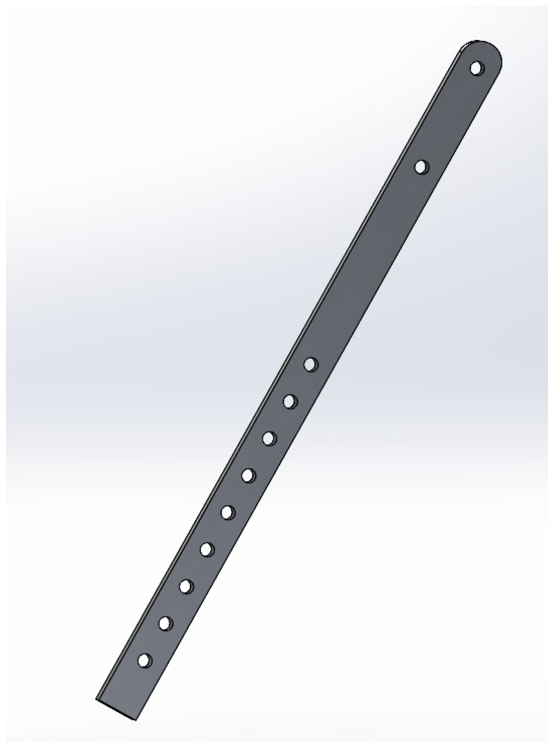


Figure 42. New foot rest to seat attachment made of ¾"x¾" aluminum tube stock.

Ergonomics and Interaction Assessment

The interactions between the caretaker and the device primarily include installing the foot support in the chair, adjusting the height of the foot box, and adjusting the angle of the foot box.

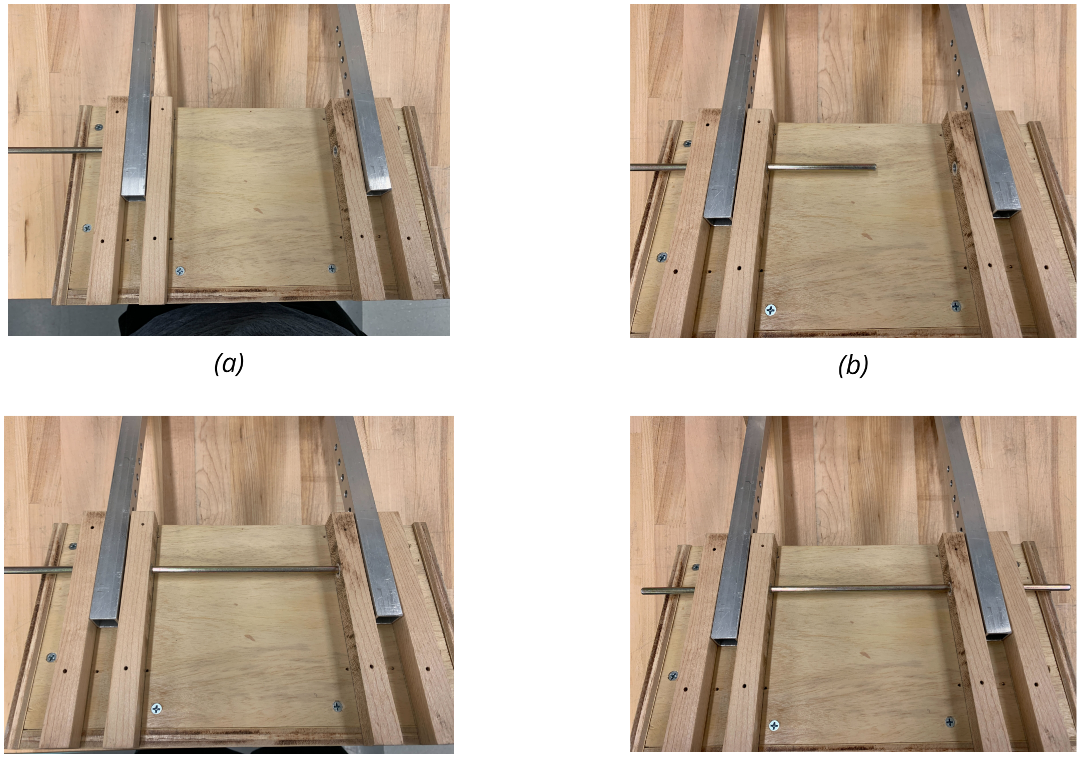
Installation in a Chair

To install the foot support in a chair, the user first needs to place the seat pad onto the seat of the chair, then secure the device in place using the three straps. The two straps which go around the seat of the chair will require the user to reach below the chair to tightly fasten them. These straps are velcro and will likely have a large area of engagement. These straps should be pulled as tight as possible before being secured to ensure the device is as stable as possible in the chair. The third strap should loop around the back of the chair. This strap has a buckle and should be tightened after engaging the buckle. Figure 43. shows the device strapped to a chair.

Figure 43. The foot support is strapped to a chair. The image on the right shows a top down view to make the locations of the straps clearer.

Height Adjustment

To adjust the height angle of the foot box, the user first has to fully remove the rod from the back of the foot box and legs, then move the foot box to the new position, then put the rod back through both legs and the back of the foot box. This procedure can be done by using one hand to remove and replace the rod and using the other hand to support and move the foot box. If a child is in the device, significant effort will likely be required to move the foot box up the legs as the weight of the child is pushing the foot box down. It is much easier to move the foot box down or adjust the foot box without a child in the device. Adjusting the height of the foot box is somewhat difficult as it is difficult to see where the holes are to ensure alignment. When adjusting the height, after the user has removed the rod, they should look from one side to make sure they have moved the foot box to a position in which the adjustment holes are aligned before pushing the rod through. After pushing the rod through one leg, the user will have to look from the other side to make sure that the holes in the other leg are also aligned before pushing the rod all the way through. Pushing the rod through the second leg may require the user to move the leg or foot box slightly as the leg may get pushed away from the back of the foot box. Figure 44 shows the rod being passed through the back of the foot box and legs.



(a) (b) (c) (d)

Figure 44. The adjustment rod is passed through the back of the footbox and both legs. In step (a), the user should look from the left side to ensure alignment. In steps (b) through (d), the user should look from the right to ensure alignment.

Angle Adjustment

To adjust the knee flexion angle of the foot support, the user first has to fully remove the rod from the knee flexion plates and legs, then move the foot box and legs to the new position, then put the rod back through both legs and knee flexion plates. This procedure can be done by using one hand to remove and replace the rod and using the other hand to support and move the foot box. If a child is in the device, it may require significant effort to move the legs up to a higher angle (for example from the 90° position to 135° position) as the weight of the child's legs pushes the legs downward. It is much easier to move the device to a lower angle (for example from 135° to 90°), and the device is easy to adjust if the child is not in the device. In order to ensure that the adjustment rod goes into the correct holes, the user will likely have to look from one side and carefully watch for alignment. The user may also need to reach behind the child's legs to push the rod through all adjustment holes if they find that they do not have enough control from just one side. Figure 45A-C shows an example of the angle being adjusted from 105° to 135° with an adult in the device. Note that because this test was performed with an adult in the chair, the amount of force needed to adjust the device in a more realistic case would be much less.

(a) *(b)* *(c)*

Figure 45. The angle of the device is adjusted from 105° to 135° with an adult in the device. (a) shows the device with the rod in place at the 105° position, (b) shows the rod being removed, and (c) shows the device being moved and the rod being replaced at the 135° position.

Engineering Analysis

With our preliminary design now selected, we began to consider different analyses we will have to conduct on our design. Although the dimensions of our design are not explicitly determined nor is the design finalized, we can conduct preliminary analysis on components we will have to examine for our design.

Dowel Pin

One element of our design that we can immediately examine is the dowel pin which will connect the bottom portion of the design (footrest) with the top (seat attachment). Figure 46 displays free body diagrams of the pin and shaft system in order to find the minimum required diameter of the pin.

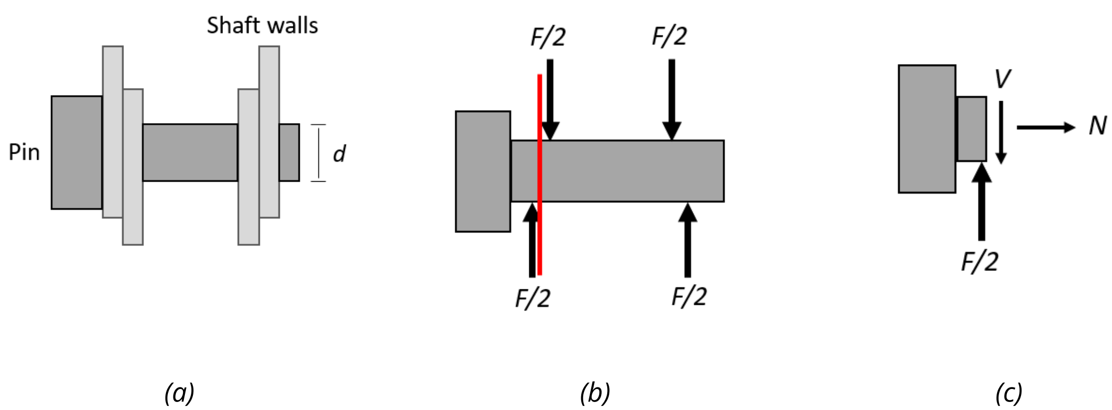


Figure 46. Pin and shaft system and free body diagrams where *F* represents the max force that one shaft would experience. For this system, we examine the internal reactions between the two shafts, denoted by figures (b) and (c). Specifically, the red line on figure (b) denotes the cross section that we are examining for the internal reactions.

In Figure 46 above, we will use *F* to be the user's weight plus the approximate weight of the footrest, which is assumed to be five pounds. We can then use equations 1 and 2 to determine the minimum diameter needed for the dowel pin to support the footrest. Equations 1 and 2 below were derived from the free body diagrams in Figure 46 and the Mohr's circle for the yield stress of steel, given in Figure 47.

$$F = 102.5\ lbs,\ V = 51.25\ lbs,\ N = 0\ lbs$$

$$\sigma_{y,\,steel} = 36.3\ ksi = 2\tau_{max,\,pin} \quad (1)\ [27]$$

$$\tau_{max,\,pin} = V/A = 18.5\ ksi \quad (2)$$

$$A = 2.82\,e^{-3}\ in^2,$$

$$d_{min} = 0.059\ in$$

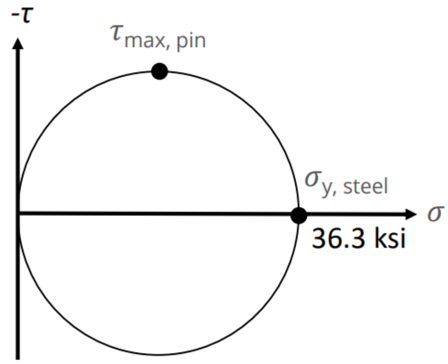


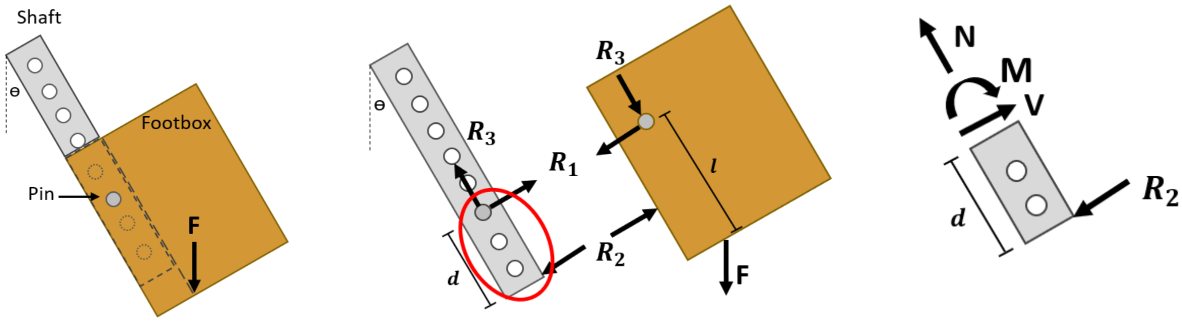
Figure 47. Mohr's circle for stresses acting on the proposed dowel pin. The yield stress for high-strength steel was found to be 36.3 ksi [27]. We see that $\tau_{max, pin}$ is exactly half of the yield stress of steel, which was then proposed to be the shear stress acting on the pin for determining the required pin diameter.

Using equations 1 and 2, the minimum dowel pin diameter for our design was found to be 0.059 inches. This proposed diameter is much smaller than what we were anticipating having to use for our design, so this is a useful indicator that a larger pin will be more than sufficient on supporting the loads acting on the foot support.

Foot Box Connection and Shaft Bending

One component of our design that we suspect will experience large amounts of loading is the footbox connecting shafts. These shafts are what is holding the load of the footbox and the user's legs to the rest of the device, and will be susceptible to large vertical forces and moments.

One way that these shafts will be loaded is by the vertical loads sustained by the footbox. Figure 48 shows free body diagrams of the shaft and footbox in this loading scenario.



(a) (b) (c)

Figure 48. Approximated free body diagrams for shafts and footbox. (a) depicts the forces acting on the overall system where F is half of the user's weight and the half of the weight of the footbox, while (b) denotes the separate reactions acting on each component, and (c) displays the internal reactions acting on the end of the shaft. The largest magnitude of forces will occur when *d* is minimized, so that scenario was considered during analysis.

Using the free body diagrams from Figure 48B, we examined the forces acting externally on our shaft and footbox, and Figure 48C allows us to solve for the internal reactions. For our stress analysis, we used the minimum possible value for *d* in order to examine the worst case loading condition for our design. Equations 3 and 4 were used to find the stresses found in the cross section of the plate, and these values were then used to form a Mohr's circle to examine the overall maximum stresses. The values used for analysis are shown below, and the resulting Mohr's circle is shown in Figure 49.

$$F = 102.5\,lbs,\ R_1 = Flcos(\theta)/d,\ R_2 = F(3l/(4dcos(\theta)) + 0.5),\ R_3 = Fcos(\theta)$$

$$\theta = 45°,\ V = 594.8\ lbs,\ M = 594.8\,lbs * in,\ N = 72.5\,lbs$$

$$d_{min} = 1\ in,\ l = 5\ in$$

$$A = 0.173in^2$$

$$\tau = V/A = 3435.7\,psi \tag{3}$$

$$\sigma = My/I + N/A = 16,661\,psi \tag{4}$$

$$\tau_{max} = (17342 + 609)/2 = 8.9\,ksi \tag{5}$$

$$\sigma_{Y,\,steel} = 36,300\,psi \quad [27]$$

$$\sigma_{Y,\,6061\,aluminum} = 40,000\ psi \quad [28]$$

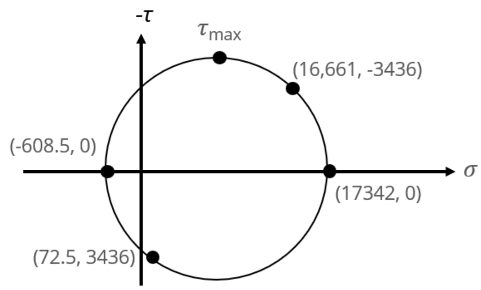


Figure 49 . Mohr's circle for stresses acting on the attachment shaft. We find our maximum shear stress to be approximately 8.9 ksi from equation 5, which is much less than the maximum shear stresses for general steel or 6061 aluminum [27, 28]. Therefore, our shaft should easily be able to withstand this loading condition.

Another loading scenario that these connecting shafts will experience is from bending due to lateral loading. Figure 50 shows free body diagrams of the shaft and footbox in this loading scenario.

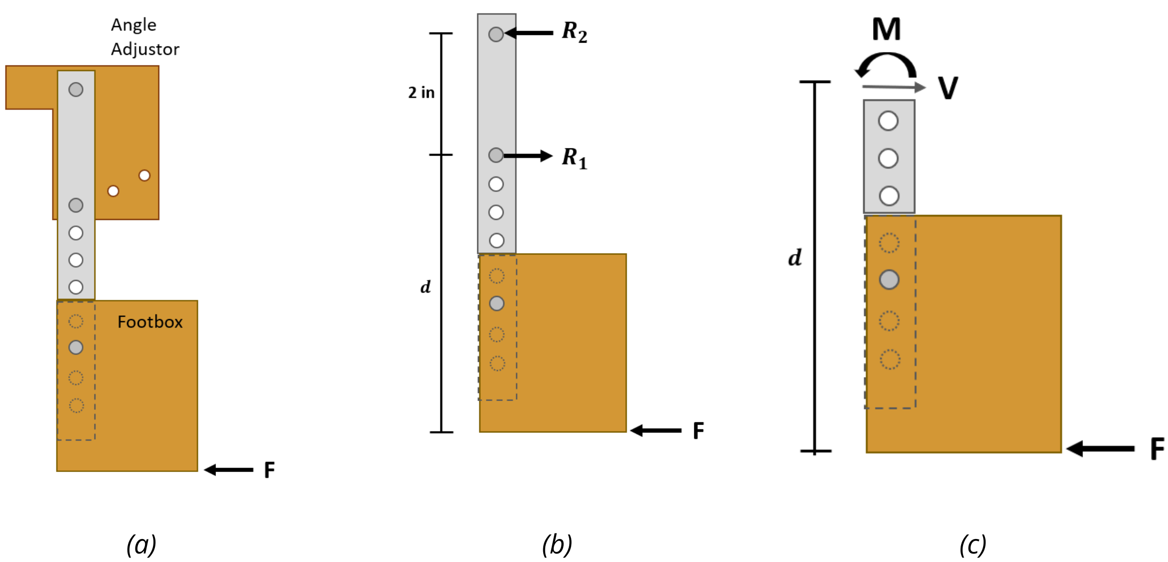


Figure 50. Free body diagram for lateral forces acting on the foot support. The maximum moments and stresses will occur when *d* is maximized, so our analysis was conducted with this worst case scenario in mind. (c) displays the internal reactions occurring inside the shaft at the cross section of interest.

Using the free body diagrams displayed by Figure 50 the internal reactions and stresses were determined using a similar process to the other loading scenarios described above. The following values were used in equations 6 and 7, and the examined stresses were formed into a Mohr's circle to examine the maximum stresses occurring in the shaft.

$$F = 50\, lbs\,,\ R_1 = F(1 + d/2),\ R_2 = F(d/2)$$
$$V = 50\, lbs\,,\ M = 700\, lbs * in$$
$$d_{max} = 16\, in$$
$$A = 0.173\, in^2$$
$$\tau = V/A = 289\, psi \quad (6)$$
$$\sigma_{bending} = My/I = 19108\, psi \quad (7)$$
$$\tau_{max} = (19108 + 4)/2 = 9.6\, ksi \quad (8)$$

$$\sigma_{Y,\, steel} = 36,300\, psi \quad [27]$$
$$\sigma_{Y,\, 6061\, aluminum} = 40,000\ psi \quad [28]$$

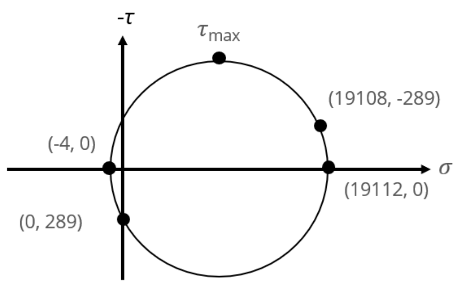
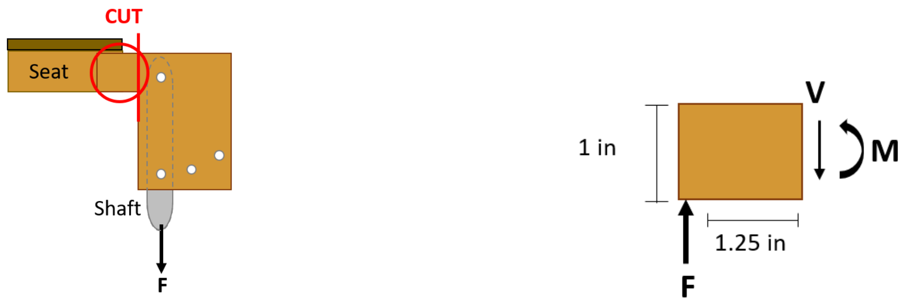


Figure 51. Mohr's circle from lateral loading condition on connecting shafts. We see that the shear stress has a very minimal effect on the overall stress experienced by the shafts. Our maximum shear stress is found to be 9.6 given in equation 8, which is much less than the maximum shear stress for general steel or 6061 aluminum [27, 28].

These shafts are expected to experience the greatest stresses in our foot support design, and we determined that the assumed loading the footrest will encounter is not sufficient to cause these shafts to fail. It will still be important to conduct empirical testing on these scenarios for the final design due to the lifetime of wood and possible warping due to prolonged stress exposure.

Angle Adjustment Bracket

One core element of our design that we wished to analyze was the knee angle adjustment plates. Because these plates are the main connection between the foot support box and the seat pad, we wanted to ensure that the components will hold under the predicted loads. Figure 52 shows free body diagrams of the angle adjustment plate.



(a) *(b)*

Figure 52. Approximated free body diagrams for angle adjustment plate. (a) depicts the forces acting on the overall system where F is half of the user's weight and the half of the weight of the footbox, while (b) denotes the internal reactions of the plate at the most critical area.

Using the free body diagrams from Figure 52B, we examined the stresses occurring within the joint. Equations 9 and 10 were used to find the stresses found in the cross section of the plate, and these values were then used to form a Mohr's circle to examine the overall maximum stresses. Figure 53 shows that there is minimal risk of the plate failing due to the maximum stress being far less than the yield strength of maple wood.

$$F = 102.5\ lbs,\ V = 102.5\ lbs,\ M = 128.125\ lbs * in$$

$$\sigma_{Rupture,\ Maple} = 12.33\ ksi \quad [29]$$

$$A = 0.5\ in^2,$$

$$\tau = V/A = 205\ psi \quad (9)$$

$$\sigma_{bending} = My/I = 1.564\ ksi \quad (10)$$

$$\tau_{max} = (1564.4 + 26.9)/2 = 0.79\ ksi \quad (11)$$

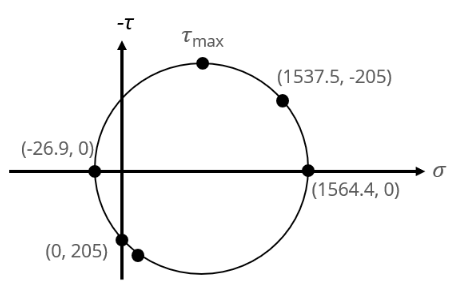


Figure 53. Mohr's circle for stresses acting on the angle adjustment bracket. The modulus of rupture for maple wood was found to be 12.33 ksi [29]. We see that the maximum stress experienced by our wooden angle bracket is significantly less than the modulus of rupture for maple wood, so there should be no concerns of our bracket failing. However, we will have to consider the strength of this wood over time, which may affect the loads it will be able to withstand.

Center of Gravity Analysis

One concern highlighted by our stakeholders is the risk of the device causing chairs to tip over. New mass is added to the overall chair system due to our footrest, and we wanted to ensure that the design does not cause tipping due to significant mass or moments. Figure 54 shows a center of gravity estimation produced by Solidworks, providing insight that our design is very front loaded.

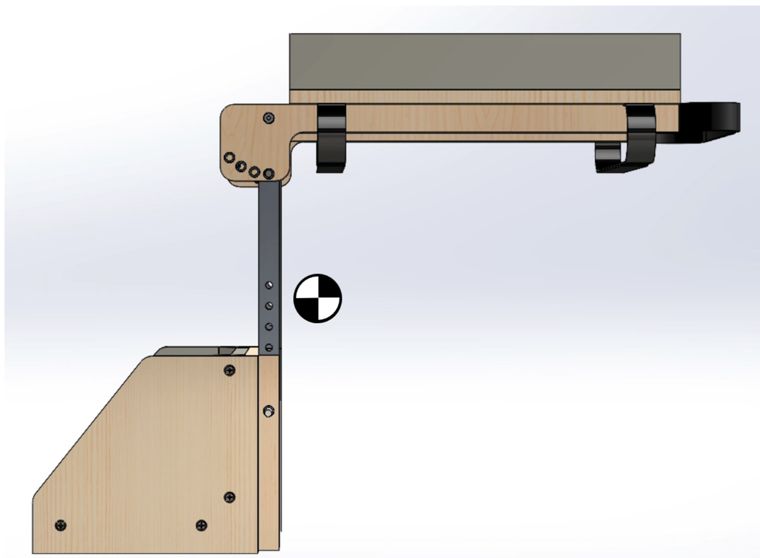


Figure 54. Center of gravity approximation of the foot support design provided by Solidworks. The center of gravity is right beneath the front of the seat pad, which may cause concern for tipping. Further testing and analysis will have to be completed to confirm the design upholds safety specifications.

