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Innovation of Crutches

Austin Reth
Elizabethtown College, retha@etown.edu

Kyle Lumbert
Elizabethtown College, lumbertk@etown.edu

Scott Romich
Elizabethtown College, romichg@etown.edu

Audrey Shultz
Elizabethtown College, shultza1@etown.edu

Catherine Stencler
Elizabethtown College, stenclerc@etown.edu

Final Paper-Innovation of Crutches

EGR 492

Kyle Lumbert, Austin Reth, Scott Romich, Audrey Shultz, and Catherine Stencler

Abstract

The following project focuses on the redesign of crutches, and more specifically, a redesign of the most common type of crutch, the axillary crutch. Every year, there are approximately 21 million Emergency Room visits for lower leg injuries, many of which would lead to short term crutch use [1]. In this project, we attempted to correct common issues associated with the use of the axillary (underarm) crutch such as pinched nerves, poor posture, and exhaustion with use. We also identified the problem of common crutches not being suited for certain body types such as the difference in body shape between men and women, therefore trying to change the overall shape of the crutch to be suitable for those of all size and shapes. Over the course of three semesters, we have successfully created three sets of prototype crutches. In these prototypes, we successfully implemented our research on structures, materials, and energy return to create a more ergonomic, safe, and user-friendly assistive device. As a culmination of the junior and senior engineering projects, this project shows how research and redesign processes can be implemented effectively.

Introduction and Background

In the United States, approximately 6.5 million people use crutches, canes, and other similar assistive devices [2]. Every year, there are about 141 million emergency room visits, 15% of which are for lower leg injuries—the type of injury that would require the short-term or long-term use of crutches [3]. Anyone who has used crutches in the past can tell you that they are painful and exhausting. To help create a more enjoyable experience for crutch users, we identified several problems with the crutches currently on the market. These problems include pinched nerves (especially under the arms), poor posture, and exhaustion with use. We also noted that most crutches are not designed to fit the shape of the body, especially for people with wider hips or broader shoulders.

In order to solve the problems listed above, we began by identifying how each part of the crutch affects its use. For example, if we wanted to solve the problem of pinched nerves, we needed to look at the part of the crutch that was causing the problem—in this case, the crutch pad. From here, we identified several design changes that needed to be made to solve the issues we identified. The problem of poor posture was determined to stem from the users need to compensate when the crutches don't fit perfectly, so to solve this problem, we made the handles infinitely adjustable to allow the user to pick a handle height that will best suit them. Energy return was also a prominent feature in our redesign. In order to prevent the user from becoming too exhausted, we integrated the MD Crutch foot to return energy to the user and create a smoother stride. To allow our crutches to fit different body types better, we brought the crutch out and away from the body which allows more space for the body and less put slippage. All these design changes contributed to our final prototype which received lots of positive reviews from people who tested it.

Project Design Specifications (PDS) and Market Analysis

When creating a PDS or project design specification, the Pugh table is used to map out the pros and cons. There are 32 Pugh subgroups all of which are interrelated to one another. Usually, you cannot change one of these 32 without having some influence on at least one of the other 31 groups. For example, size and weight naturally go hand in hand with each other. The larger the size, the more the product will weigh due to fundamental physics. The more material or mass there is, the more the object will weigh. Another example of these interconnections within the subgroups is the relationship between product lifespan and timescales. They are related because the timeframe of the product must be much shorter than the lifespan. The reason for this being that you do not want the product to be unavailable to the customer while there is still demand. In other words, you want to create the product in a shorter amount of time than it takes for the product to deteriorate to an unusable state. Our timescale is a little different since our product is not being produced for the market yet. The ultimate goal for the time frame is to be able to build several pairs of crutches within a day's work while each crutch lasts for years. There are numerous other examples of this within the subgroups.

All of the 32 subgroups relate to customer requirements and expectations, mainly because our product was specially designed for the customer’s needs. Crutches need to be redesigned to be more user-friendly; this means that our product design specifications are based on the needs of our clients.