We see from Figure 54. that our footrest design is front loaded in relation to the seat. Considering the location of the center of gravity when the knee flexion angle is at the most favorable 90° position, we plan to conduct heavy verification testing to ensure that any position of the footrest will not ensure tipping. It is important to note that the weight of the footrest itself remains low at approximately 4 lbs, however the moment arm created by the footrest shaft may be the main concern for this testing case.

On-Site Required Analysis

Much of the analysis we have currently conducted were on design elements that we felt were the most critical. There are certain elements of the design that are left to be examined by our stakeholders themselves to ensure that the design meets their requirements.

One element of our design that we were unable to fully address in our analysis is the method of constraining any shafts or pins we use for adjustability. This will be recommended later in the

“Detailed Manufacturing Plan” and “Discussion and Recommendations” sections, but adding some lateral constraint will have to be considered for the inserted shafts.

Another area of analysis that we were unable to fully address is the tipping failure mode of the footrest/chair system. This concern was highlighted by our stakeholder, however we do not have a sufficient method of testing this failure mode due to the high variability of chair structures and user weight. We will conduct empirical testing given the materials we have in our laboratory setting, however our stakeholders will have to conduct their own form of testing to ensure tipping does not occur on the chairs they will use.

Given the time constraints, one portion of our specifications we plan to address is focusing on the lifetime degradation of our design components. The current analysis conducted on our design elements examined new, non-corroded parts. However, these calculations will not hold overtime as wood and fabric tend to degrade much more quickly after being exposed to water and prolonged stresses. We plan to examine our design components again when examining the final prototype to determine vulnerable components of our design during different use cases, and highlight key warning signs of possible failure points to inform our users of any required maintenance.

Failure Modes Effects Analysis

Our design has three primary components: the seat pad, adjustable legs, and foot box. For these components, we identified and analyzed six total possible failure modes which are all laid out in Table 7 on the next page. From this analysis, we identified two primary failure modes, namely the device tipping out of the chair and becoming uncomfortable over time. To mitigate the device tipping, we could increase the strength and number of straps connecting the device to the chair as well as redistribute the mass of the device to shift its center of gravity further back in the chair. We plan to conduct thorough testing to ensure that the straps of our device are strong enough and the device will not tip out of the chair. To try and prevent the comfort of the device from degrading over time, we could choose more durable materials, particularly a more durable foam, as well as improve the bonding between the foam and the wooden board beneath it. Additionally, while mold and corrosion of materials are significant concerns, they are not themselves failure modes of the device, although they may contribute to potential failures. For example, mold on the wooden knee flexion joint may be the reason that part of the device is too weak to support the necessary force and breaks. Mold and corrosion related failures can be mitigated by ensuring all parts of the device are properly coated, whether that be in clear coat for the wood, paint for steel, or vinyl for foam, and avoiding wet environments whenever possible.

Table 7. Failure modes effects analysis of our device showing six total failure modes. Each failure mode is categorized based on the component of the device that is most closely related to it.

Seat Pad

Function	Failure Mode	Effects	Sev	Justification	Potential Causes	Occur	Design Controls	Detec	Justification	RPN	Possible Mitigation
Connect foot support to chair	Seat Pad slides forward off the chair	Device falls forward, child falls out	9	Safety issue if the child falls out of the chair, especially forward, primary function of attachment to chair is lost	Connection to chair (straps) are not secure enough or break, CoG shifts too far forward	4	Mass distribution, seat attachment methods and strength, both can be verified using hand calcs and prototyping	1	It will be clear that the device is moving by an amount that is unsafe. Movement that is undetectable by observation is not a concern.	36	Increase strength of straps connecting to chair, use more connecting/securing straps, redistribute mass to back of seat pad
	Side motion of device (device slides around on chair)	Device slides around in chair causing discomfort and making tipping more likely	7	Likely will not make the device unsafe to use, but it will certainly make the attachment less secure	Straps are not tight or secure enough, seat pad is not level or otherwise not resting on the chair well	2	Location and length of straps	1	It will be clear that the device is moving by an amount that is unsafe. Movement that is undetectable by observation is not a concern.	14	Increase strength of straps connecting to chair, use more connecting/securing straps, tighten straps, velcro to chair or otherwise bond more strongly to chair
Make a comfortable surface for the child to sit on	Padding wears down or comes off (within defined use window of 3 years defined in specs)	Seat is no longer comfortable for the child, seat pad becomes thin and may lose some stability	5	Comfort is secondary function after securement/attachment to the chair, would be degraded in this case	Repeated load on foam, poor bonding between foam and wood, repeated friction, corrosion of materials	4	Material selection - seat pad, rigid base/frame, bonding agent, covering	2	Will be easy to notice degradation of seat pad, pad will become noticeably thinner and worn, may be difficult to determine when "failure" occurs	40	Choose more durable materials, improve bonding between foam and wood, properly coat all materials to prevent corrosion, reapply coating or choose a different coating if needed

Adjustable connecting legs

Function	Failure Mode	Effects	Sev	Justification	Potential Causes	Occur	Design Controls	Detec	Justification	RPN	Possible Mitigation
Connect foot box to seat pad	Legs break	Foot box is disconnected from the rest of the device, sharp metal may be a safety hazard	9	Footbox would end up end up falling off, and the primary function of the device would be lost (supporting feet), safety hazard of broken/sharp metal or wood	Excessive lateral or bending load (realistic longitudinal loads would not pull the material apart), repeated wear at metal wood interfaces, corrosion of materials	1	Material used for legs connecting foot box to seat pad, material used for pins, leg/pin interface	1	It will be very easy to notice if the legs break, and there will likely be some warning that the legs are about to break	9	Use stronger leg materials (i.e. metal rather than wood), minimize metal to wood interfaces
Adjust height or angle of foot box	Position locking pins fall out or break while in use	Foot box slides off or does not stay in the correct position while in use	7	No major safety concerns, but the primary function of the component (adjustability) would be lost or at least be worse	Holes for locking pins are too loose, Pins are too difficult to keep in place, Holes in wood get larger over time due to softening of wood	2	Size of locking pins, shape of locking pins, locking mechanism	2	Very easy to notice shifts in position, may be slightly more difficult to anticipate	28	Larger pins with tighter hole size tolerances, More secure locking mechanism (for pins themselves or overall), Different materials which are less likely to soften over time
Adjust angle of legs and foot box	Angle adjustment plates break	Foot box is disconnected from the rest of the device, wooden splinters may be a safety hazard	9	Footbox and legs would end up end up falling off, and the primary function of the device would be lost (supporting feet), safety hazard of broken/sharp metal or wood	Excessive lateral or bending load (realistic longitudinal loads would not pull the material apart), repeated wear at metal wood interfaces (bushings and wood), corrosion of materials	1	Material used for knee flexion joint, material used for pins, joint/pin interface, connection between joint and extrusions, spacing of holes in joint	1	It will be very easy to notice if the joint breaks, and there will likely be some warning that the knee flexion plate is about to break, cracks will be noticable visually and likely audibly	9	Use stronger materials (i.e. metal rather than wood), minimize metal to wood interfaces, avoid press fits in woodto minimize intial cracks

Foot box

Function	Failure Mode	Effects	Sev	Justification	Potential Causes	Occur	Design Controls	Detec	Justification	RPN	Possible Mitigation
Support feet of user	Parts of foot box break or disconnect from each other	Foot box falls apart, likely at the interfaces between pieces of wood	9	Exposed screws and wooden splinters may cause safety hazards, primary function of supporting the user's feet would no longer be achieved	Excessive force on interfaces, repeated wear at metal wood interfaces, corrosion of materials, fasteners (screws) come loose	1	Material used for foot box, material used for fasteners, location and number of fasteners (screws)	1	It will be very easy to notice if the foot box breaks, and there will likely be some warning that it is about to break	9	Use stronger materials (i.e. metal rather than wood), use more screws/attachment points, Reapply or modify coating to improve corrosion resistance

Build Plan

The build plan consists of a build overview detailing the high level considerations, a bill of materials with material pricing and sourcing, and a detailed manufacturing plan that outlines the steps required to produce the foot support device.

Build Overview and Considerations

Throughout the requirements generation, conceptualization, prototyping, and design process, many considerations were discussed to ensure manufacturing potential of the foot support device in Nicaragua. Requirements impacting build are shown below in Table 8.

Table 8. Requirements impacting material selection and manufacturing.

Requirement	Specification
Sourced via common and affordable materials	Devices shall be made from only common materials in Nicaragua such as wood, metals, canvas, cloth, sponge/foam, common scrap materials, vinyl, and velcro. (Cipoletti, M., McKenna, S., video call, September 28, 2021.)
The device shall be manufactured via readily available methods in Nicaragua	All parts shall be manufactured with locally available skills and expertise.
The device shall minimize cost	Device shall cost less than 100 USD.

We have sourced most materials at a hardware store available in multiple Nicaraguan locations, as well as ensured manufacturability with common power and hand tools, minimizing the need for machine shops and more advanced manufacturing equipment. The most advanced tools we propose are wood/metal chop saws and a drill press. While not strictly required, the quality of the end product will be significantly better if these are used, and power tools such as those are generally available given the input from FNE and other stakeholders.

Bill of Materials

To source materials locally in Nicaragua, research was conducted to find online vendors commonly dispersed throughout the country. Materials are almost entirely sources from common hardware stores in Nicaragua, with exception to a few items that must be bought elsewhere. Table 9 below shows the full bill of materials list to develop the foot support. Some sources are still being determined as the bill of materials was sent to FNE to confirm availability of general items.

Table 9. Bill of materials for an adjustable foot support device. Material may be sourced from additional vendors, note that prices and availability may change from the time this report was created.

Item	Qty	Price per Purchase	Units per Purchase	Units Needed	Net Price	Material	Material Source	Manufacturing Method
Seat Foam	1	$30.00 [30]	1	1	$30.00	Foam 2"-3" Thick, 18" x 18" firm seating foam	UBuy Nicaragua, if unable to find locally	Boxcutter Knife
Foot Support Foam	1	$5.00	1	1	$5.00	Foam or pillow type material	Local supplier	Boxcutter Knife
Seat Cover	1	$5.78 [31]	1	1	$5.78	Vinyl shower curtain	SINSA or other available store	Boxcutter Knife
Seat Beams	2	$5.23 [32]	1	0.5	$2.62	2" x 2" x 6 feet wood beam	SINSA or other available store	Table Saw, Circular Saw, or Hand Saw
Seat Plywood	1	$38.30 [33]	4608 in^2	324 in^2	$2.69	~18" x 18" x 12mm (0.5") Plywood	SINSA or other available store	Table Saw, Circular Saw, or Hand Saw
Foot Support Beams	1	$5.23 [32]	1	0.5	$2.62	2" x 2" x 6 feet wood beam	SINSA or other available store	Table Saw, Circular Saw, or Hand Saw
Foot Support Base	1	-	4608 in^2	120 in^2	$1.00	0.5" x 18" x 18"	SINSA or other available store	Table Saw, Circular Saw, or Hand Saw
Foot Support Back Wall	1	-	4608 in^2	96 in^2	$0.80	Currently plywood, using wood	SINSA or other available store	Table Saw, Circular Saw, or Hand Saw
Foot Support Side Panels	2	-	4608 in^2	80 in^2	$1.33	Currently plywood, using wood	SINSA or other available store	Table Saw, Circular Saw, or Hand Saw
Foot support Legs	2	$14.41 [34]	216 in	40 in	$5.34	1" x 1" x [Length]	SINSA or other available store	Miter Saw/Circular Saw/Other Hand Saw
Knee Flexion Pivot Rod	1	$2.02 [35]	1 ft	1 ft	$2.02	Smooth Iron Rod	SINSA or other available store	Chop saw, sandpaper
0.25" ID, 0.375" OD Shoulder Bolts	2	$1.67 [36]	1	2	$3.34	Steel	Local Source or similar to McMaster Carr	-
Knee Flexion Adjustment Rod	1	$2.02 [35]	1 ft	1 ft	$2.02	Smooth Iron Rod	SINSA or other available store	Chop saw, sandpaper
Footbox	1	$2.02 [35]	1 ft	1 ft	$2.02	Smooth Iron	SINSA or other	Chop saw,

Support Adjustment Rod						Rod	available store	sandpaper
Chair Securement Straps	3	Unknown	3 set	3 set	Unknown		Local Source	Boxcutter Knife
Velcro Foot Straps	1	$9.98 [37]	1	1	$9.98	Velcro	SINSA or other available store	Boxcutter Knife
Cotter/Hitch Pins	6	~$0.50	1	1	~$3.00		Local Source	-
Quick Drying Enamel	1	$5.48 [38]	1	1	$5.48	Aerosol Enamel	SINSA or other available store	-
Totals		**$129.31**			**$85.03**			

The final device cost per unit is $85.03, which represents the scaled cost to manufacture multiple devices. However, the cost to buy all required material is $129.31 because some items (plywood, rods, etc) can only be bought in large sizes, and must be cut to smaller dimensions for use on the chair. This makes this an economical design to scale up, and if smaller materials can be found, this initial cost would decrease to the roughly 85 dollar figure. Also note that at large consumer hardware stores such as SINSA, it may be possible to only buy the required smaller sizes and have items like plywood cut into smaller pieces, making initial cost manageable. This may vary depending on the store and availability.

Items that still need to be sourced are generally very accessible items and can generally be found in many locations, so no concern is present to source these items. Stakeholders specified items like different foam types, hardware, and straps can easily be found. One item that was difficult for us to find online for pricing was sheets of vinyl to overlay on the seat and foot support foam. However we found vinyl shower curtains that can be cut to appropriate shapes, providing a waterproof and hygienic surface for the child to sit on. If desired, a removable and washable cloth or other covering may be placed over the vinyl for comfort purposes.

Another difficult item to source without being in-country was chair securement straps. Straps like backpack straps, buckles or other straps will work as long as they are robust and tight enough without breaking.

Manufacturing Steps

The following section outlines details needed in order to manufacture our foot support device. While most details have been included to eliminate required planning, it may be required to rework and adjust device elements while building to fit to a specific chair, user, or material choices. It is recommended that a skilled craftsperson assists in the manufacture of the device.

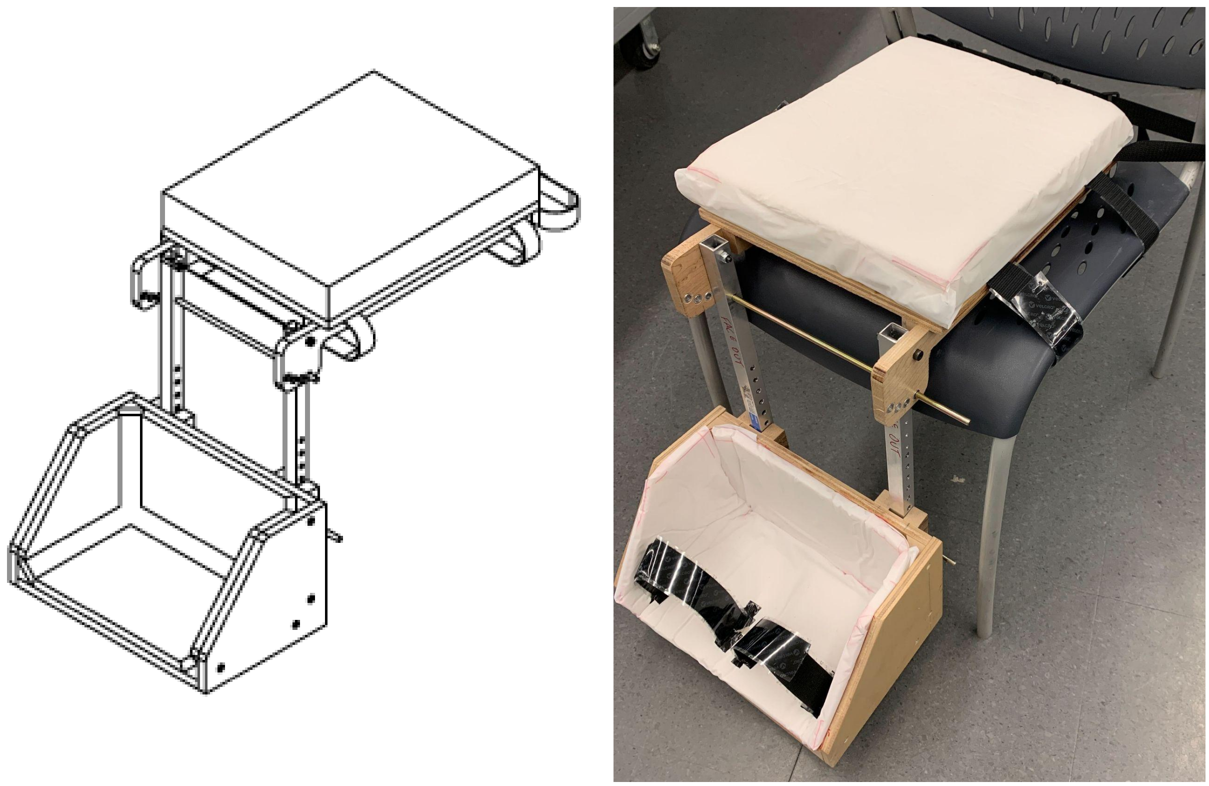


Figure 55. Side by side view of full foot support assembly schematic and a fully manufactured prototype.

To manufacture a foot support device that can be scaled for various users and chairs, measurements must be taken. Table 10 below lists the three dimensions that must be taken of the user's chair or seat that directly impact device fit. These are incorporated in engineering drawings.

Table 10. Dimensions of the desired chair that the foot support device will attach onto. These are incorporated into engineering drawings to provide sizing modifications when building the device

Dimension	Reference Letter
Chair Seat Width	W
Chair Seat Depth	D
Seat Height above ground	H

Tools

The following tools are recommended for manufacturing the foot support device.

- Drill press with a vise and/or clamp to ensure perpendicular holes are drilled
- Table Saw to ensure straight wood cuts
- Band Saw to make extra cuts
- Planer to bring wood down to precise dimensions. A band saw, table saw, or large belt sander may be substituted
- Standard Imperial Drill bit set
    - Ensure that a ¼" drill bit, ⅜" drill bit, and ⅛" drill bit are included.
- If a "U" size drill bit can be found, this is a slightly smaller drill bit than a ⅜". This is used to drill holes that ⅜" diameter bushings can press fit into. A 23/64" drill bit can also be used.
- Additionally, a 17/64" drill bit may be useful to drill ¼" holes larger for fitting the adjustment rods. Depending on the diameter and tolerance of the rod, this may be necessary
- Center Drill Bit

Match Drilling Technique

Match drilling is a technique to stack materials that you need the same feature in (holes and cuts). Stack the two materials together, clamp them onto a drill press or saw table, then make the required cut through both materials at once.

This ensures that all holes and cuts in both parts are identical and aligned. For example, parts that need to go on both sides of the support device are both exactly the same. This is also a good way to produce parts more quickly. Figure 56 and 57 below shows how match drilling is performed.

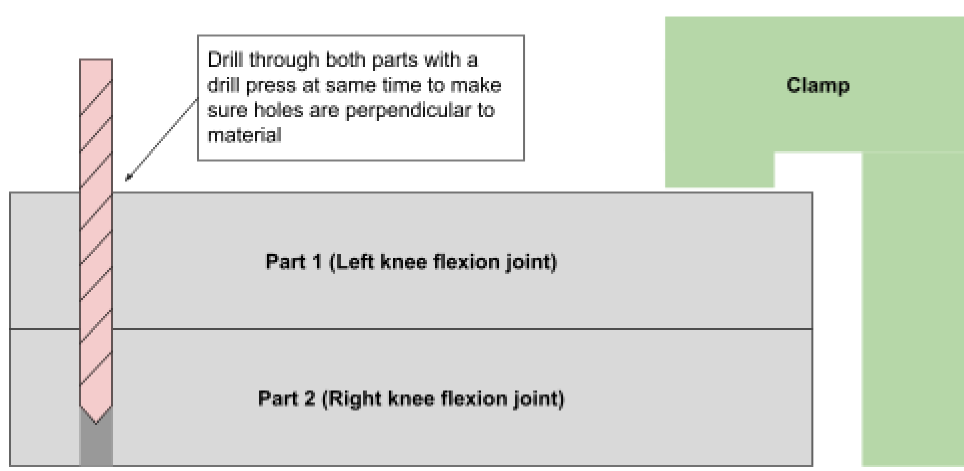


Figure 56. Match drilling example. Both parts are identical, and used symmetrically on the device. A drill press should be used to ensure perpendicular holes. Always center drill prior to drilling through with the intended drill bit.

Figure 57. Match drilling example on a drill press. Both parts are identical, and used symmetrically on the device. Multiple clamps keep the parts aligned with each other and secure on the table.

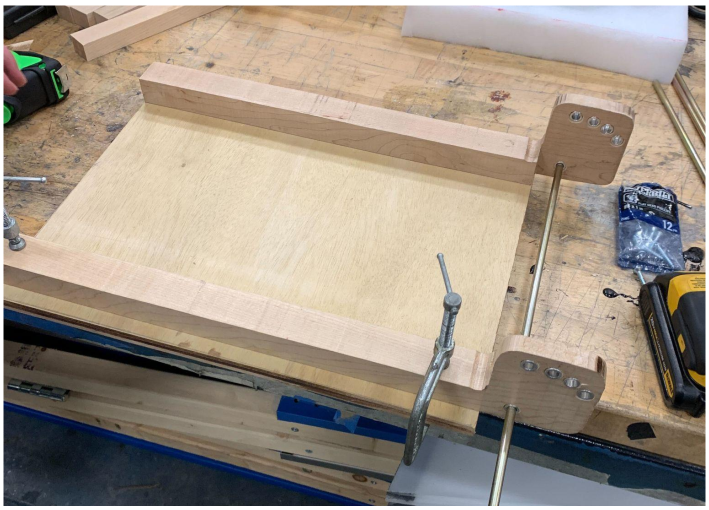
Detailed Manufacturing Plan

> ***Important Note:*** *Pilot holes can be pre-drilled, however it may be beneficial to drill them just prior to screwing the respective screws in to ensure the holes in both parts being assembled align.*

Table 11. Step-by-step overview of the foot support manufacturing plan. Drawings are located in the Appendix D.

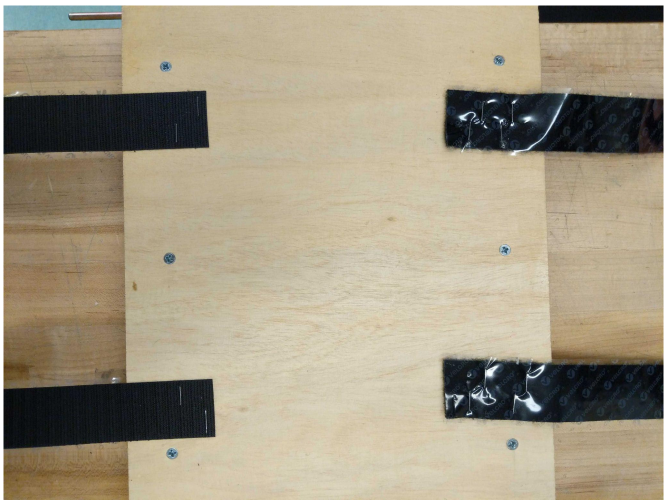
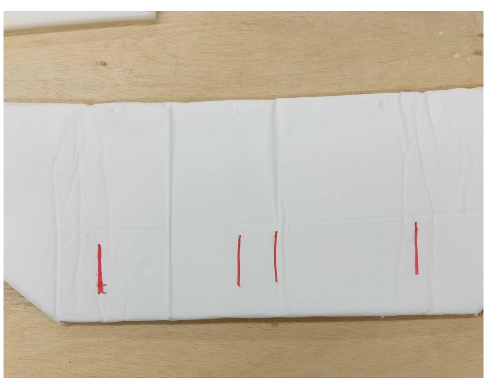
Step	Description and Images	Drawing Name
1	Measure and Note all chair dimensions: • Chair Depth (D) • Chair internal width (W) • Seat height (H) • Any interfering items like old foot supports, etc, that may require modification of the support device	Full Assembly
2	Cut Seat Board to required dimensions based on the drawing Drill pilot holes and other holes required.	Seat
3	Cut foot support plywood to required dimensions in drawing Drill pilot holes in foot supports	Foot Rest Side Plate Foot Rest Back Foot Rest Bottom
4	Cut support structure pieces **Match drill** all holes in support structures from previous step 	Right seat bracket Left seat bracket Foot Rest Legs (Right/ Left) Horizontal Anchor (Right/ Left) Vertical Anchor Back Horizontal Anchor
5	Cut adjustment rods to length	Knee Rod Foot Rest Rod
6	Spray all wooden parts thoroughly with spray enamel or spray paint with glossy finish	-
7	Insert any bushings (0.375" OD, 0.25" ID metal tubes cut to length of holes) into the device where required (all 0.375" diameter holes)	-

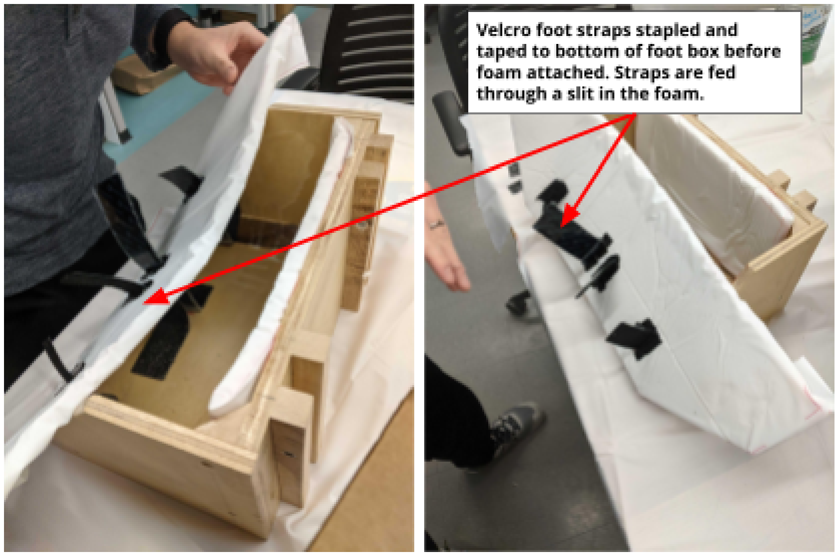

8	Assemble Seat assembly	Seat Assembly



9	Assemble foot box assembly	Foot Box Assembly

10	Assembly foot support beams to connect foot-box and seat together	Full Assembly

11	Attach adjustment rods Use rubber stoppers to secure to the seat, or drill holes in ends and put pins in to secure rods from sliding out.	Full Assembly
12	Cut accessories to size (foam, straps, etc)	-
13	Wrap the foam seating in vinyl on all sides and secure with glue or other methods. Glue the seat pad to the seat. Repeat for foam covering all internal surfaces of the foot box. 	-
14	Foot straps are stapled and taped to the foot box where required prior to attaching foam. Slits must be cut in foot box foam pieces to slide the foam around the foot straps before glueing. The slits are covered with tape to ensure the strap does not damage the vinyl.  	-

		
15	To secure the adjustment rods axially, we recommend two potential methods in order of preference: ● Drill holes on the outside ends through the adjustment rod so that a cotter pin may be placed through [39]  ● Buy a rubber stopper with a small hole through the center and fit the small hole around each end of the rod. The friction of the rubber should prevent axial movement of the rod under expected loading.	-
16	Debur and remove any splinters from seat components.	-

The step by step overview of manufacturing shows major steps to build the device. Critical steps include using appropriate saws for cutting straight lines, since these are used as measuring (datum) surfaces. Additionally, match drilling both pilot holes and final size holes to appropriate dimensions is critical for hole alignment and symmetry of the device.

Alignment of the axis of rotation of the knee flexion joint as well as the holes for the support height adjustability are important to safety, comfort, and quality of the device. Hole patterns in the adjustable height beams are particularly challenging to make, so match drilling will alleviate many issues. To accommodate for locational misalignment, we suggest using nominal drill bits for the ¼" holes in the legs but stepping up the hole size as needed to allow for misalignment. This is an iterative way to minimize potential movement of the device but accommodate misalignment where needed. Figure 58A and 58B below shows the alignment locations of the foot support adjustments.

Figure 58A. Foot support adjustment alignment locations. These axes are critical to be aligned symmetrically about the midplane of the device. The distance shown at the bottom is critical (shown in 44B on the right, as the beam needs to abut against the back of the footbox as shown.

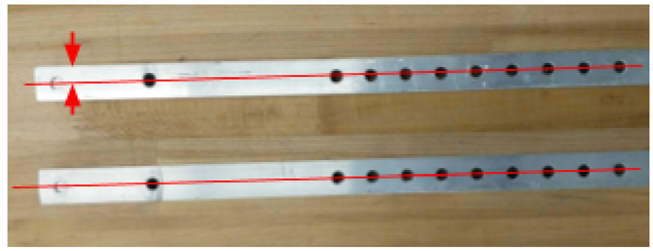


Figure 58B. Hole patterns in the adjustable foot support rods that must be collinear and equidistant to one side of the beam. The beam side abuts to the back of the foot support box, constraining rotation of the device and allowing height adjustability.

A quick manufacturing rig for repeated hole patterns is encouraged to be constructed prior to manufacturing the chair. Figure 59 below shows a drill press rig that can be used to ensure any holes are aligned in one axis.

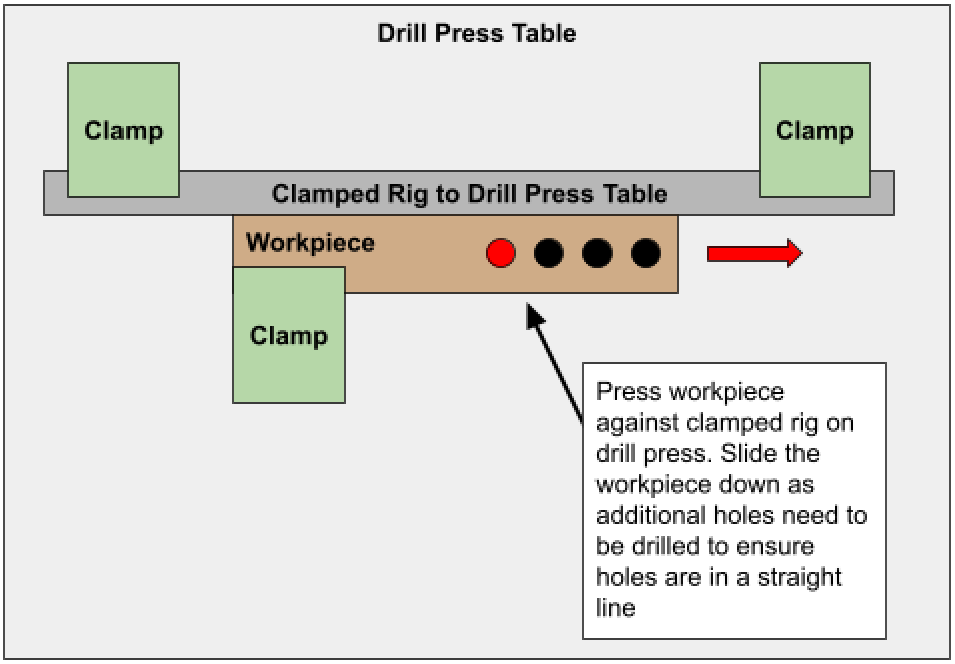


Figure 59. Drill press manufacturing rig for repeating holes in a single axis. Clamp a straight piece of material to the drill press table. Slide the workpiece along the rig as more holes are needed to be drilled in a single direction (as in the foot support legs, which have many ¼" holes spaced 0.75" apart). The red hole indicates the current hole being drilled, and the piece may be shifted right to drill additional holes.

Prior to using the device, the adjustment rods must be secured axially. While we found that the weight of a user on the foot support was sufficient to hold the adjustment rods in place, they must still be secured. This can be done in a variety of ways. We recommend using cotter pins through the end of each shaft as a removable but secure method. Additionally, rubber stops or other methods may be used as a frictional fit to prevent the rod from sliding.

Lastly, all manufactured parts must be safe and deburred, splinters removed, and all safety hazards removed. Personal protective equipment and proper operating procedures should be used at all times when using tools. Surfaces that may degrade, splinter, or otherwise cause harm over time must be covered or enamel/paint must be sprayed on the surfaces. Note in the manufacturing plan that all wood surfaces are spray painted or enameled prior to assembly for further protection. Coverings are used (foam, vinyl, cloth) to cover raw material where possible.

Critical features have been noted in engineering drawing notes. Ultimately, careful attention to hole positioning and material size/selection will most directly impact the quality of the finished product. It is recommended that a skilled tradesperson or woodworked manufactures the device or assists in the manufacturing process.

Operation Procedure and Failure Prevention

Prior to device usage and operation, always check that none of the items below pose a safety issue or indicate deterioration of the materials of the device.

Table 12. Operational procedures and failure identification required prior to using the seat device. All liability is placed on the users and caretakers for ensuring proper operation and safety of the device.

Item	Description
Device is securely attached to the chair and does not move.	Check the straps: Ensure they are not fraying anywhere, ensure the straps are properly connected and tightened, ensure the “buckles” of the straps are not broken anywhere.
Foot support is either secured or removed prior to securing the user in the seat.	Check that the foot support is either fully secured to the legs of the device, or that it is completely off and out of the way in order to help the child into the chair. When the child is seated, check that the foot supports are properly secured and do not move.
Appropriate adjustment positions are known.	Prior to placing the child in the chair, take approximate measurements of the child to fit the foot support adjustments. This will make minor adjustments easier when the child is in the chair.
No mold, moisture, or corrosion of wood and metal is present.	Visually check that there is no wood or foam/fabric damage from moisture. Check for water spots, black mold growth, stains in wood, or damp parts.
Surfaces are clean and free of debris.	Visually check for dust and dirt on all surfaces of the device - make sure there is no visual dirt
No visible splitting or deformation of the wood and metal elements.	Visually check that there is no splitting of wood and physically move parts to ensure that parts do not break under normal loading.
Bolts and screws are not loose or stripped. Any bolts are tightened properly prior to use.	Check bolts before tightening them so that they are not damaged. Ensure all bolts are tightened before placing the child into the device.
Foam coverings are not broken through.	Make sure there are no tears in the seat cover, make sure there is no exposed foam anywhere on the device
No splinters, sharp edges, or pinch points are present where the user or caretaker will be at risk.	Visually check for splinters and pinch points. Remove sharp edges or protect the dangerous surface before placing the child in the device.

Verification and Validation Testing

Verification and validation of our design is a key step in ensuring that our design actually accomplishes the goals it needs to. This is achieved by systematically testing our requirements and specifications and ensuring our design solution meets each one of them.

Verification Plan

Our verification tests focus on the adjustability, robustness, and assemblability specifications of our design. The first test focuses on the vertical adjustability of the footrest. We want to ensure that the footrest can be positioned at regular intervals from 11 inches to 18 inches below the seat. We'll test that capability under multiple conditions: when the footrest is loaded with a weight and when the footrest is being adjusted by one or multiple people.

The next specification we'll test is the range of motion for the knee flexion mechanism. This should be able to be adjusted from 60° to 90°. We will also perform this verification test under multiple conditions like a loaded footrest and having one or multiple adjusters. This will ensure that the footrest assembly can be adjusted easily in a variety of conditions, which will undoubtedly be useful when the footrest is in regular use.

The device should also be robust enough to not plastically deform when subjected to 200lb parallel to the user's legs and 50lb perpendicular to the user's legs. This is especially important to ensure that the device does not break during operational use. This verification test will be performed by applying both continuous and shock loads to the footrest while the device is secured to a seat. This aims to replicate real-world load cases as closely as possible.

The ability of the device to attach to a separate seat quickly while still being secure is an important part of the problem statement provided to us. Therefore, our device must be attachable in under 2 minutes. We will verify this by testing the attachment procedure under conditions like installing it outside and having one versus multiple installers. This will cover most of the range of scenarios in which the device will have to be installed.

The device must also be portable. This is important for allowing the users and their caretakers to easily transport the device when it is not in use. Specifically, the device must fit within a 9 inch by 20 inch by 20 inch volume. We will verify that the device meets this specification by ensuring that the device fits within a box of this volume when in its stowed configuration.

Empirical testing that we will conduct includes a characterization of the deformation of the footrest when subjected to loading. The result of this will likely include a plot and ensuring that the device doesn't tip under loading. We will also test the friction between the device and typical seat materials it might be mounted on to ensure that the straps provide enough force to eliminate any motion of the device relative to the seat.

Verification Testing

Table 13. List of verification tests and associated specifications

Test Number	Specification	Verified?
1	Feet position shall adjust from 11" to 18" below the seat	Yes
2	The foot support shall adjust so the knee is extended from 60° - 90° of flexion	Yes
3	The device should not plastically deform when subjected to 200 lbs in the direction parallel to the user's legs or 50 lbs in any direction perpendicular to the user's legs	Yes
4	The device should take less than 2 minutes to install onto a chair	Yes; it took 57 sec
5	The device should fit within a 9"x20"x20" box during transport	No; the device takes up a rectangular volume of 15” x 19” x 11”, but this could be changed in future designs
6	Device shall weigh less than 10 lbs	Yes; the device weighed 7.1 lb

Table 13 shows verification tests that were performed to verify that the device met these specifications. These specifications were deemed the most important to the proper function and operation during everyday use. Figure 60 below shows the basic setup used for these tests.

Figure 60. The testing setup used for verification testing.

Testing was conducted using one of our team members as a placeholder for the user of the device. Since the members of our team are larger than the intended users (about 2-3 times the user's weight), actions like adjusting the height and angle of the footrest were more difficult than anticipated. For both of these adjustments, it was more difficult to raise the footrest than to lower it, due to the caretaker having to support the weight of the user's legs while adjusting the device. However, adjusting both the height and angle of the footrest were both doable by one caretaker. This gives us confidence that the device, when used by its intended users, will be easily adjustable even with one caretaker.

Figure 61. The device tipping when the user puts their weight onto the footrest

In addition, when testing with our team members, the entire device had a tendency to tip forward when the team member put their weight onto the footrest, as shown in Figure 61. This will require further testing with wheelchairs to ensure that the device is safe and stable.

Figure 62A. Shock testing on the footrest

Figure 63B. We used pieces of foam between the mallet and footrest to avoid damage to the wood

We also conducted some shock testing on the footrest to ensure durability, as shown in Figure 62A and Figure 62B above. We did this testing by striking the footrest with a rubber mallet with a piece of foam in between the mallet and the wood of the footrest with a piece of foam in between.

There are verifications that we didn't formally test due to not having formal testing procedures. These tests and the reasons we didn't test them are listed below in Table 14.

Table 14. List of specifications we did not verify and why they were not tested

Specification	Reason
Feet shall not extend outside the width of the seat	We did not have access to test subjects with feet the same size as the intended users; the footrest was sized to the size of the children's feet to meet this specification
Use of the device shall score less than 3 on the Revised-FLACC Observational Pain Tool	We did not have access to test subjects with CP that would be able to provide accurate test results
Foot shall be able to move a maximum of 1 inches in each direction with respect to the foot	We did not have test subjects with a foot size similar to the intended users

support	
Material shall last at least 3 years without replacement when in use for an average of 16 hours per day	This test could not be completed in the timeframe of our project
Material shall be resistant to water and UV damage	This test would ideally take place over a long period of time, longer than the timeframe of our project; this was mitigated by choosing materials and coatings that would resist these environmental factors
Devices shall be made from only common materials in Nicaragua such as wood, metals, canvas, cloth, sponge/foam, common scrap materials, vinyl, and velcro	While we selected materials online from a Nicaraguan hardware store for our Bill of Materials, we could not formally verify this ourselves from the US
All parts shall be manufactured with locally available skills and expertise	We could not verify this ourselves from the US
Device shall cost less than 100 USD	The proper way to verify this would be to buy the materials in Nicaragua, which we could not do from the US
Device should be attachable to chairs with widths ranging from 10"-18"	We could not find chairs with widths at the proper intervals to formally test this, but we factored this into our design.
Maintenance shall require no more than 2 commonly available tools	Our testing was more focused on adjustment than maintenance; however, our design only requires a drill/bits and a hex key/wrench
Exchanging parts of the device should require no more than 2 commonly available tools and take less than 10 minutes	Our design only requires a drill/bits and a hex key/wrench

Validation

Validation is less of a quantitative process than verification; instead of focusing on the engineering specifications, we focus on the initial stakeholder requirements and create ways to ensure that the design meets those requirements.

The primary function of the device is to support the feet and promote comfortable and proper foot and leg positioning for the user. We will validate this by having our stakeholders confirm that the user finds the device comfortable and that it promotes better foot and leg positioning.

Another requirement is that the device must be made from materials that are common, accessible, and affordable for the stakeholder so that they can build it. We will validate this by sharing our BOM (with material sourcing) with the stakeholders and confirming that all materials are suitable for the stakeholders to use.

In order for the device to be successful, it must be affordable. This ensures that the device can be produced in large numbers for multiple users. To validate this, we will confirm with the stakeholders that the materials and manufacturing cost was less than our budget (100 USD).

The device also needs to be able to be used in a variety of environments. This requires it to be resistant to environmental factors like water and UV damage. The device should be able to last 3 years without replacement when in use for an average of 16 hours per day. This is outside of the scope of our project, since our project was a lot shorter than 3 years. To validate this, we or a future team will confirm with the stakeholders that the device has not degraded too much. The stakeholders can also reference our operating procedures for maintenance information and prevention strategies for different environmental factors.

Finally, the device must be easy and affordable to install and maintain. We will validate this with stakeholders by ensuring that maintenance requires no more than 2 common tools, as well as using the results of our installation time verification test. Together, these tests will validate that our design meets this requirement.

Discussion and Recommendations

Problem Definition

Given more time and resources, we would likely explore the use cases further by traveling to Nicaragua to observe the children and their families and see how they use their wheelchairs now and better understand what they need. Although the information from FNE and SPTLN is very helpful, it is inherently filtered, and we would benefit from being able to conduct observations ourselves. Unfortunately, given the current situation surrounding COVID-19 in Nicaragua, a visit would likely not be possible even with more time and resources.

Design Critique

After multiple prototypes and verification of the design, design critiques were discovered that influence our recommendations in the next section.

First, alignment issues were present in the device prior to modifications made. Many of these issues were expected, and with a device manufactured primarily with wood, alignment issues will not be able to be eliminated. We experienced alignment issues when inserting our adjustment rods into the knee flexion brackets (angle adjustment) and footrest height adjustment. A few root causes included our bushings were not entirely concentric, so though the locational accuracy of the press-fit hole was satisfactory, the bushing hole itself caused misalignment when inserting the adjustment rod in the knee flexion bracket. Additionally, misalignment of wood support pieces on the back of the foot box made the aluminum legs tightly fitted, also affecting the alignment of the adjustment rods. The solution was to drill out the bushing holes larger after the device is assembled. After drilling out any tightly fitting or misaligned holes (as long as it was not excessive), the alignment was fixed and it was very easy to adjust the footrest. As the manufacturing process cannot be tightly controlled, we expect this remedy to be used in Nicaragua.

Another challenge we found was with press fit bushings in the knee flexion bracket. Initially, we used wooden legs with press fit bushings to eliminate a wood-on-metal surface contact between the adjustment rods to enhance durability. However, the press-fit nature of the bushings imparted tensile stresses on the wood (its weakest loading direction) and split the wood during testing. We switched to metal legs, eliminating the issue of wood-on-metal contact, and increasing strength while maintaining our device weight requirement. We still opted to use bushings in the knee flexion joint to avoid a wood-on-metal contact. However, this may present a potential point of failure due to the tensile stresses in that region.

Our members sat in the device for over an hour during testing. They noted that it was comfortable even though they are over six feet tall, which was when the device was in its tallest configuration. We tested foot adjustment with a ~200 lb person, and noted that it was slightly difficult to support the weight of the legs pushing down and align the adjustment rods, however we anticipate that with a much lighter user (child), this issue will be significantly reduced. We also note that the current device likely cannot be placed on a bench unless the bench has slits or boards through which a securement strap may be wrapped around. This applies to any chairs without room for securement straps to be placed. Based on our analysis of images of chairs sent to us by the stakeholders that their end users would use, our design is compatible with those.

If we were to redesign the device, potential improvements would be in the alignment features of the device to eliminate the need for post-assembly adjustments. Due to the almost exclusive use of wooden structural elements, this is highly dependent on the quality of wood, material sourcing, and manufacturing resources available. We would perform extensive research with our stakeholders to determine exactly what tools are accessible to guarantee manufacturability. While we made extensive efforts to understand the constraints in Nicaragua, knowledge of exact machines available would allow us to optimize our design. With additional time, we would be sure to test durability with fatigue loading scenarios and expose the device to harsh UV light and moisture-rich environments to gauge degradation over time.

Recommendations

When manufacturing the device, we recommend match drilling components and using high precision measurements whenever possible. During manufacturing and testing, the most significant issue we noticed was misalignment of adjustment holes as this made it very difficult to change positions. Match drilling and high precision measurements will both help avoid these misalignments. Additionally, we recommend drilling the adjustment holes to be slightly larger than the rod which goes through them to ensure that the rod can move smoothly through even with some misalignment. We also recommend drilling holes for the bushings to be as close to the size of the bushing as possible without being too large, to allow the bushings to be pressed in. This is to avoid cracks in the wood once the bushings are in place.

When installing the device in a chair, we recommend securing the strap on the back half of the seat of the chair before the strap in the front of the chair. This will anchor the device and keep it from tipping forward during installation. Additionally, we recommend using the device in a sturdier, heavier chair or using some external support to keep the chair from tipping. When testing, we found that placing lots of weight on the foot box, like when someone is getting out of the device, would cause the whole chair to tip forward if a lightweight chair was being used. From our testing, this was less likely to happen in a heavier chair as the weight of the chair helped counterbalance the force near the front of the device. Another way to prevent tipping would be to simply avoid putting significant weight on the foot box. From our testing, we found that there was no danger of tipping when the user is sitting in the device, even if they lean forward. Tipping only occurred when the user was getting out of the device and placed most of their weight on the foot box. We did our testing with adults who weigh more than 150 lbs, so it is possible that the weight needed for tipping is far more than the weight of a child who might use the foot support. However, since the load required for tipping is dependent on the chair used, we recommend further testing is performed to ensure the device will not tip when the child is being helped out of the device before a child is placed in the device. We would also recommend further testing or investigation regarding the durability of our device over time. Additionally, we recommend using a rubber stop or pin to keep the adjustment rods from moving laterally.

For future iterations of this design, we would recommend changing the interface between the legs of the device and the foot box. Because the wooden pieces on the back of the foot box span the entire height of the foot box, it is very difficult to see where the holes for height adjustment on the leg are, making height adjustment challenging. We recommend either making these pieces smaller, having them only on one side of each leg, or making them transparent to mitigate this problem. Additionally, we recommend including something to keep the legs from moving away from the foot box during height adjustment as we found that made hole alignment more difficult. This could be easily accomplished by including a piece of wood or metal on the back of the wooden pieces attached to the foot box. In the future, the design might also be changed to allow for continuous adjustment rather than just discrete intervals, although this would likely make manufacturing more complicated. Additionally, if a manual milling machine could be found and used, this would open many opportunities for more robust, precise parts if desired in the future.

Additional Social Considerations

Public Health, Safety, and Welfare

While this foot support is closely related to the health and safety of the user, it does not relate closely to public health, safety, or welfare. The direct impacts of the device are limited to the user and their caretakers, and the device is small and easy enough to manufacture that the implicit effects of the device being made and disposed of are small. As a result, this device will likely not impact enough people significantly to have an effect on public health, safety, or welfare.

Global Context

Our device is inherently global. It is designed to be completely sourced, manufactured, and used in Nicaragua. With some minor adjustments in material selection, this device could be made and used anywhere in the world. These adjustments would primarily serve to ensure that the materials can easily be sourced and manufactured in that particular region.

Economic and Social Impacts of Manufacturing and Disposal

The effects of the manufacturing and disposal of a single device are rather small as the device itself is not very large and uses only common materials. Based on our team’s experience during manufacturing the final prototype, a skilled craftsperson would likely be able to build one of these foot supports within a day or two. As such the manufacturing of one of these devices would likely only impact the single craftsperson and their employer economically. The material costs would not be large enough to impact the suppliers or manufacturers. Regarding social impact, there would likely have to be some sort of relationship between the manufacturer and end user to ensure that any necessary dimensions could be customized. There would also be some small environmental impacts from the production of the wood, metal, and foam used in the device as well as from the electricity needed to operate tools like a drill press during manufacturing.