The six most important of the thirty-two subgroups are the performance, customer, installation, size, quality/reliability, and safety. The other twenty-six subgroups are valuable to the product as well, but they are not as crucial in the conceptualization and design stages of the process. Also, the above six are the most important because, in the overall picture of the product, these six fit into the other twenty-six categories in one way or the other. Therefore, the product design specifications will mostly contain those above six.

While not all of the 32 PDS can be related to our specific project, most of them have been successfully manipulated to encase all crucial specifications that should be taken into account when designing an original new product or redesigning an inferior one. The 32 PDS that we used in the full Pugh Table which can be found in Appendix H by following the link to the entire table, to get a comprehensive view of how each design aspect affects the product.

Currently, the market has two main types of crutches and some specialty crutches. The axillary crutch is the most common crutch used in the United States of America today. The axillary crutch is the traditional V-shaped crutch that sits under the arm. The forearm crutch, most commonly found in European and Asian countries, use a cuff around the forearm and handle. Both the axillary and forearm crutches require the user to place their weight on their hands. Some adaptations of the forearm crutch allow some weight to be distributed on the forearm as well. These common types of crutches can be used for virtually any kind of lower-body injury that requires weight to be kept off (or mostly off) of the extremity [4]. Other devices that compete with conventional crutches include leg crutches and scooters. As these devices require the use of the upper leg, they are suitable only for lower leg injuries (below the knee). These designs rely on bending the leg back at the knee as well as having the device bridge the gap between the upper leg and the ground. Leg crutches attach to the thigh or knee and act as a replacement lower leg, similar to a peg leg. The Scooter places the affected leg on wheels, which allows for rolling, rather than walking.

For the sake of this project, the main focus of our time and research was on standard crutches specifically the axillary crutch. The reason for choosing this focus is that the majority of the population of the United States is familiar with this type and it is the most commonly used type of crutch. Despite being the most common, axillary crutches are also the type that is the most flawed and therefore needs the most design adjustments.

Most of the products that are already on the market show improvements in at least one of the many aspects that our group is working on redesigning. However, no product currently on the market has all of the elements that we identified as being able to improve crutches for the consumer. A prime example of this is the MD Crutches [5]. While excellently designed, they incorporate a lot of ideas that are similar to what our group came up with during brainstorming; we can still see flaws with this design. For example, the designed shock absorption factor within the MD Crutch is similar to what we were thinking of creating. However, we are trying to directly avoid any design where all of the person's weight is put in only one place, which is precisely what the MD Crutches do. Another attractive design that may be considered to be an "out there" idea is a crutch constructed out of bamboo. This is an exciting idea that has crossed the minds of our group members. However, it did not fit the bill for easily workable or attainable. This was just one of the many factors that were taken into consideration in the pugh design section of the project.

Crutches are a commonly used product as they are prescribed for most lower body injuries that require minimal to no weight to be placed on an affected area. Most often, having to use crutches is only temporary, making the clients short-term users as they recover from an injury, but some people have a disability that may require assistance with walking on a more permanent basis.

Although it is necessary for modification of long-term crutch use, our project is going to be focused more on the "short-term" applications. The definition of a short term that we are assuming is anything that will not be a permanent disability. Crutches span a broad demographic of users including anyone from children to the elderly. Due to limited time and resources, we will not be able to focus on all ages. Therefore, the group decided to focus on the age range of

18-25 because this is when the most injuries that require crutches, such as sports or related injuries, occur. While each person has different needs from their crutches, everyone can agree on the aspects of the crutch that will ensure that the most basic needs of comfort are met.

On the current market, many needs are left unfulfilled by crutches. Each type of crutch design has advantages, but they all also have drawbacks that should be addressed. To fit a range of people, crutches must have a way of adjusting the height to promote good posture, and they should be natural to use for any body type, without excess rubbing or jerking. When crutches get uncomfortable, slouching occurs, which can cause further injuries as prolonged improper use can harm the nerves beneath the arms. Crutches should also be safe to use, with durable feet for traction, and padding where it comes into contact with the body. Some users also report an interest in having shock absorption built into the design, so that some of the energy is returned to the user. Additionally, crutches can be inconvenient to travel with, so they should be able to be folded, collapsed or stored for convenience in tight spaces.