Disposal of the device would also likely have a fairly small economic and social impact due to the relatively small size of the foot support. The device as a whole could be disposed of in a landfill easily; this would have the least economic impact but the most significant environmental impact. Alternatively, the device could be taken apart and fasteners, straps, and rods could be reused while the wood, metal, and foam could be recycled or repurposed. This would require the device to be fully disassembled and for the clear coat to be removed from the wood, however. As a result, this method of disposal would have a much more significant economic impact as a result of the labor costs associated with disassembly in exchange for a much smaller environmental impact associated with the inherent biodegradability of wood and reusability of non-recyclable components.

To identify the social and economic costs related to our foot support, we used only a stakeholder and ecosystem map which can be seen in Figure 2. Because our device is relatively small and only uses common, well understood manufacturing processes and materials, we did not feel more sophisticated tools such as an eco-audit would be necessary to understand these impacts.

Effects of Cultural Similarities and Differences

Although each member of the team comes from a different background, we all are part of the same culture as college students in America. As a result, we were able to easily communicate with each other and develop a strong rapport which is integral to the proper functioning of a team. This would still be possible if we did not have a shared culture, but it would have taken more time and effort throughout the semester. Because we shared cultural similarities, our team was able to easily work together and understand each other. Additionally, because each of our members has a very similar academic background, we are all familiar with the same design processes and tools coming from our shared curriculum. This allows us to better understand our design process and focus on the nuances amongst any differing opinions and ideas.

Our sponsors also shared some important cultural similarities. Many of the sponsors and stakeholders we spoke with were American which meant there was a shared understanding of the environment we were designing in. This also meant that during our discussions, there was no language barrier or issue with discussions of units. These barriers do exist, however, between us and our end users. Because we are American, we typically work with imperial units and in English, so we designed our device using those units and language. However, our end users in Nicaragua will likely require instructions to be in Spanish and use metric units instead. As a result, significant work will be needed to convert our final build plan into a form which can be easily used by craftspeople in Nicaragua. Additionally, because of the language barrier, it was sometimes difficult to find out if certain materials or processes are available in Nicaragua. Therefore, we were left with uncertainty about the potential implementation of our design at times and had to guess whether or not the materials and manufacturing processes we planned to use would be available. Additionally, because we are students and the stakeholders we met with were mostly healthcare professionals, we had to maintain professional interactions throughout. This created an interesting dynamic because as engineers, we also had significant power in this relationship.

Conclusion

Cerebral palsy (CP) is a lifelong congenital disorder of movement and muscle tone which varies greatly in symptoms and severity among those affected by the disorder. While the condition itself is non-progressive, musculoskeletal symptoms can worsen with age and severity of the disorder, if proper support devices are not used. In the United States, custom chairs and orthotics are commonplace, but these are often very expensive. Due to significant economic challenges in Nicaragua, we have been tasked to develop an adjustable foot support that is sustainable and affordable. This support should allow for children with CP to better engage with society and reduce discomfort sitting in chairs for long periods of time.

Our primary stakeholders include Monica, a teenage girl with Stage 3-4 cerebral palsy in Nicaragua, and her parents who serve as her main caregivers. We are working with BLUELab EASE and nonprofit organizations FNE International and Salud Para Todos Los Niños to develop a solution which will work for Monica and that can be scaled for other children with CP. To fully understand the challenge at hand, we analyzed primary use cases which were used to develop requirements and specifications. Our main requirements ensure that the foot support will promote proper foot and ankle positioning, be sustainable for manufacturing in Nicaragua, and be safe and easy to maintain with few required resources.

We have worked through our concept generation process and made use of multiple ideation techniques, including brainstorming, morphological analysis, and design heuristics. After gathering a multitude of different concepts, our initial cluster of over 100 designs was iterated upon and narrowed down to five final designs. A Pugh chart was used to compare how well these final designs fulfilled our design requirements and specifications. Given these considerations, our alpha design was determined to be an attachable seat pad with a height/angle adjustable foot box.
With our alpha design selected, we moved forward with iterating our alpha design to fit the needs of our stakeholders

After receiving critique from stakeholders regarding the alpha design, we made Design improvements to better align with the design requirements. Design improvements we made to our alpha design include removing the telescoping extrusions under the seat, incorporation knee flexion into the shafts, and adding foam to the inside of the footbox for added comfort. We made other minor modifications as well as flushed out design uncertainties when iterating through design ideas and prototyping. After making final design modifications, we moved forward with constructing our final design prototype for verification and validation testing. Throughout manufacturing and assembly, we discovered many design weaknesses regarding manufacturability, ease of use, and precision, but also discovered many design strengths during verification and validation testing such as the high rigidity and comfort of the end product. Along with this final prototype, we have also developed a detailed manufacturing plan to pass along to BLUELab EASE and FNE International to review and iterate upon in order to determine the viability of our design for its intended use.

Acknowledgements

This project has been a fantastic design and learning experience for all of our team members, and it would not have been possible without many fantastic people who have helped us throughout our design process.

First and foremost, our team would like to thank ME 450 Team 3, composed of Sara Groenke, Layla Mohamed, Charles Newton, and Mary Tindall. This team has kept in close communication with us to discuss design changes and updates regarding stakeholder preferences, and Sara especially has made it super easy for our team to stay updated on the status of our stakeholders. They were super great to work with, and were our companions during this design project course.

Next, we would like to acknowledge FNE International, SPTLN, and BLUELab EASE for remaining flexible with their schedules, and always providing valuable feedback for our design process. They were crucial for our understanding of the design problem, especially with providing us with all of the information we needed regarding our primary stakeholders who we were unable to directly contact.

Our team would also like to express gratitude to Hunter Gandee, Donn Hilker, and Joanna Thielen. Especially in the beginning while gathering background information of our design problem, Hunter Gandee and Donn Hilker provided us with incredibly valuable information regarding cerebral palsy, how patients counteract its symptoms, and understanding technical and social contexts of orthotic medical devices. Joanna Thielen greatly streamlined our research process. After consulting with her about research methods and traversing academic databases, our efficiency increased tremendously and we were much more successful in finding highly valuable, relevant information.

We would also like to extend our thanks to the staff members of the ME Shop and CSED Prototyping Laboratory, for allowing our team members to use their machinery and assisting us with manufacturing processes such as table sawing. Without them, we would not have been able to manufacture our prototypes to the degree that we did.

Finally, our team would like to express our deepest regards to the ME 450 Teaching Staff and especially Prof. Steven Skerlos. ME 450 and its curriculum has provided us with the necessary resources to ensure that we would effectively tackle our design problem with best design practices. Prof. Steven Skerlos ensured that we followed a productive path, and provided us with the necessary advice to successfully accomplish our goals. He provided us with invaluable insight on how to approach a complex social design problem, and how to handle the potential challenges. Our team has been highly motivated to absorb this insight surrounding design engineering, and has been a fantastic mentor in guiding us to our final deliverable.

References

[1] “Prevalence of Cerebral Palsy,” CerebralPalsy.org, Stern Law, PLLC, accessed September 28, 2021, https://www.cerebralpalsy.org/about-cerebral-palsy/prevalence-and-incidence.

[2] “QUICKIE Tilt-In-Space Wheelchairs,” QUICKIE wheelchairs, Sunrise Medical, accessed October 1, 2021, https://www.sunrisemedical.com/manual-wheelchairs/quickie/tilt-in-space-wheelchairs.

[3] “Gross national income per capita in Nicaragua from 2010 to 2020,” Statista, Ströer, published September 15, 2021, https://www-statista-com.proxy.lib.umich.edu/statistics/1070158/gross-national-income-per-capita-nicaragua/.

[4] “Design Thinking,” IDEO U, IDEO, accessed October 7, 2021, https://www.ideou.com/pages/design-thinking.

[5] “Spastic Cerebral Palsy,” Types of cerebral palsy, Cerebral Palsy Alliance, updated November 18, 2015, https://cerebralpalsy.org.au/our-research/about-cerebral-palsy/what-is-cerebral-palsy/types-of-cerebral-palsy/spastic-cerebral-palsy/.

[6] “Gross Motor Function Classification System,” Severity of cerebral palsy, Cerebral Palsy Alliance, accessed October 4, 2021, https://cerebralpalsy.org.au/our-research/about-cerebral-palsy/what-is-cerebral-palsy/severity-of-cerebral-palsy/gross-motor-function-classification-system/#collapseOne.

[7] “Cerebral palsy,” Diagnosis & treatment of cerebral palsy, Mayo Clinic, published September 1, 2021, https://www.mayoclinic.org/diseases-conditions/cerebral-palsy/diagnosis-treatment/drc-20354005.

[8] S. Buxton, N. O'Reilly, A. Alshehri, L. Hampton, K. Jackson, R. Gadgil, S. Ajeyalemi, G. Prudden, A. Patro, and S. Winter, “Orthotics in cerebral palsy,” Physiopedia, accessed September 28, 2021, https://www.physio-pedia.com/Orthotics_in_Cerebral_Palsy.

[9] “Graham-Field Everest and Jennings Wheelchair Footrest,” Healthy Products for You, accessed October 3, 2021, https://www.healthproductsforyou.com/p-graham-field-everest-and-jennings-wheelchair-footrest.html

[10] “Orion II 500 Tilt-in-space Tilting Bariatric Wheelchair 500lbs - WMA5FM010 by Future Mobility,” American Quality Health Products, accessed October 3, 2021, https://americanqualityhealthproducts.com/rehab-wheelchairs/5000-orion-ii-500-tilt-in-space-reclining-wheelchair.html#/front_riggings-omit_front_rigging/foot_plate-composite_flip_up_footplates_large/future_mobility_back_pins_prism_backs_only-no_thanks/arm_type-2_point_fixed_height_heavy_duty_arm_standard/pushbar_options-stroller_bars_fixed_low_standard/back_color_if_back_is_not_omitted-i_omitted_the_back_option.

[11] “Wheelchair Legrest Padding,” RehabMart.com, accessed September 25, 2021, https://www.rehabmart.com/product/wheelchair-legrest-padding-40102.html.

[12] Wei, P., Fan, P., Wang F., Liu X., Child end seat for cerebral palsy. CN208925601U, filed May 7, 2018, issued June 4, 2019

[13] Christensen Jr, T. B., Foot Rest, CA2067281A1, filed April 27, 1992, issued December 11, 1992

[14] Applegate, J., Campau, J., Froling, K., Grebovic, H., and Tran, M., 2021, “Postural Support Device for Children in Low-Income Families,” University of Michigan MECHENG 450.

[15] Sees, J. and Miller, F., 2021. The Foot in Cerebral Palsy. *Foot and Ankle Clinics*, published August 17, 2021, https://www-clinicalkey-com.proxy.lib.umich.edu/#!/content/journal/1-s2.0-S1083751521000711?scrollTo=%23hl0000165.

[16] “Determining seat width for a wheelchair,” Karman Healthcare, Karman Healthcare, Inc., accessed October 3, 2021, https://www.karmanhealthcare.com/determining-the-seat-width-for-a-wheelchair/.

[17] International Organization for Standardization. *Wheelchairs. Determination of dimensions, mass, and manoeuvering space*. BS/ISO 7176-5:2008. London, England, UK: BSI, published September 30, 2008;

[18] International Organization for Standardization. *Wheelchairs. Wheeled mobility devices for use as seats in motor vehicles*. BS/ISO 7176-19:2008+A1:2015. London, England, UK: BSI, published December 31, 2015.

[19] ASTM International, *Standard Performance Specification for Water-Resistant Rainwear and All-Purpose, Water-Repellent Coat Fabrics.* D7017-20. West Conshohocken, PA: updated August 13, 2020.

[20] Cooper, Heather L., "ME Capstone Design Process Framework", Presentation in ME 450 Capstone Design Course, Ann Arbor, MI, 2020

[21] Singh, A. P., “Knee Range of Motion and Movements,” Bone and Spine, accessed October 3, 2021, https://boneandspine.com/knee-range-of-motion/.

[22] Miller, F., 2019, “Ankle Equinus in Cerebral Palsy”, “Cerebral Palsy”, Miller, F., Bachrach, S., Lennon, N., and O’Neil, M., Springer Nature Switzerland AD, Switzerland, p.p. 7.

[23] “Sitting Techniques: the 90° Rule,” Northeast Spine and Sports Medicine, published May 4, 2016, https://www.northeastspineandsports.com/sitting-techniques-using-90o-rule/.

[24] Green, C., “Do you get back pain from sitting at your desk?,” OrthoCarolina, published June 24, 2015, https://www.orthocarolina.com/media/do-you-get-back-pain-from-sitting-at-your-desk.

[25] Malviya, S., Voepel-Lewis, T., Burke, C., Merkel, S., and Tait, A. R., 2006, “The revised FLACC observational pain tool: improved reliability and validity for pain assessment in children with cognitive impairment,” Pediatric Anesthesia, 16(3), pp. 258-265.

[26] International Organization for Standardization. *Wheelchairs. Requirements and test methods for static, impact and fatigue strengths*. BS/ISO 7176-8:2014. London, England, UK: BSI, published December 31, 2014; amended July 31, 2016.

[27] “Young’s Modulus, Tensile Strength and Yield Strength Values for some Materials,” The Engineering Toolbox, Engineering Toolbox, 2003, https://www.engineeringtoolbox.com/young-modulus-d_417.html. [Accessed: 25-Oct-2021].

[28] “Aluminum 6061-T6; 6061-T651” ASM Aerospace Specification Metals Inc., MatWeb LLC, accessed 15 December 2021, http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6

[29] “Wood, Panel and Structural Timber Products - Mechanical Properties,” The Engineering Toolbox, Engineering Toolbox, 2011, https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html. [Accessed: 16-Nov-2021].

[30] "UBuy Nicaragua" Seat cushion design, UBuy Co., accessed 23 November, 2021, https://www.ubuy.com.ni/en/search?q=seat+cushion+design

[31] "VINIL ARO FROST" SINSA hardware store, SINSA, accessed 23 November, 2021, https://www.sinsa.com.ni/accesorios-decorativos/cortina-ba%C3%B1o-vinil-aro-frost-150x200-cm-hplus/producto/100717261_100717261

[32] “CUARTON 2 X 2 X 8 PIES” SINSA hardware store, SINSA, accessed 15 December 2021, https://www.sinsa.com.ni/madera-seca-y-cepillada/cuarton-2-x-2-x-8-pies-seco-y-cepillado-victoria/producto/100683531_100683531

[33] "PLYWOOD 4 x 8 PIES", SINSA hardware store, SINSA, accessed 23 November, 2021, https://www.sinsa.com.ni/plywood/plywood-4-x-8-pies-1-2-12mm-b-b/producto/100998226_100998269

[34] "TUBO CUADRADO NEGRO 6MTS" SINSA hardware store, SINSA, accessed 23 November, 2021, https://www.sinsa.com.ni/tuberia-negra/tubo-cuadrado-negro-6mts-ch-16-1x1/producto/100780796_100780913

[35] "HIERRO LISO 1/4 6MM NAC", SINSA hardware store, SINSA, accessed 23 November, 2021, https://www.sinsa.com.ni/angulares/angular-metalico-6mts-3-x-3-x-1-4-x-6-mts/producto/100713411_100713411

[36] “Alloy Steel Shoulder Screw”, McMaster Carr, McMaster Carr, accessed 15 December 2021, https://www.mcmaster.com/91259A544/

[37] "CINTA ADHESIVA VELCRO" SINSA hardware store, SINSA, accessed 23 November, 2021, https://www.sinsa.com.ni/fijacion/cinta-adhesiva-velcro-3-42x5pies-crema/producto/100924382_100924446

[38] “SPRAY HARRIS 11 ONZA:BRILLANTE TRANSPARENTE” SINSA hardware store, SINSA, accessed 15 December, 2021, https://www.sinsa.com.ni/spray/spray-harris-11-onza-brillante-transparente-brillante-superior/producto/100771347_100771486

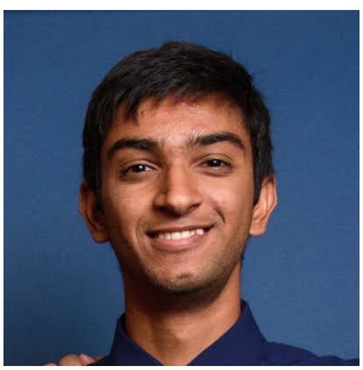
[39] “Hairstyle Style Cotter Pin” Stainless Depot, Jacob Schmidt and Son., accessed 15 December, 2021, https://stainlessdepot.com/products/hairpin-style-cotter-pin-fits-3-8-7-16-shaft

Biographies

Vince Scalise

I am currently a senior studying Mechanical Engineering with a minor in Computer Science. I plan to return to the University of Michigan next year to pursue my Master’s degree in Mechanical Engineering with a concentration in Design through the SUGS program. I was born in Chicago, IL and have lived there my whole life. In the future, I hope to work in a product design role in one of the following industries: automotive, robotics, consumer electronics, or healthcare. This is the reason why I was always interested in mechanical engineering. I never knew for certain what industry I wanted to work in, but I knew that no matter what decision I made, I could get there through mechanical engineering because of the breadth of knowledge you gain as a mechanical engineering student, and so far this has proved to be true. Outside of school, I am the president of Theta Tau Professional Engineering Fraternity and I am also a member of MRacing, the Michigan student Formula SAE Electric team. Hobbies of mine include playing basketball, playing guitar, and singing, and I have recently become a bit of a 3D printing enthusiast.

Arjun Sundararajan

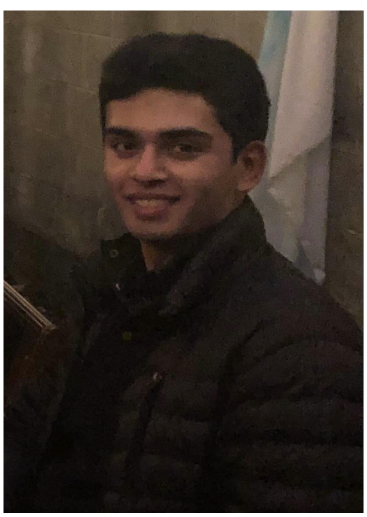


I am currently a senior studying Mechanical Engineering with minors in Computer Science and Math, and I intend to pursue a Master’s degree in Mechanical Engineering through the SUGS program next year. I am originally from Naperville, Illinois, and in the future, I hope to work in the aerospace industry, specifically in the civilian space sector, before returning to school to pursue a PhD and continue in academia. My interest in mechanical engineering stems from its versatility. Coming into college, I had very little idea of what I wanted to do, so I was drawn to mechanical engineering by its breadth of possibilities. Since then, I have become more interested in manufacturing as well as mechanical design in general. Outside of the classroom, I am a member of MASA, which is the student rocketry team at U of M, as well as Tau Beta Pi (TBP), the engineering honor society. Through TBP, I served as a director for the 2021 Fall Engineering Career Fair hosted by SWE/TBP. In addition, I am currently a research assistant in the Computational Physics Group and an Instructional Aide for Engineering 110: Design Your Engineering Experience. In my free time, I enjoy playing video games, watching basketball, and trying new foods.

Wonyul ("Sean") Lee

I am a senior studying Mechanical Engineering with a minor in Computer Science with the intention of pursuing a Master's degree in Mechanical Engineering through the University of Michigan's SUGS program. I grew up in Ann Arbor, Michigan right next door to U of M, and have always aspired to become a Wolverine and an engineer. Growing up, I always had an interest in STEM, but it wasn't until my high school mechanical physics class that I decided to pursue mechanical engineering. I have a strong interest in structural mechanics because I think it is super cool to understand how the world behaves, and why structures are built the way they are. Combining this with the desire to express my creativity whenever possible, I plan on pursuing a career in product design/design engineering after graduation with the intent of making meaningful contributions to society through design. I am currently part of Michigan Club Swimming, Michigan Melee, and the Korean-American Scientists and Engineers Association (KSEA) here at the University of Michigan while also being employed as an Instructional Aide for MECHENG 211, Intro to Solid Mechanics. Some of my favorite hobbies include swimming/water polo, calisthenics, cooking, and playing video games with my friends.

Rohan Valluri



I am a senior in Mechanical Engineering, with the intention to continue to either the Space Engineering Masters through the SUGS program or a Masters in Aerospace Engineering at a different school. I am from Ashburn, Virginia and chose Mechanical Engineering to get a broad background in different aspects of engineering. I'm passionate about spaceflight and space exploration and avidly keep up to date with events in the industry. Outside of class, I am the Instrumentation and Sample Handling lead for the Michigan Mars Rover Team and I'm also involved in the Northrop Grumman Satellite Servicing team through the Multidisciplinary Design Program. I hope to work in the civil space industry once I graduate. In my free time I enjoy fencing (I'm part of the Michigan club team), reading science fiction, playing with my dog, and playing video games.

Michael Kalata

I am a senior studying Mechanical Engineering with the intent on pursuing a Masters Degree in Mechanical Engineering through the SUGS program post-undergrad. I am from Grosse Ile, MI, and throughout my life have always been passionate about aerospace and engineering. I chose Mechanical Engineering because I felt it was a broad and applicable discipline where I can make the most impact on society, working in the aerospace industry and beyond. While pursuing my undergraduate degree, I have been an active member on the Michigan Mars Rover team, designing and testing a Mars-like rover each year from the ground up to compete in the Utah desert. This has furthered my interest in the aerospace industry, taught me so many practical engineering skills, and also broadened my horizons to understand how I can make an impact on society. I find engineering most rewarding when leading and seeing other people grow as engineers alongside me. My future plans post-graduation include SUGS and working within the Aerospace and/or Sustainable energy industry on some of the most vital challenges to society today. Some of my personal hobbies include boating, working on my Private Pilot's License, hiking/backpacking during the summer months, and working out.

Appendix A: Reference Dimensions for Wheelchairs with Handrims

Table 15. Table describing dimensions of wheelchairs with handrims. A similar table for wheelchairs without handrims is included, and the relevant dimensions for footrests (highlighted in red) are the same for both cases [17].

Table 1 — Reference set-up values for wheelchairs with handrims

Item Differing terms used in ISO 7176-7 and ISO 7176-22 are given in [brackets].	**Reference set-up values** Occupant mass group I (< 50 kg)	 II (50 to 125 kg)	 III (> 125 kg)
Seat plane angle (degrees)	4	4	4
Effective seat depth (millimetres)	340	450	450
Effective seat width [a] (millimetres)	320	450	500
Seat surface height at front edge (millimetres)	470	520	520
Back support angle [backrest angle] (degrees)	10	10	10
Back support height [backrest height] (millimetres)	340	420	420
Handgrip height (millimetres)	820	950	950
Back support width [backrest width] (millimetres)	320	450	500
Footrest to seat (millimetres)	340	450	450
BUT NO LESS THAN: Footrest clearance (millimetres)	50	40	40
Footrest length (millimetres)	150	150	150
Footrest to leg angle (degrees)	90	90	90
Leg to seat surface angle (degrees)	90	97	97
Armrest height (millimetres)	160	200	200
Front of armrest to back support [front of armrest to backrest] (millimetres)	200	320	320
Handrim diameter (millimetres)	490	530	530
Manoeuvring wheel diameter [propelling wheel diameter] (millimetres)	560	610	610
Wheelbase (millimetres)	340	400	400
Camber (degrees)	–3	0	0
Horizontal location of wheel axle (millimetres)	20	20	20
Vertical location of wheel axle (millimetres)	166	184	184
Castor wheel diameter (millimetres)	150	175	175
Castor trail (millimetres)	35	50	50
Track of drive wheel or manoeuvring wheels [drive wheel track width]	mid-position		
Track of castor wheels or pivot wheels [castor wheel track width]	mid-position		
Movable wheel, horizontal position [castor stem housing position, horizontal]	mid-position		
Movable wheel, vertical position [castor stem housing position, vertical]	mid-position		
Movable wheel, vertical axle position [castor wheel axle position, vertical]	mid-position		
Castor rake [castor stem angle, fore-aft plane] (degrees)	vertical +1 / –0		
Castor cant [castor stem angle, lateral plane] (degrees)	vertical ± 0,5		

[a] Since the nominal seat width (as measured in ISO 7176-7 as "seat width") is measured in various ways the results are not comparable. Therefore, the effective seat width is used as the reference value since this dimension both provides reliable comparison between the values and meets the occupant's real needs.

[b] These adjustments are used only when they do not conflict with any seating adjustments.

Appendix B: Loading Scenarios of Traditional Wheelchair Foot Supports

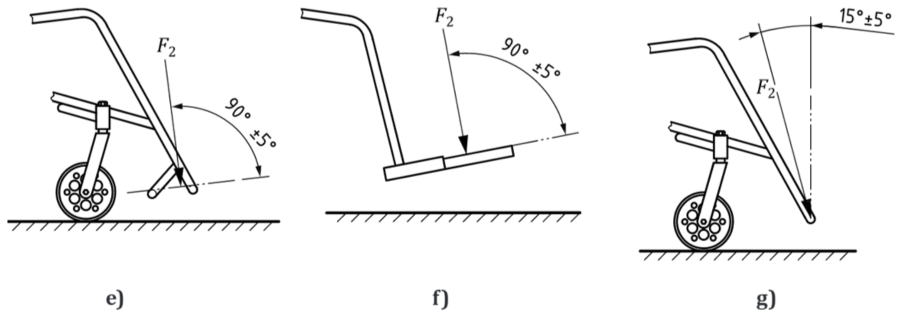


Figure 11 — Location of foot support loads for different foot support types

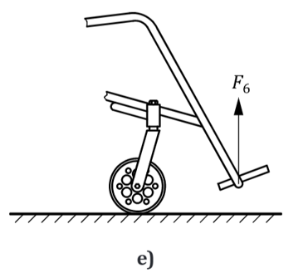


Figure 17 — Location of foot support upward forces

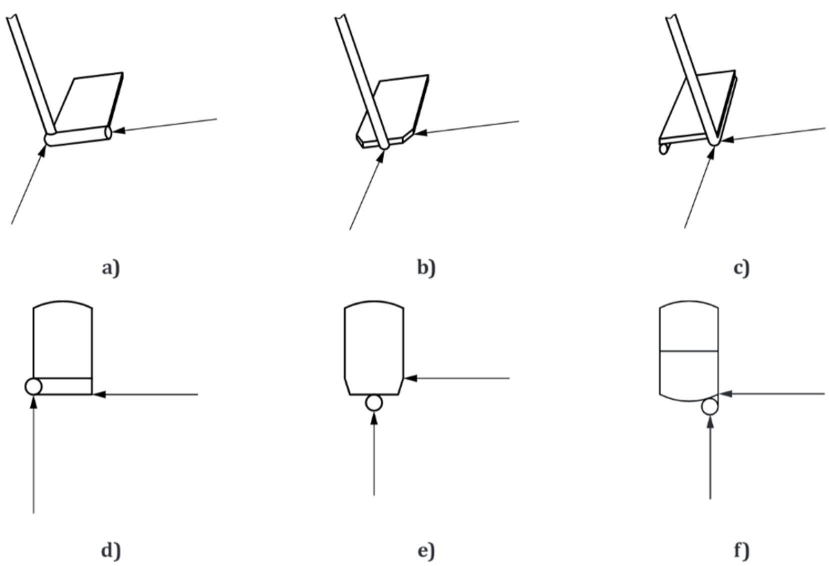


Figure 27 — Location of impact force on various foot supports

Figure 63. Various loading scenarios of traditional wheelchair foot supports. The three loading scenarios each have different magnitudes of loading, and are offered different testing procedures for each case [26].

Appendix C: Sketches of Some Ideas from Concept Generation

Some of our initial 112 concepts are presented here, grouped by the technique we used to generate those concepts. For the sake of clarity and brevity, many of these concepts are excluded.

Brainstorming

Figure 64. Idea 89: Adjustable rod support

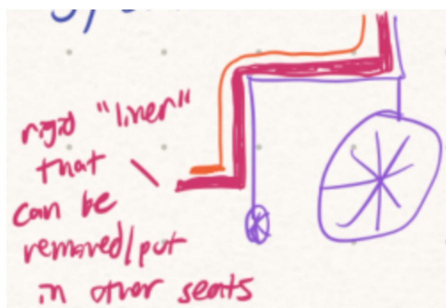


Figure 65. Idea 72: Seat liner footrest

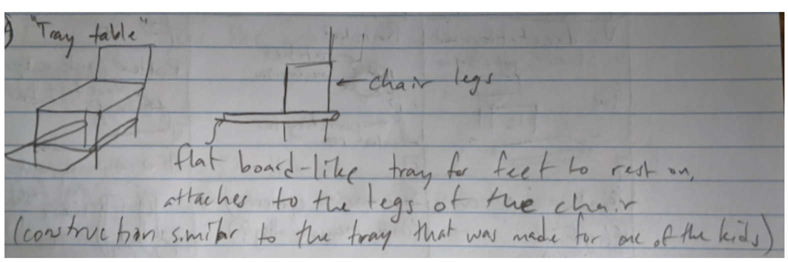


Figure 66. Idea 34: Tray Table

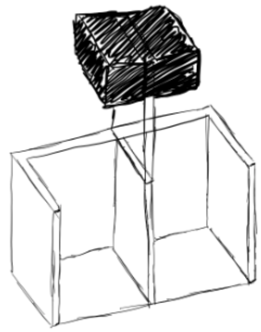


Figure 67. Idea 92: Separate box support with pommel

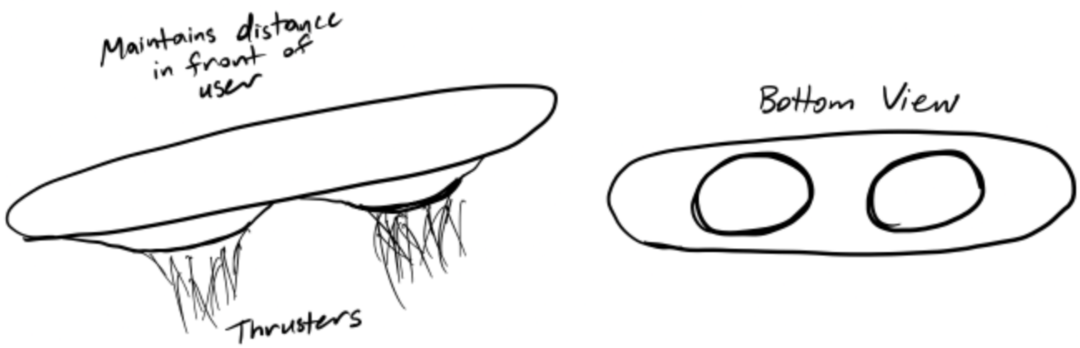


Figure 68. Idea 38: Hoverboard

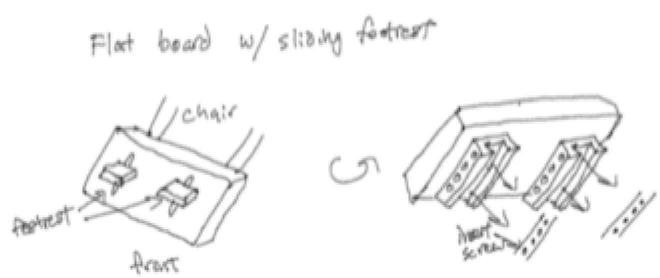


Figure 69. Idea 33: Simple plank with adjustable foot platform

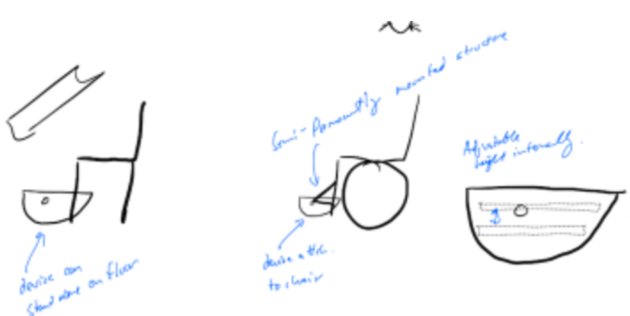


Figure 70. Idea 24: Rocking roller device

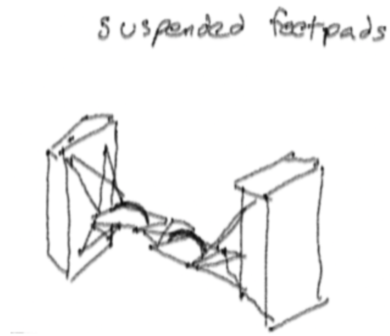


Figure 71. Idea 51: Suspended footpads

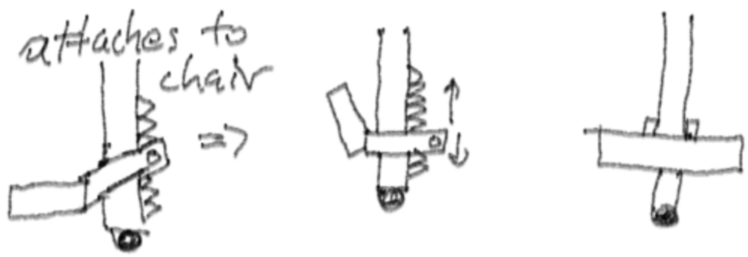


Figure 72. Idea 50: “Weight Machine” adjustable footrest

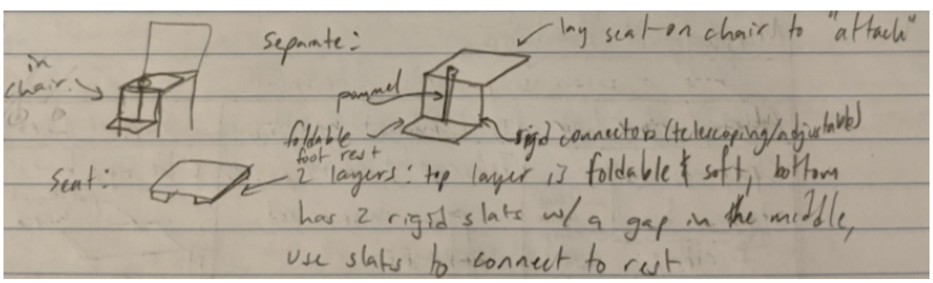
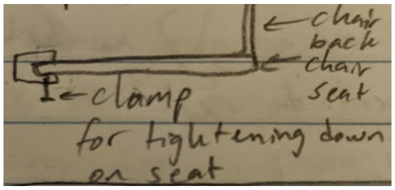
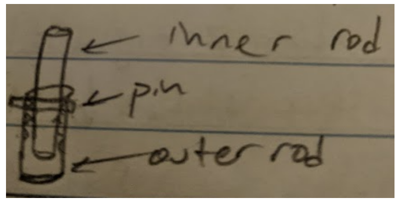
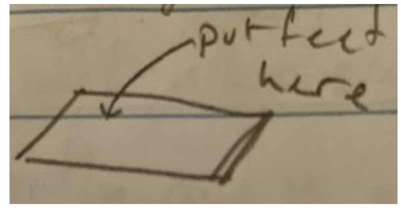
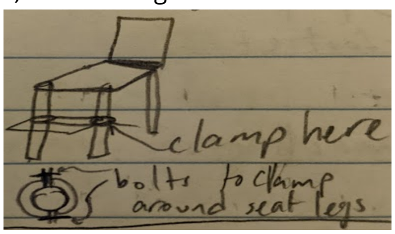
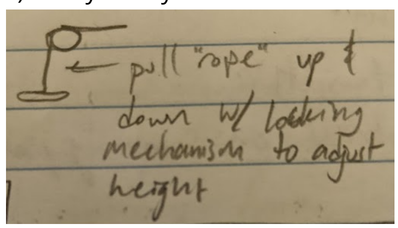
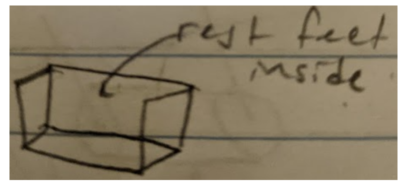
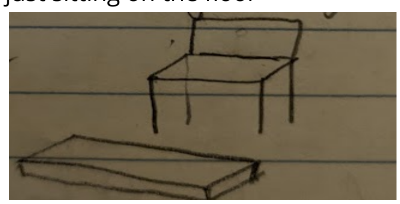
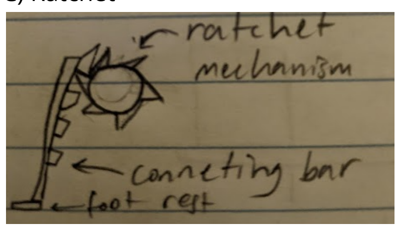
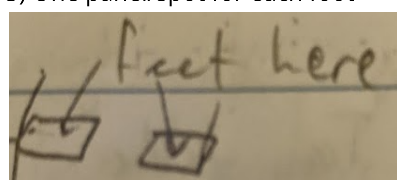
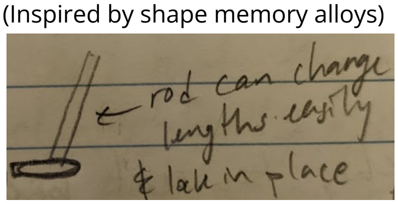
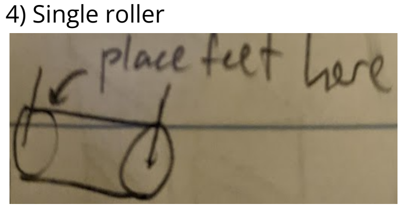
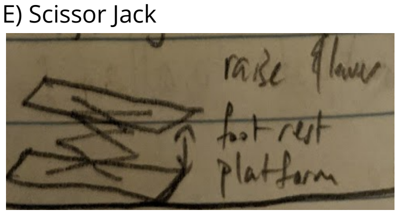
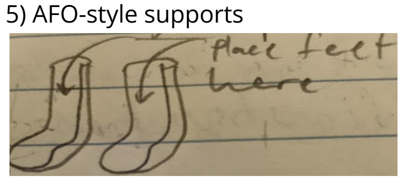
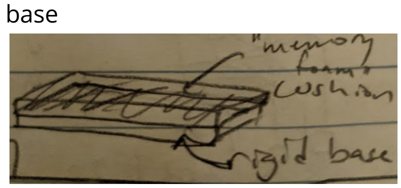


Figure 73. Idea 29: Foldable seat and rest with pommel

Morphological Analysis

Table 16. Morphological Analysis chart showing different functions and concepts to fulfill each function. Each concept is labelled with an uppercase letter, lowercase letter, or number to make it easier to keep track of the combinations used as complete ideas.

Adapt to Chair	Adjust Height	Support Feet
a) Clamp to seat 	A) Telescoping rods with pin locks 	1) Flat rigid board 
b) Attach to legs 	B) Pulley-like system 	2) Box in feet 
c) No direct attachment to chair, just sitting on the floor 	C) Ratchet 	3) One panel/spot for each foot 
d) Seat placed on chair 	D) Semi-elastic connecting rod (Inspired by shape memory alloys) 	4) Single roller 
	E) Scissor Jack 	5) AFO-style supports 
		6) Deformable board with rigid base 

Design Heuristics

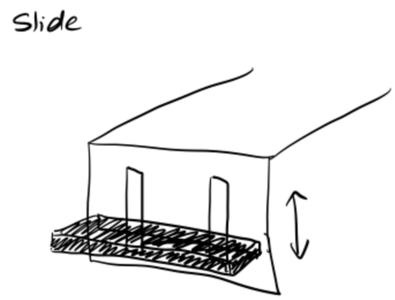


Figure 74. Idea 107 using Card 61 - “Slide”: Vertical Sliding Foot Platform

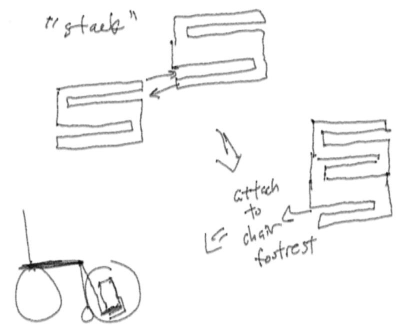


Figure 75. Idea 112 using Card 62 - “Stack”: Stackable Block Attachments for Height Adjustability

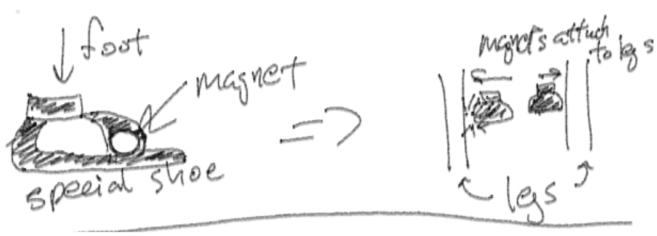


Figure 76. Idea 109 using Card 15 - “Attach Product to User”: Magnetic Shoe and Foot Support

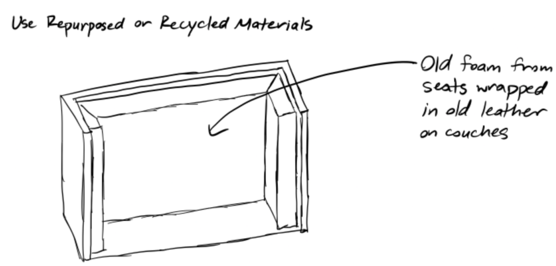


Figure 77. Idea 104 using Card 74 - “Use Repurposed or Recycled Material”: Recycled Padding

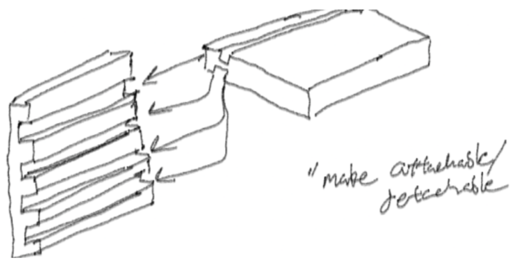


Figure 78. Idea 110 using Card 42 - "Make Components Attachable/Detachable": Slide Insert Foot Support

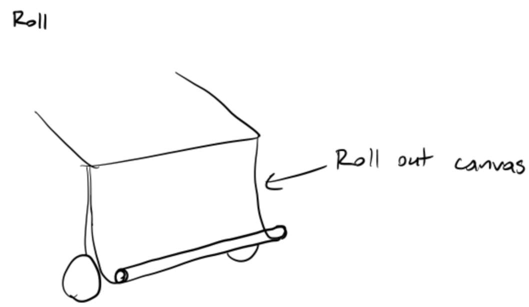


Figure 79. Idea 108 using Card 56 - "Roll": Roll-out Canvas Support

Figure 80. Idea 98 using Card 7 - "Align Components Around Center": Central Pivot Rod

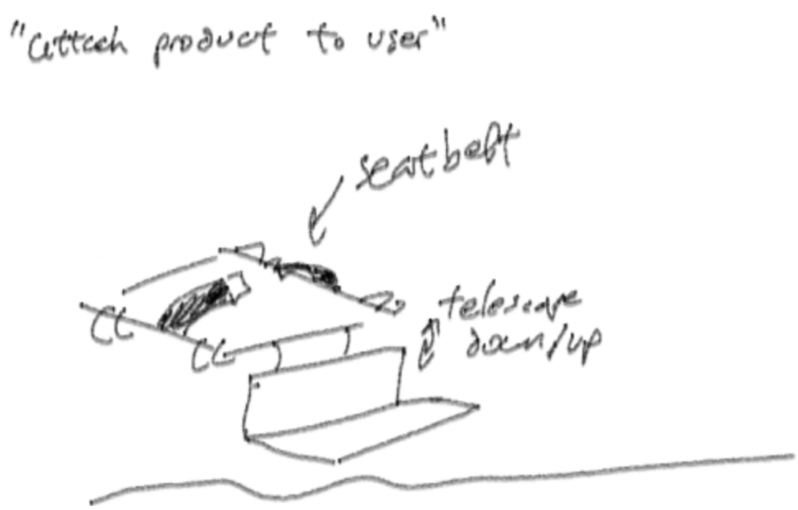


Figure 81. Idea 106 using Card 15 - "Attach Product to User": Seating pad with footrest and seat belt to strap in user

Appendix D: Engineering Drawings

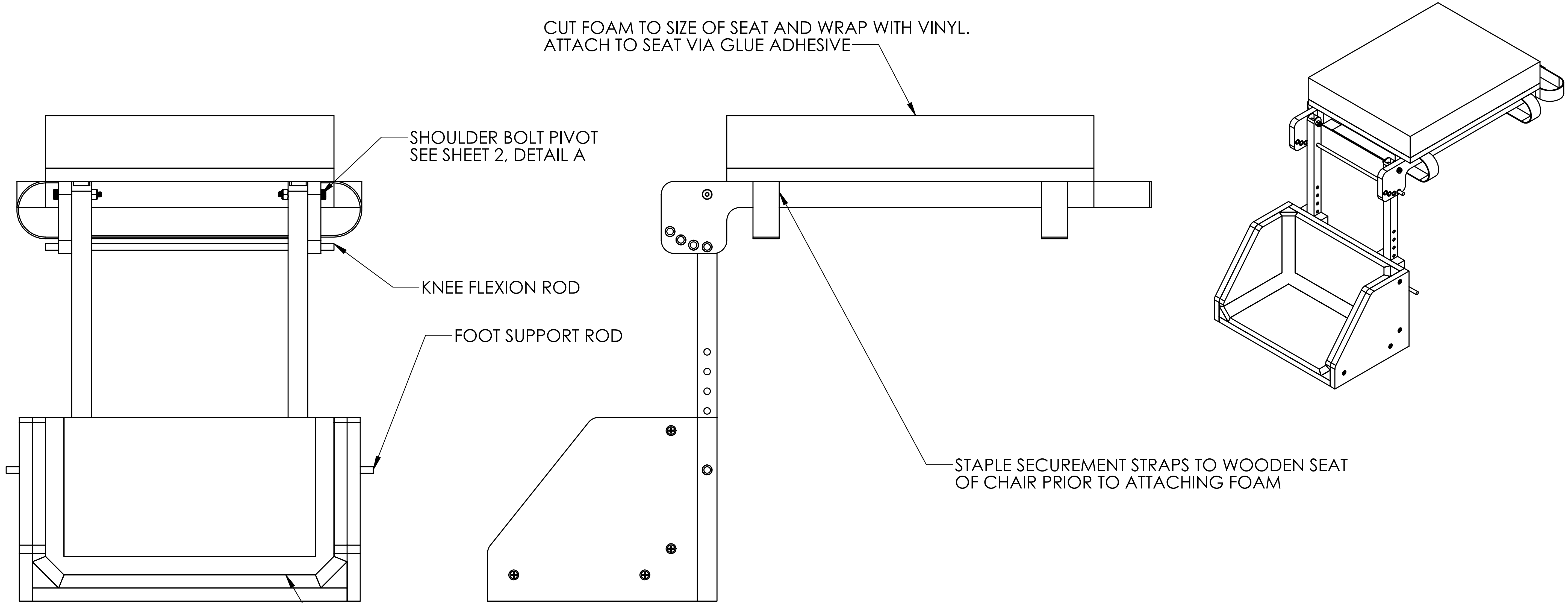
Engineering drawing PDF's have been attached to this report. Please reference the drawings and the prototype, if available, for manufacturing additional foot supports.

Assembly Drawings

- Full Assembly
- Seat Assembly
- Foot Rest Assembly
- Full Assembly Bill of Materials

Part Drawings:

- Seat
- Right Seat Bracket
- Left Seat Bracket
- Legs
- Foot Rest Rod
- (Knee) Rod
- Back Attachment
- Back Plate
- Foot Rest Bottom
- Foot Rest Side Plates
- Foot Rest Back Horizontal Anchor
- Foot Rest Right Horizontal Anchor (This is identical to the Left Anchor, so two must be made)
- Foot Rest Right Vertical Anchor (This is identical to the Left Anchor, so two must be made)



NOTE: DIMENSIONS OF DESIRED CHAIR MUST BE MEASURED. SEE TABLE BELOW. ANY DIMENSIONS OF SUPPORT DEVICE DEPENDENT ON THESE SEAT DIMENSIONS WILL BE INDICATED WITH A CIRCULAR NOTE WITH THE REFERENCE LETTER.

DIMENSIONS	REFERENCE LETTER
SEAT WIDTH	W
SEAT DEPTH	D
SEAT HEIGHT ABOVE GROUND	H

EXAMPLE: (W)

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DEBUR AND SAND
DO NOT SCALE DRAWING

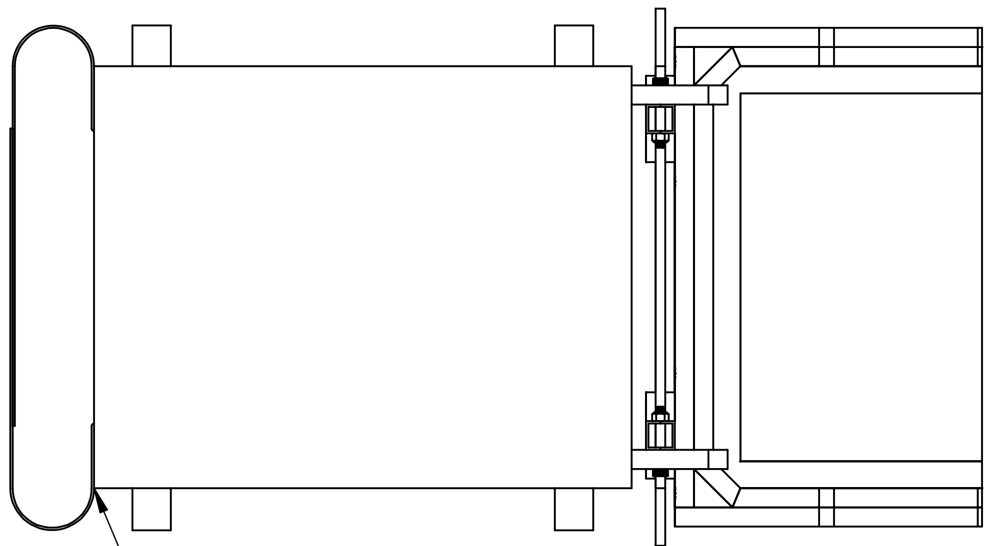
	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

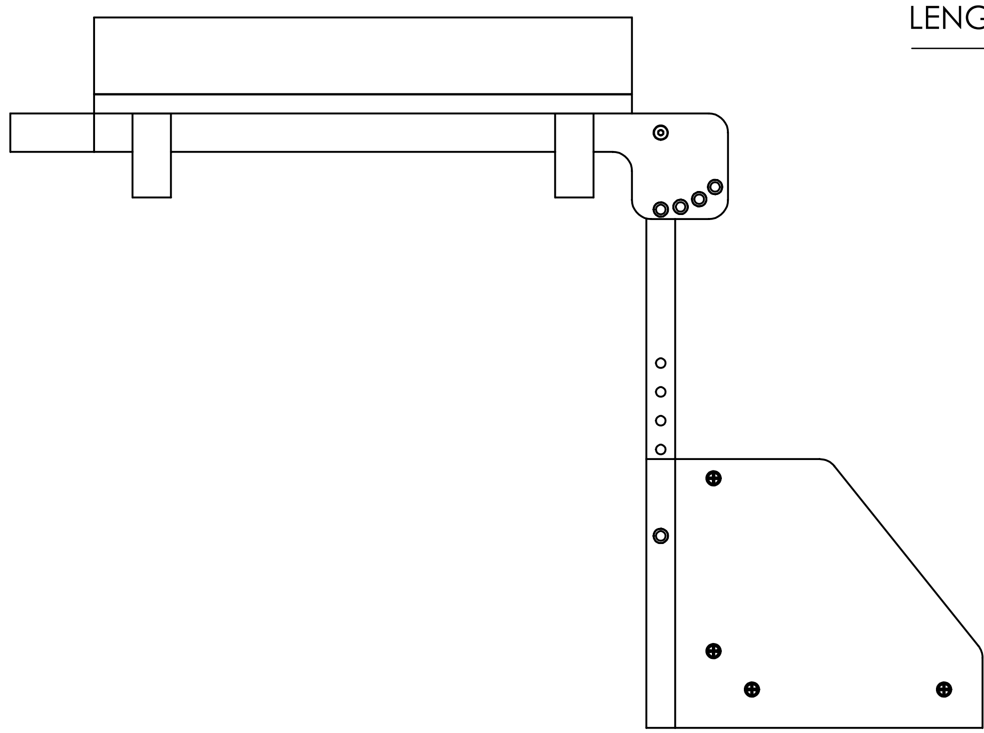
COMMENTS:
ASSEMBLY OF SEAT AND SUPPORT. DO NOT ASSEMBLE WITHOUT PROPER PILOT HOLES

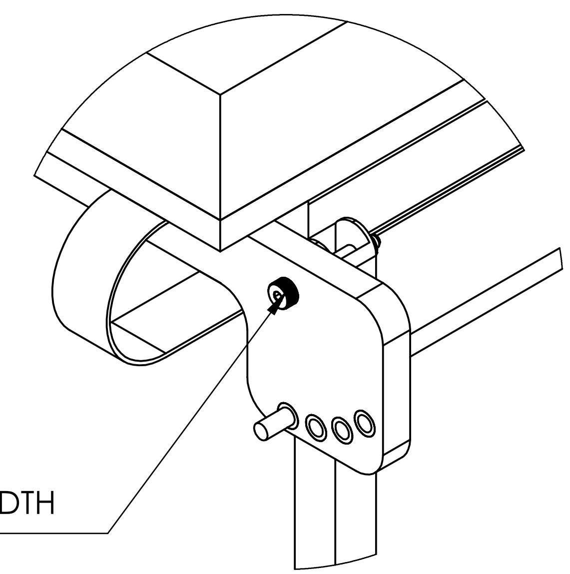
TITLE:
Full Foot Support Assembly

SIZE B | DWG. NO. Full Assembly | REV

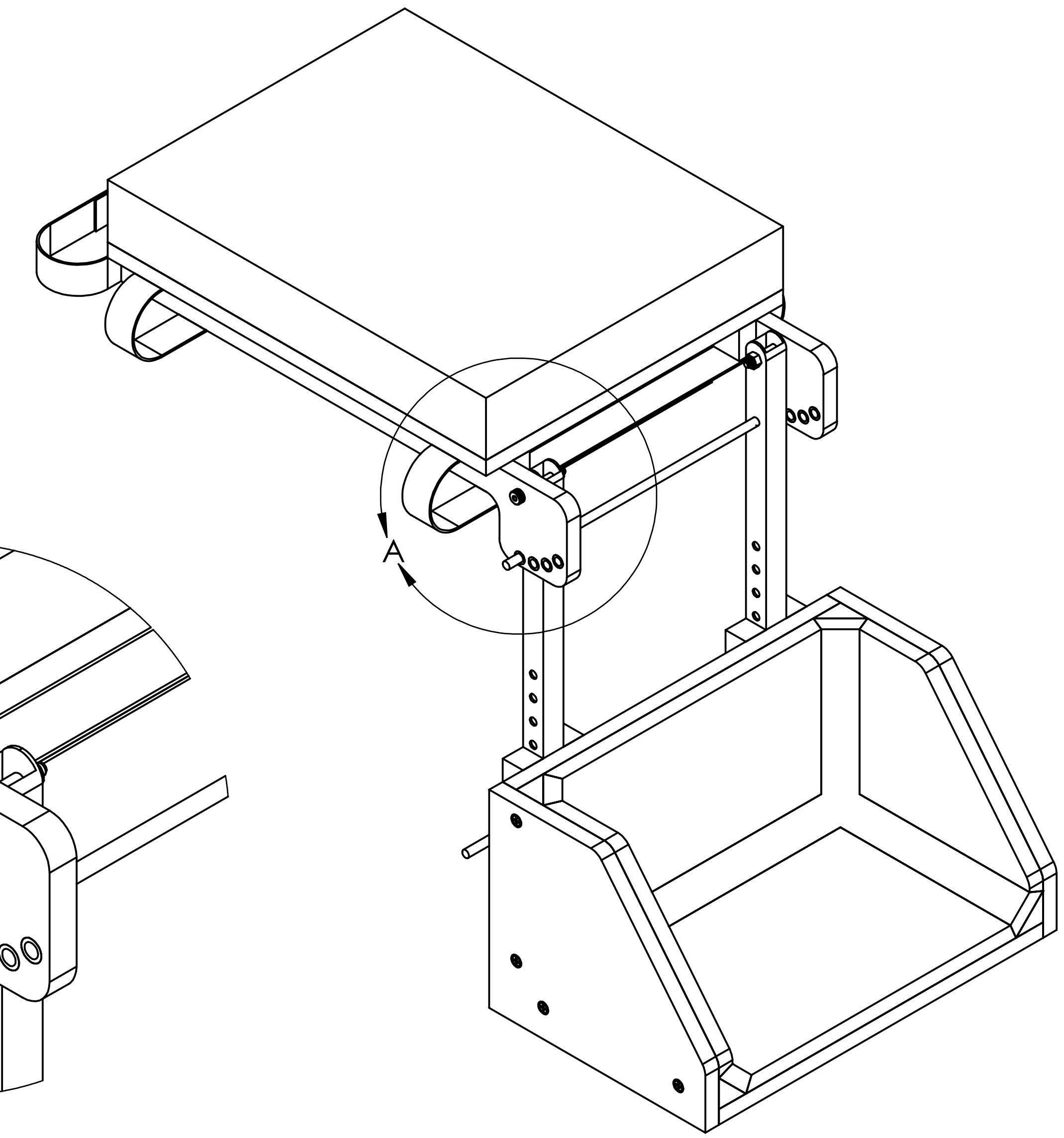
SCALE: 1:4 | WEIGHT: | SHEET 1 OF 3







DETAIL A
SCALE 2 : 5



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APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:
Foot Support Assembly

SIZE	DWG. NO.	REV
B	Full Assembly	

SCALE: 1:3 WEIGHT: SHEET 2 OF 3

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	SEAT	0.5" PLYWOOD	1
2	KNEE BRACKET LEFT	HARDWOOD	1
3	KNEE BRACKET RIGHT	HARDWOOD	1
4	KNEE BRACKET BUSHING	3/8" OD, 1/4" ID METAL CIRCULAR TUBE	10
5	M3 X 1 INCH WOOD SCREW		14
6	SEAT FOAM	SEATING FOAM	1
7	FOOT REST BOTTOM	0.5" PLYWOOD	1
8	FOOT REST BACK	0.5" PLYWOOD	1
9	FOOT REST BACK ATTACHMENT		4
10	FOOT REST BUSHING		4
11	FOOT REST LEFT SIDE	0.5" PLYWOOD	1
12	FOOT REST RIGHT SIDE	0.5" PLYWOOD	1
13	FOOT REST LEFT HORIZONTAL ANCHOR	HARDWOOD	1
14	FOOT REST LEFT VERTICAL ANCHOR	HARDWOOD	1
15	FOOT REST BACK HORIZONTAL ANCHOR	HARDWOOD	1
16	FOOT REST RIGHT VERTICAL ANCHOR	HARDWOOD	1
17	FOOT REST RIGHT HORIZONTAL ANCHOR	HARDWOOD	1
18	M3 X 0.75 INCH WOOD SCREW		20
19	SEAT STRAP TOP		2
20	SEAT STRAP BOTTOM		2
21	BACK STRAP INSIDE		1
22	BACK STRAP OUTSIDE		1
23	SHORT HORIZONTAL ANCHOR FOAM		2
24	VERTICAL ANCHOR FOAM		2
25	FOOT REST BOTTOM FOAM		1
26	LONG HORIZONTAL ANCHOR FOAM		1
27	FOOT REST BACK FOAM		1
28	FOOT REST LEFT SIDE FOAM		1
29	FOOT REST RIGHT SIDE FOAM		1
30	METAL FOOT REST SEAT ATTACHMENT		2
31	91259A544	1/4" DIAM ALLOY STEEL SHOULDER SCREW	2
32	91831A011	18-8 STAINLESS STEEL NYLON-INSERT LOCKNUT	2
33	FOOT REST ROD	1/4" STEEL ROD	1
34	KNEE ROD	1/4" STEEL ROD	1

NEXT ASSY | USED ON

APPLICATION

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL

FINISH

DO NOT SCALE DRAWING

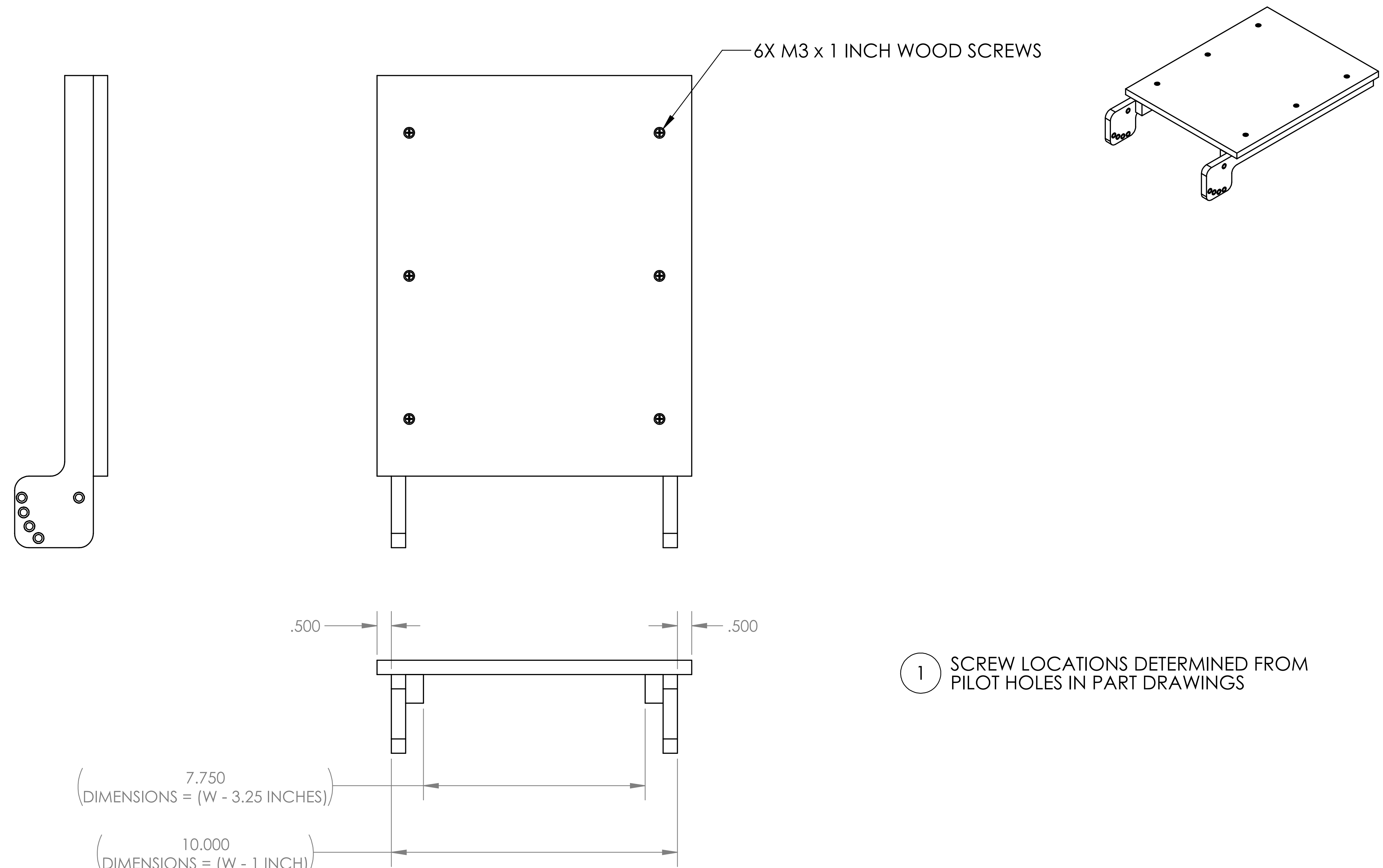
	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Bill of Materials

SIZE **A** | DWG. NO. | REV.

SCALE:1:4 | WEIGHT: | SHEET 3 OF 3



(1) SCREW LOCATIONS DETERMINED FROM PILOT HOLES IN PART DRAWINGS

ITEM NO.	PART NUMBER	QTY.
1	SEAT	1
2	KNEE BRACKET LEFT	1
3	KNEE BRACKET RIGHT	1
4	KNEE BRACKET BUSHING	10
5	M3 X 1" WOOD SCREWS	6

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

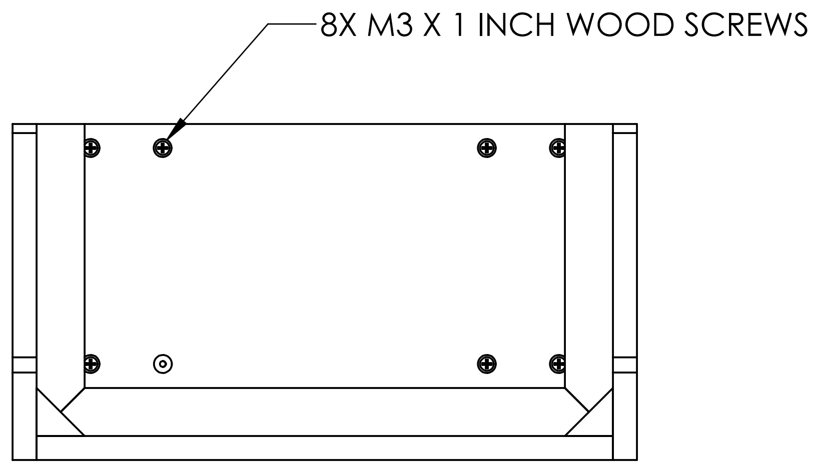
	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

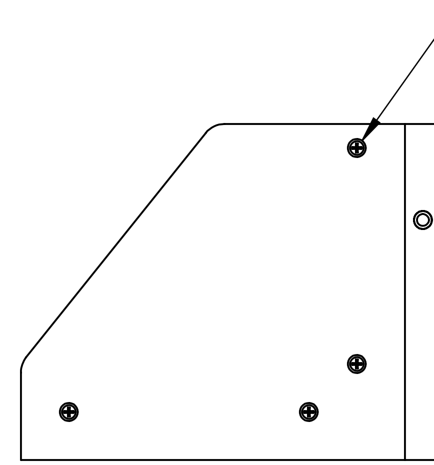
COMMENTS:

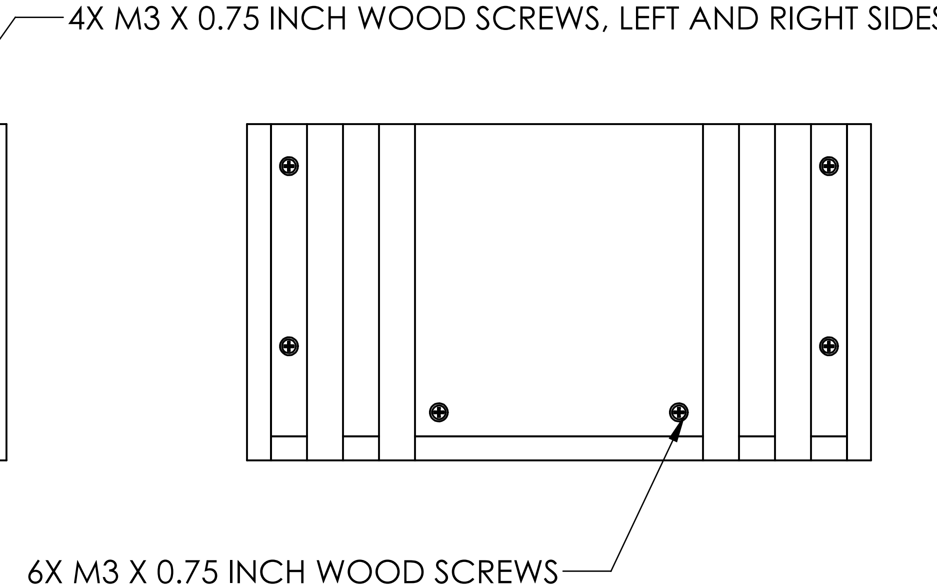
TITLE:
Seat Assembly

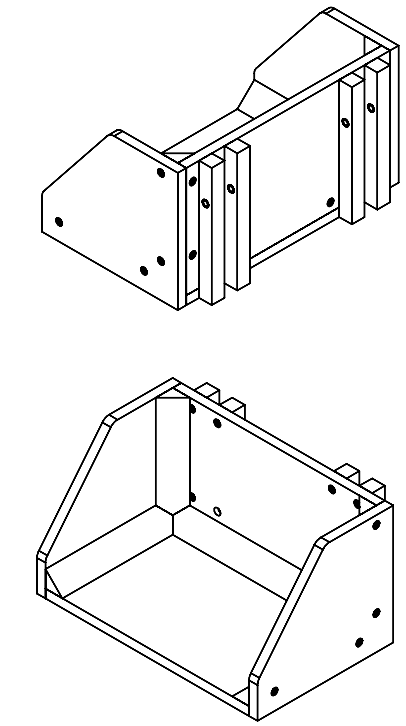
SIZE **B** DWG. NO. Seat Assembly REV

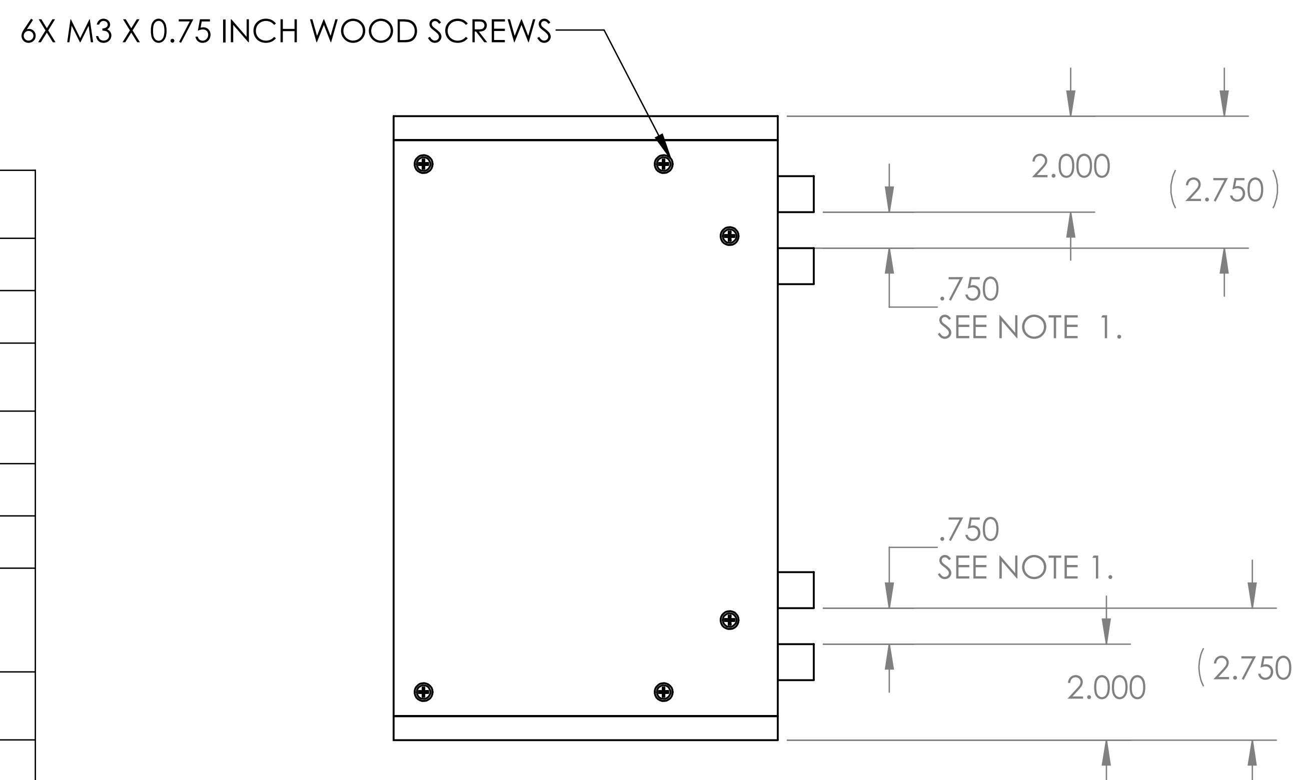
SCALE: 1:4 WEIGHT: SHEET 1 OF 1











ITEM NO.	PART NUMBER	QTY.
1	FOOT REST BOTTOM	1
2	FOOT REST BACK	1
3	FOOT REST BACK ATTACHMENT	4
4	FOOT REST BUSHING	4
5	FOOT REST LEFT SIDE	1
6	FOOT REST RIGHT SIDE	1
7	FOOT REST LEFT HORIZONTAL ANCHOR	1
8	FOOT REST LEFT VERTICAL ANCHOR	1
9	FOOT REST BACK HORIZONTAL ANCHOR	1
10	FOOT REST RIGHT VERTICAL ANCHOR	1
11	FOOT REST RIGHT HORIZONTAL ANCHOR	1
12	M3 X 0.75" WOOD SCREWS	20
13	M3 X 1" WOOD SCREWS	8

1. CHANGE IN LEG TUBE DIMENSIONS DIRECTLY IMPACT SPACE BETWEEN BACK BEAMS (0.750)
2. WOOD SCREW LOCATIONS DETERMINED FROM PILOT HOLES IN PART DRAWINGS.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

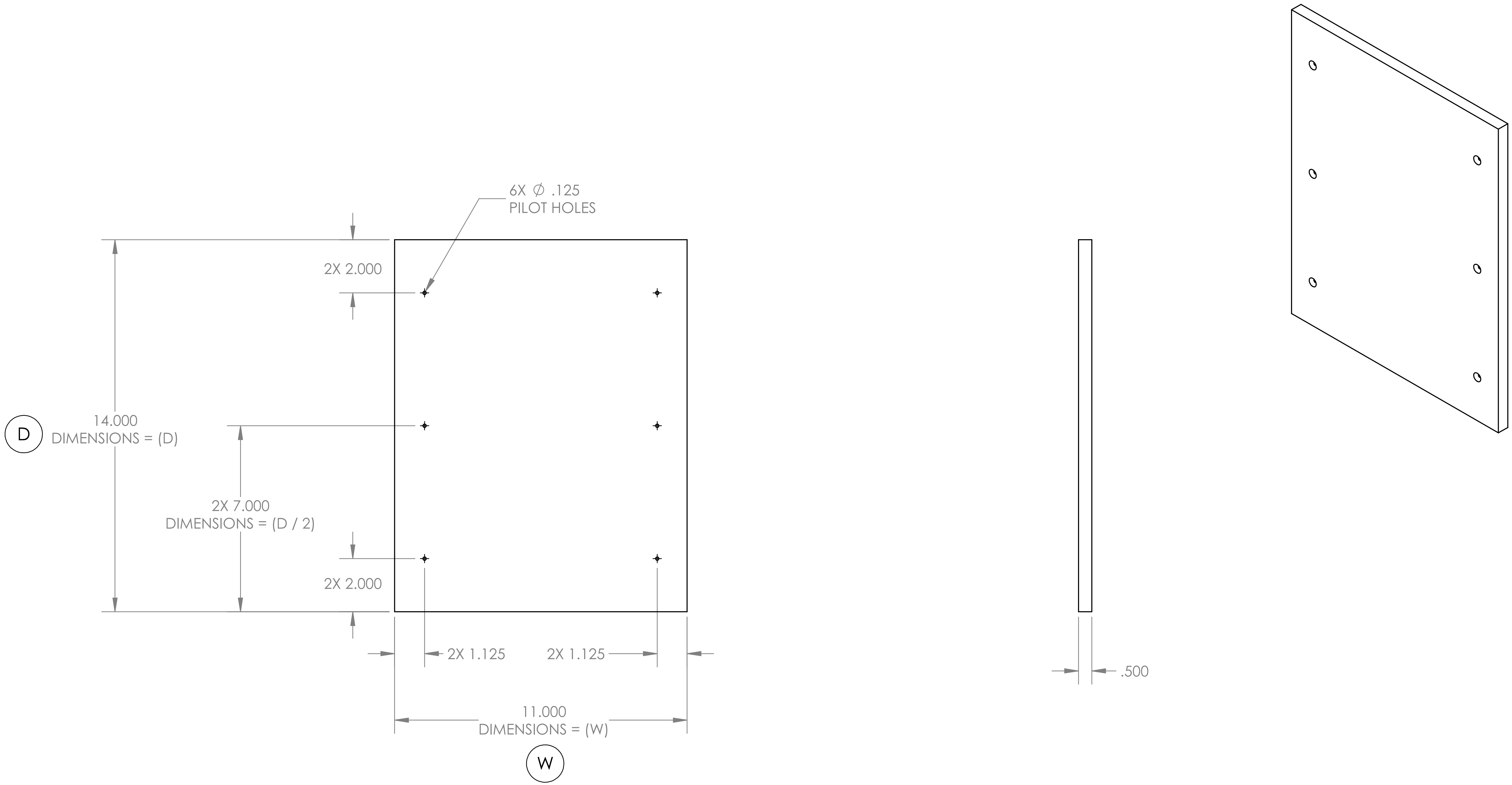
	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Foot Rest Assembly

SIZE **B** DWG. NO. Foot Rest Assembly REV

SCALE: 1:4 WEIGHT: SHEET 1 OF 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 0.5" THICK PLYWOOD

FINISH: SANDED, PAINTED

DO NOT SCALE DRAWING

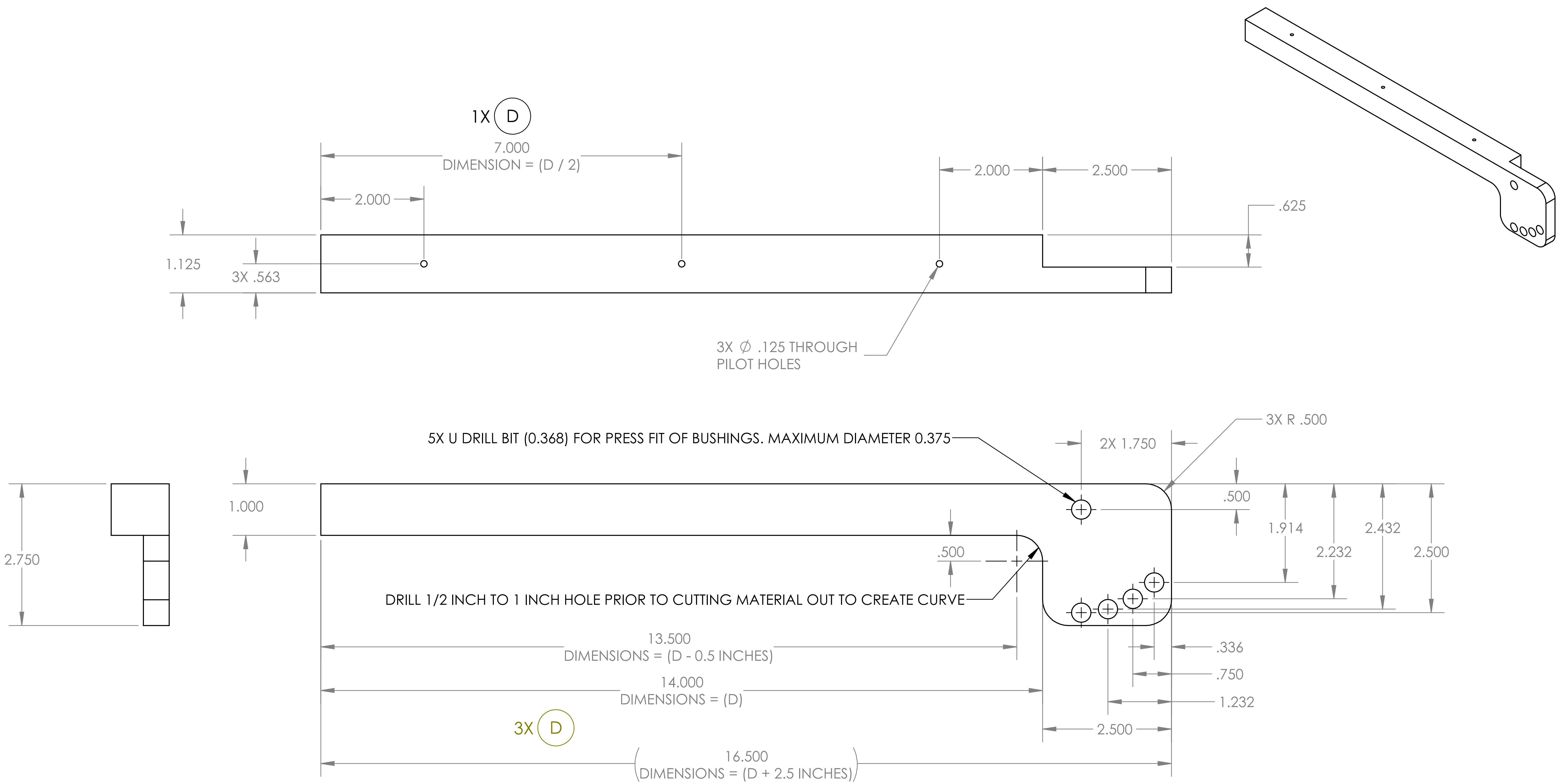
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 1, PILOT HOLES MUST BE ADDED BEFORE ASSEMBLY

TITLE:
Seat Plywood

SIZE	DWG. NO.	REV
B	Seat	

SCALE: 1:4 WEIGHT: SHEET 1 OF 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: HARD WOOD BEAM

FINISH: SANDED, PAINTED

DO NOT SCALE DRAWING

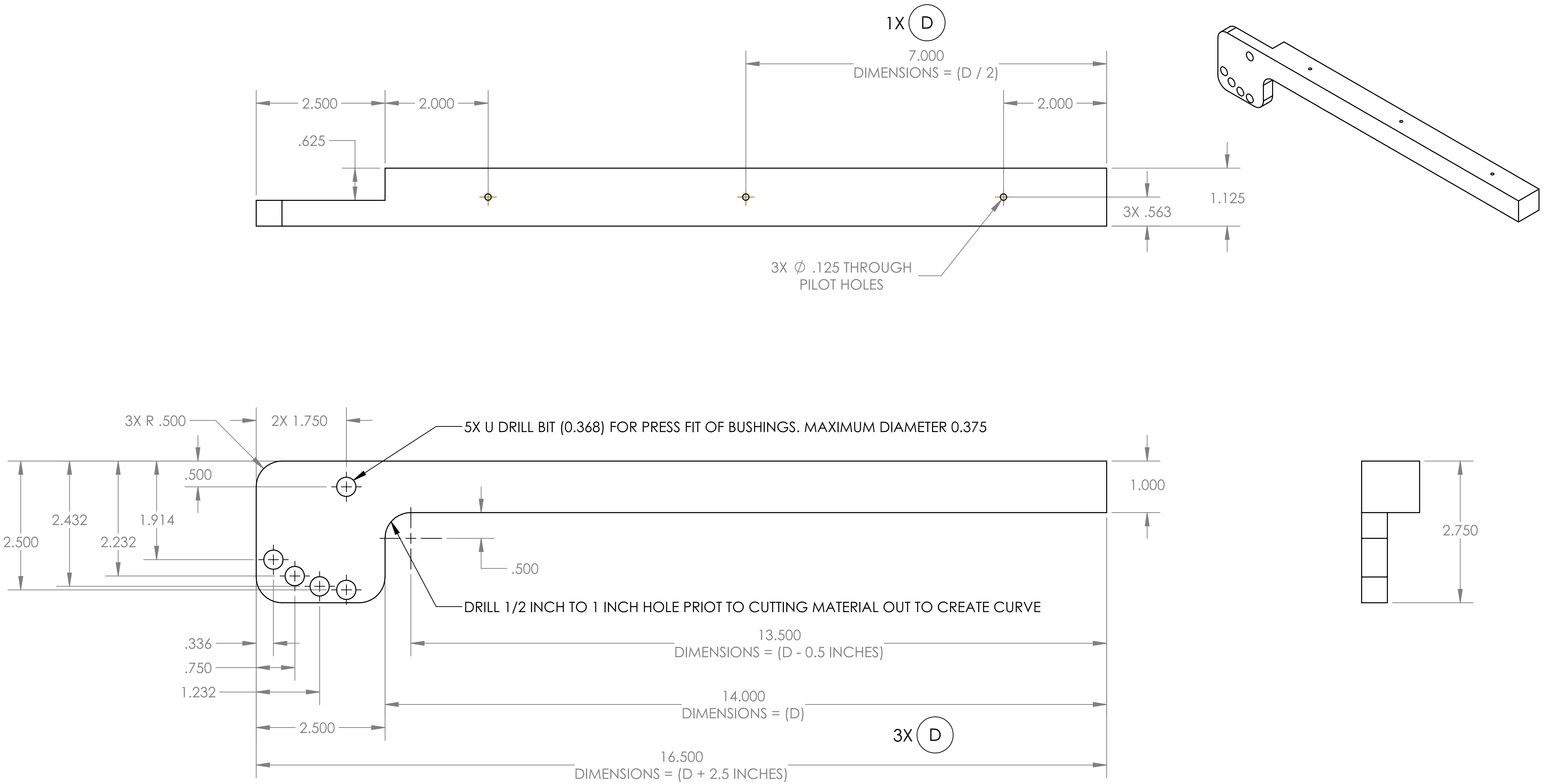
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 1, PILOT HOLES MUST BE ADDED BEFORE ASSEMBLY

TITLE:
Under-seat Bracket

SIZE: **B** | DWG. NO.: Right Seat Bracket | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: HARDWOOD

FINISH: SANDED AND PAINTED

DO NOT SCALE DRAWING

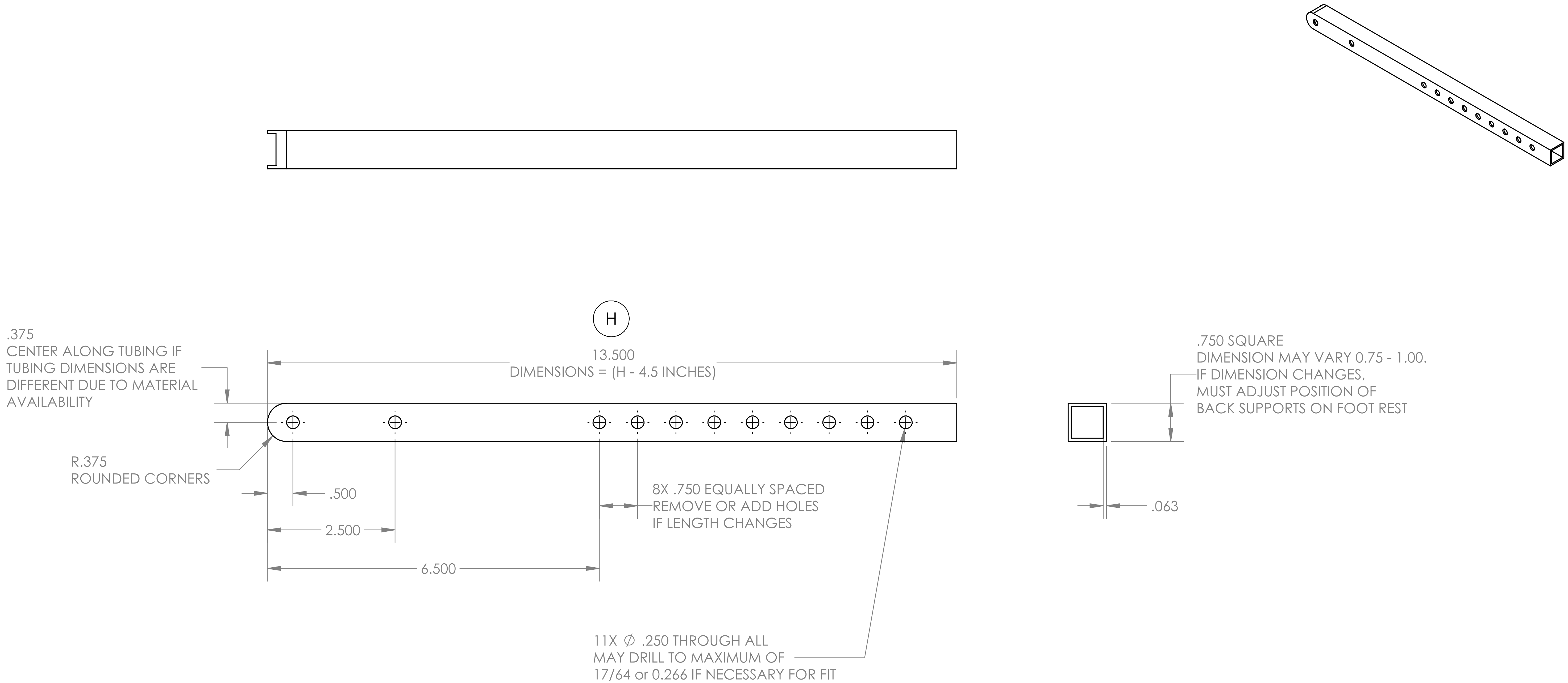
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 1, PILOT HOLES MUST BE ADDED BEFORE ASSEMBLY

TITLE:
Under-seat Bracket

SIZE	DWG. NO.	REV
B	Left Seat Bracket	

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



NOTE: MATERIAL MAY BE 3/4 to 1 INCH SQUARE ALUMINUM OR STEEL TUBE

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
0.75" - 1.00" METAL TUBE
FINISH
DEBUR AND PAINT
DO NOT SCALE DRAWING

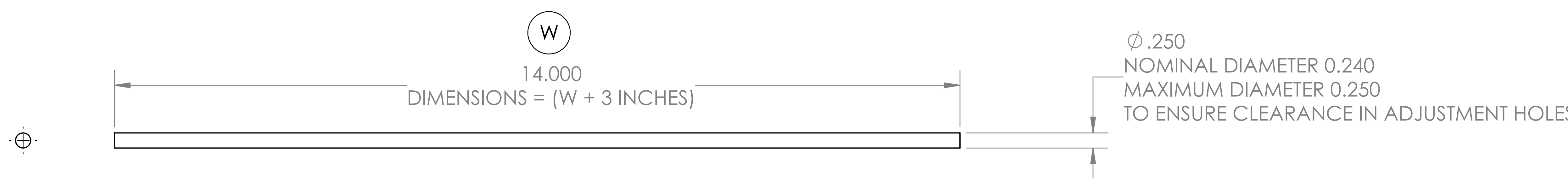
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 2,
TUBING DIMENSIONS WILL IMPACT OTHER DRAWINGS

TITLE:
Foot Rest Legs

SIZE **B** DWG. NO. Legs REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
STEEL

FINISH
DEBURRED

DO NOT SCALE DRAWING

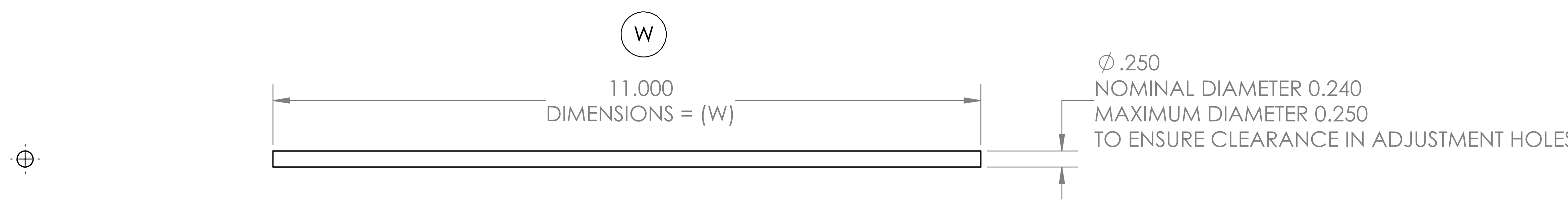
	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 1

TITLE:
Foot Rest Rod

SIZE	DWG. NO.	REV
B	Foot Rest Rod	

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: STEEL

FINISH: DEBURRED

DO NOT SCALE DRAWING

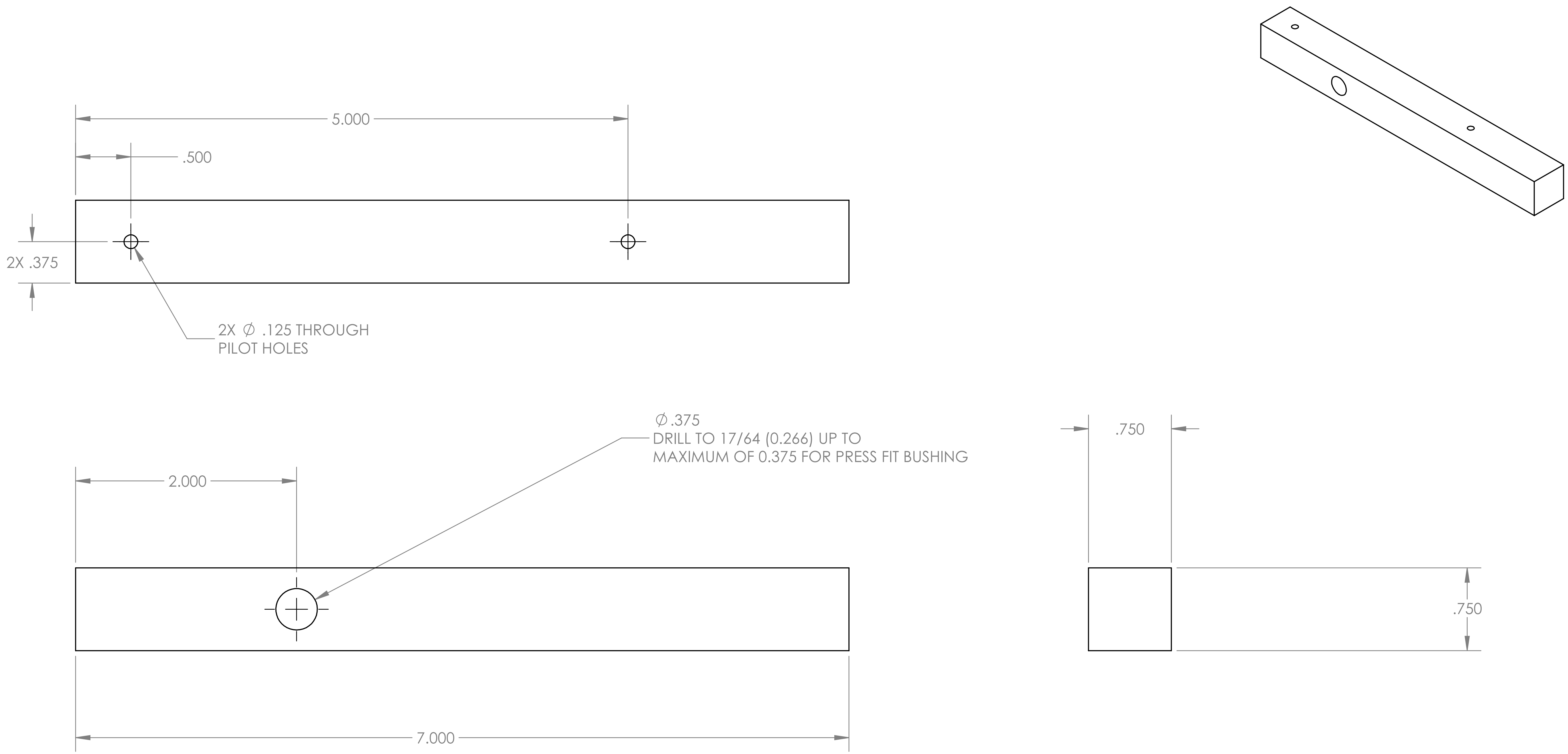
	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 1

TITLE:
Knee Rod

SIZE **B** | DWG. NO. Rod | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
HARD WOOD

FINISH
SANDED AND PAINTED

DO NOT SCALE DRAWING

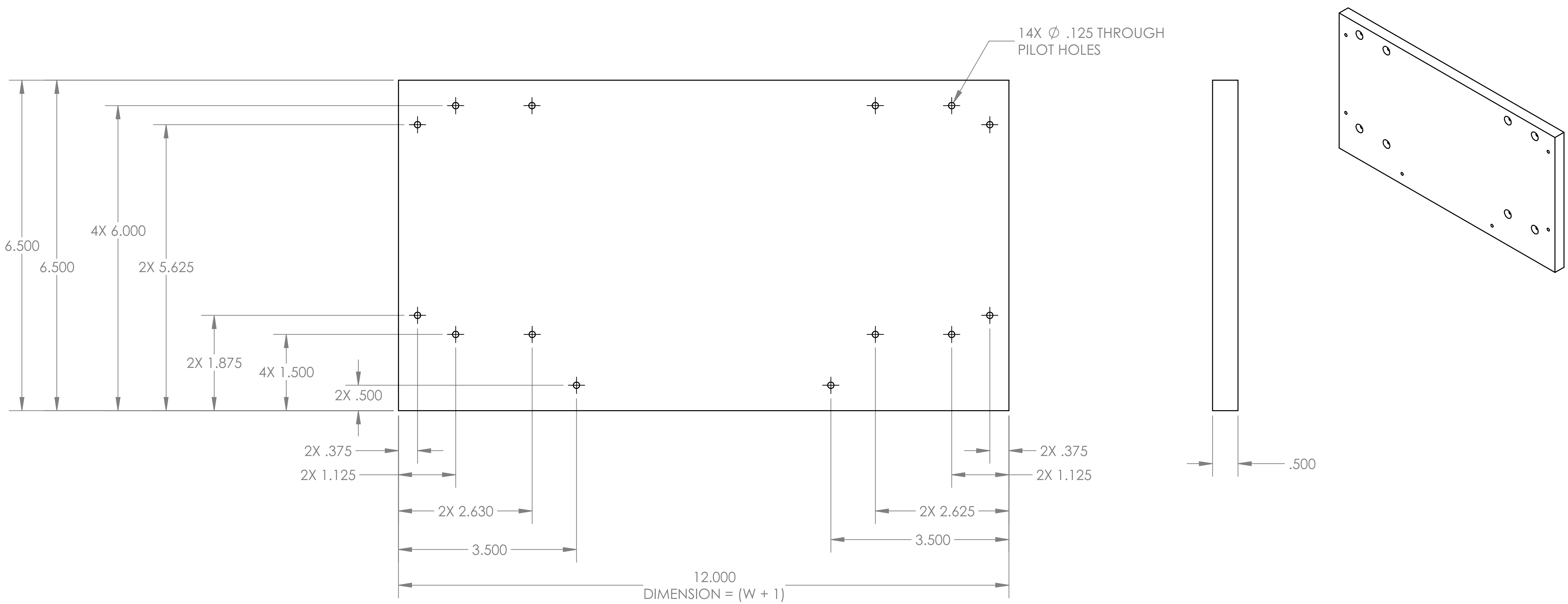
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 4. PRESS BUSHINGS INTO HOLE

TITLE:
Foot Rest Back Attachment

SIZE **B** DWG. NO. Back Attch. REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



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APPLICATION	

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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
0.5" THICK PLYWOOD

FINISH
SANDED AND PAINTED

DO NOT SCALE DRAWING

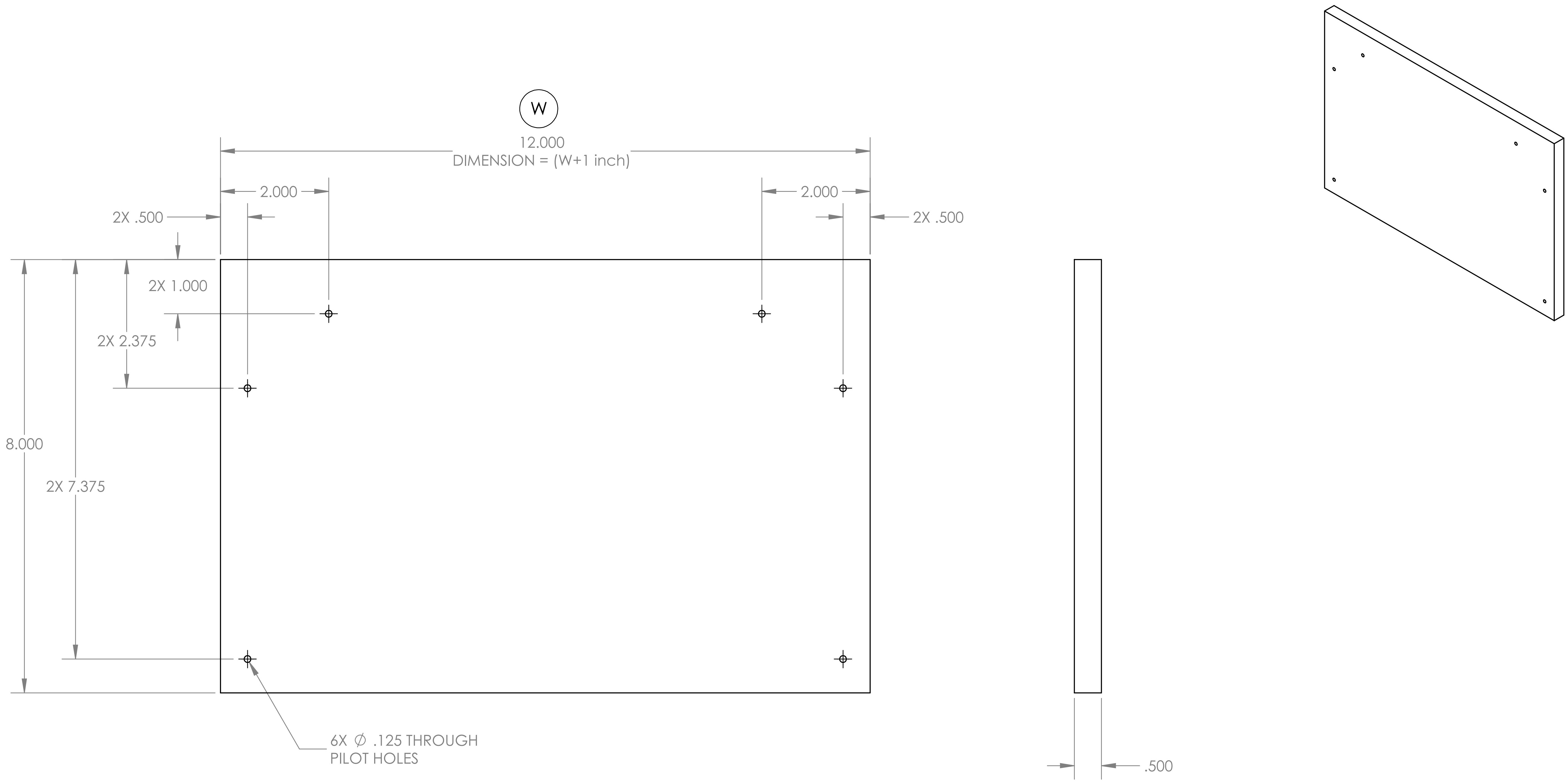
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 1, NOTE PILOT HOLES FOR SCREWS WILL BE NEEDED

TITLE:
Foot Rest Back

SIZE **B** DWG. NO. Back Plate REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



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APPLICATION	

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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
0.5" THICK PLYWOOD

FINISH
SANDED AND PAINTED

DO NOT SCALE DRAWING

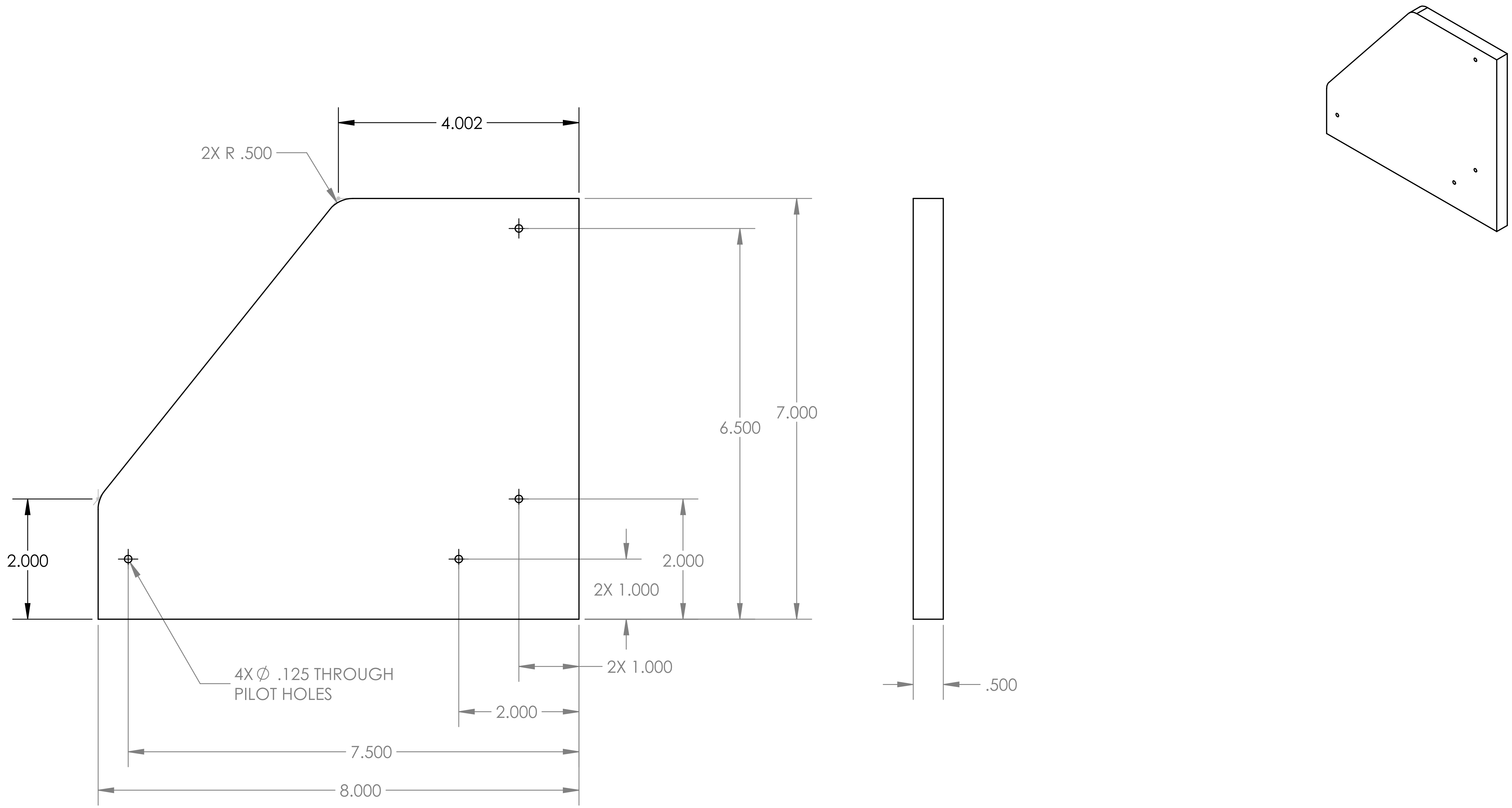
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 1, NOTE THAT PILOT HOLES MUST BE ADDED BEFORE ASSEMBLY

TITLE:
Foot Rest Bottom

SIZE	DWG. NO.	REV
B	Bottom	

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 0.5" THICK PLYWOOD

FINISH: SANDED AND PAINTED

DO NOT SCALE DRAWING

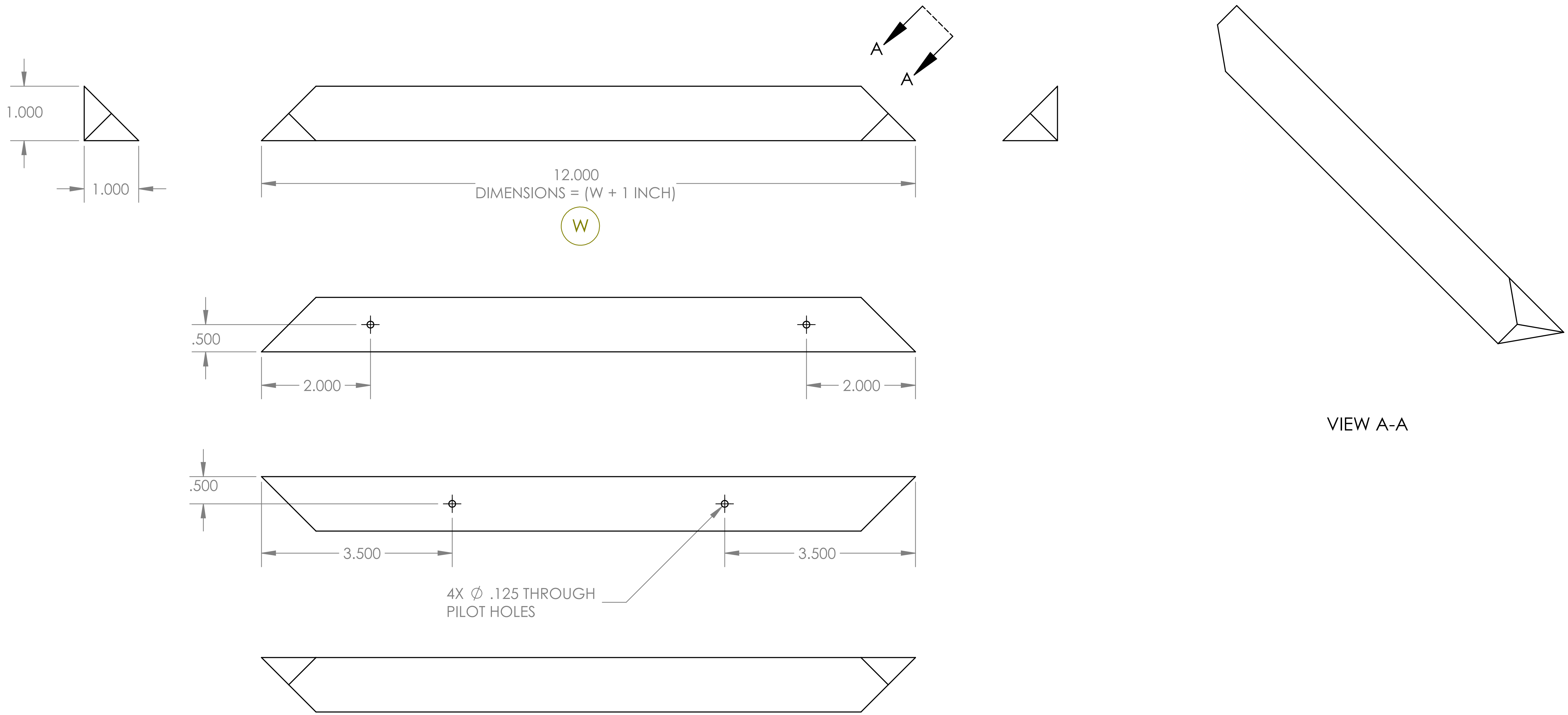
	NAME	DATE
DRAWN	MK	12/13/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

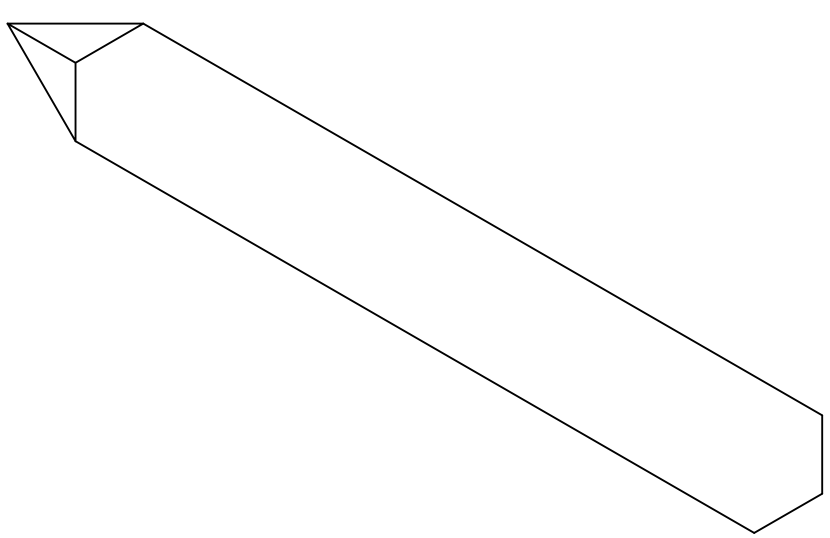
COMMENTS: QTY: 2, NOTE THAT PILOT HOLES MUST BE ADDED BEFORE ASSEMBLY

TITLE: Foot Rest Side Plates

SIZE: **B** | DWG. NO.: Side Plate | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1





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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: HARDWOOD

FINISH: SANDED AND PAINTED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

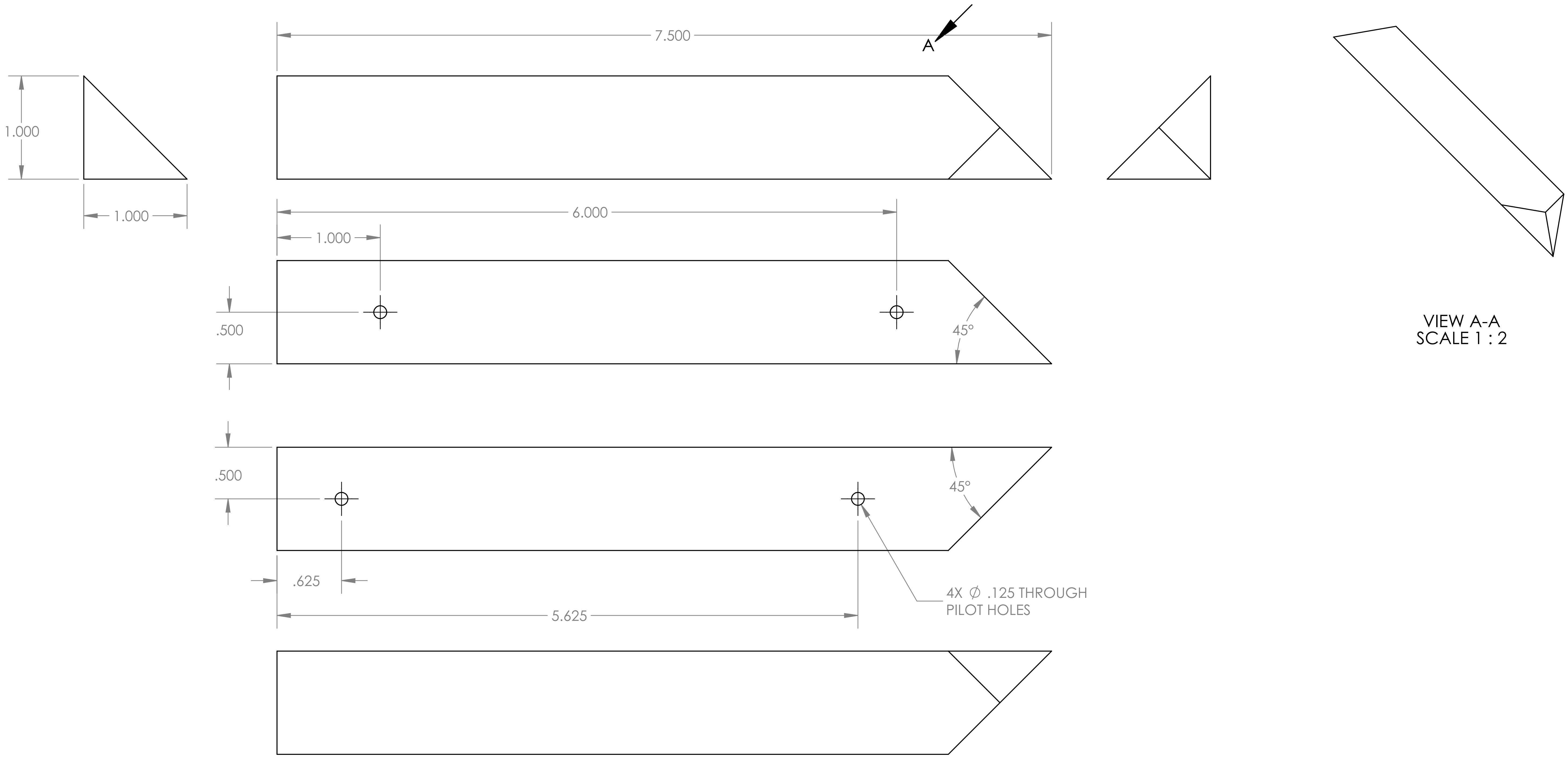
QTY: 1, MUST DRILL PILOT HOLES BEFORE ASSEMBLY

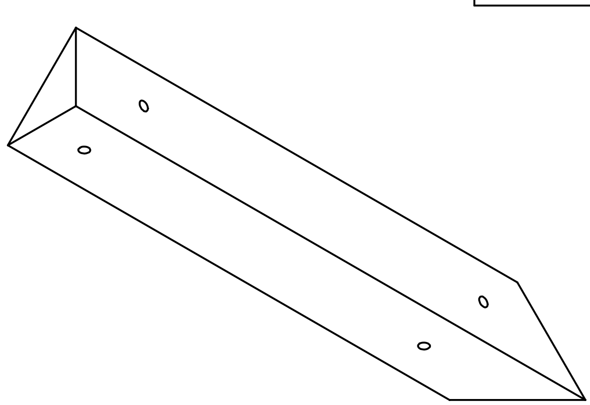
TITLE:

Foot Rest Back Horizontal Anchor

SIZE	DWG. NO.	REV
B	Back Horizontal Anchor	

SCALE: 1:2 WEIGHT: SHEET 1 OF 1





PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: HARDWOOD

FINISH: SANDED AND PAINTED

DO NOT SCALE DRAWING

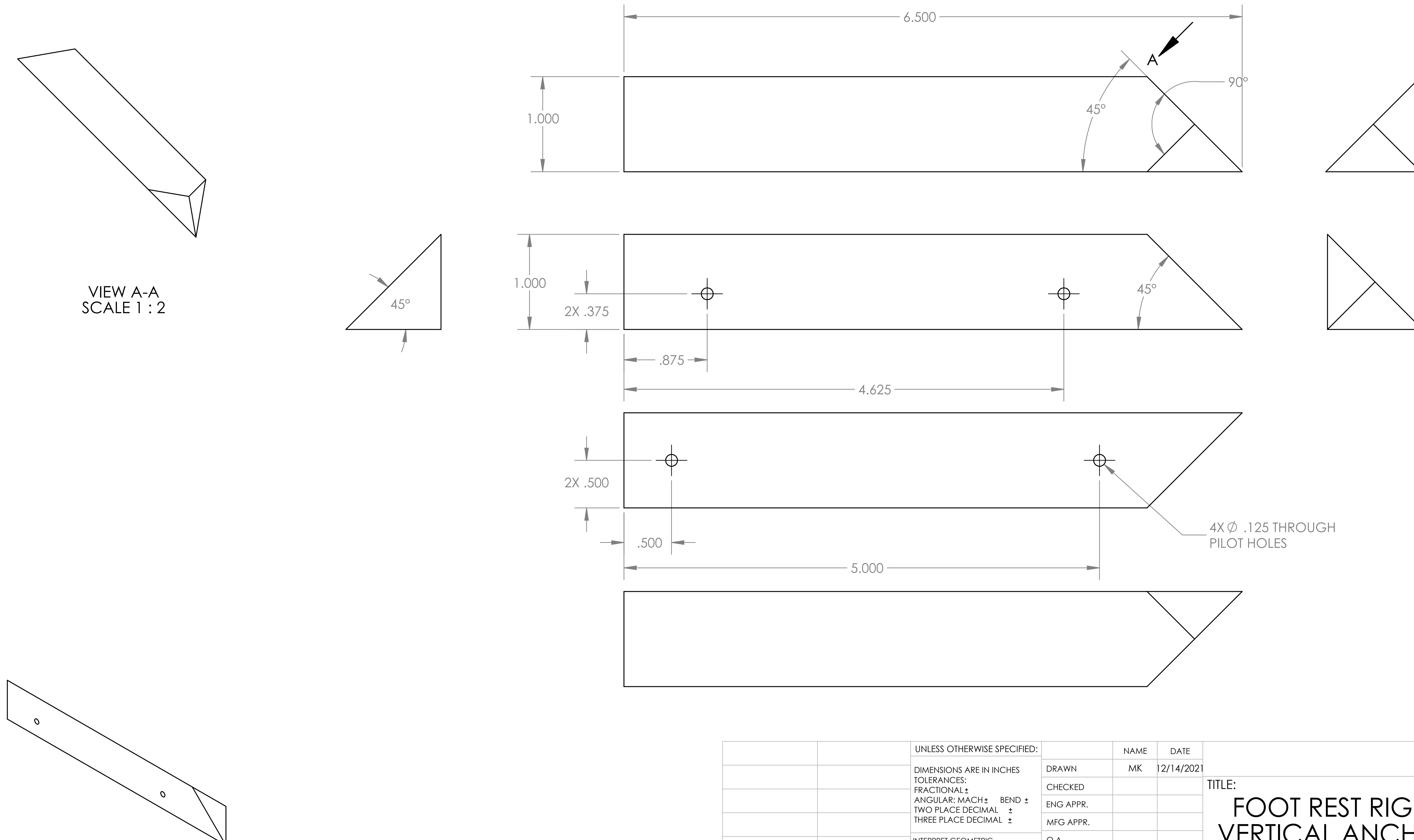
	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 2, PILOT HOLES MUST BE DRILLED BEFORE ASSEMBLY

TITLE:
Foot Rest Right Horizontal Anchor

SIZE	DWG. NO.	REV
B	Right Horizontal	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



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APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: HARDWOOD

FINISH: SANDED AND PAINTED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MK	12/14/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
QTY: 2, DRILL ALL PILOT HOLES BEFORE ASSEMBLY

TITLE:
FOOT REST RIGHT VERTICAL ANCHOR

SIZE	DWG. NO.	REV
B	RIGHT VERTICAL	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1