Project Management

We easily maintained time management for this project with the use of a chart which outlined our goals and where we wanted to be at the end of senior year. Since our team got along so well, and our communication was frequent, we did not need much incentive or motivation to stay on task. We assigned tasks that aligned with the group member’s likes and dislikes. Table 1 shows how we stayed on task and recorded progress throughout the three semesters. Since we all had the same goal and took on roughly the same amount of work for each week, there was no reason to micromanage each other. Instead, we all knew that we were counting on one another which was enough motivation and accountability.

Table 1: Grading Rubric for Full Year: This table shows the proposed grading scale for this class throughout the project. By SCAD day, we intended to have a prototype that was tested and redesigned into a better model. This model should be functional but not necessarily polished. Our current crutch design sits in the A range, with only final polishing needed to be showroom ready.

Grade:	**A**	**B**	**C**
Features: ***Foot/Spring** ***Adjustable** ***Redone shape** ***Handle** ***Armpiece** ***New material**	75%-100% of features (Has 4-6 of the features completed)	50%-75% of features (Has 3-4 of the features completed)	Finalized Design of the overall project Including less than 50% of features
Functionality	Full Functionality	Mostly functional with slight malfunction	Cannot function as a traditional crutch
Weight	Holds proper weight (250-300 lbs)	Holds sufficient weight (150-175 lbs)	Holds minimal weight (25-30 lbs)
CAD	Completed crutch looks like our drawings	Near Net shape based on drawings	Full set of CAD Shop drawings Ready to go and start building
Product Testing	We have full confidence in our product	Have a tested product	Untested
Aesthetic	Only final polishing needed to be showroom ready	Unpolished product Rough looking Not aesthetically pleasing	Looks similar to an axillary crutch

Budget

For this project, we started with a total budget of $1000.00 for our group consisting of five members. Of the budget, we spent a total of $279.40 on materials, leaving us a final remaining budget of $720.60. The following table is a breakdown of the materials used and their cost:

Table 2: Budget and Spending: Table 2 shows the budget and spending over the last two semesters. The initial prototypes were made from scavenged materials and therefore are not included in this chart. This budget shows the breakdown of costs from Prototypes II and III.

Electrical conduit and fittings	$89.75
Fabric	$11.86
Memory Foam	$32.99
Memory Foam Shipping	$12.99
MD Feet	$52.99
Memory Foam 2.0	$25.97
Aluminum Handle	$7.00
Aluminum Adapter	$9.50
Drawstrings	$16.77
Shop Misc.	$10.00
	Remaining Balance: $720.60

Starting at the top of the table, we used the electrical conduit and fittings that we bought from home depot to create the overall skeleton and shape of the product. The fabric from Joann Fabrics was used to create the removable and washable sleeve covers for the shoulder pad and handle. The memory foam was used to create the padding for the shoulder and handle on both crutches, and the drawstrings were used to make sure the covers were easily removable. Moving on the MD Feet were bought to act as the feet of the crutch from a crutch that is already on the market, and the aluminum handle and aluminum adapter were both machined in the fabrication lab for our project.

With such a large budget we knew that would have no problem keeping under that limit. Regardless we still wanted to minimize costs, leading us to buy larger quantities of materials so that we not only had to make fewer trips to the hardware stores but also provided plenty of extra material in case of problems in the shop. We also used the excess material to experiment with different kinds of bends and to test the limits of what we could do with the bender in the shop.

Social, Ethical, and Environmental Improvements

When creating this project, we investigated the overall design aspects of the original axilliary crutch and tried to find the issues that could be improved. When looking at the Social and Ethical aspects of the crutch, we wanted to make the new crutch easier-to-use and more comfortable. To achieve this, we provided our crutch with more padding and return of energy to allow comfort and the conservation of momentum. The result of changing these aspects of the axillary crutch was a more user-friendly product. In testing, we proved that our design was much friendlier to the user and caused no pain with the added padding. For environmental improvements, we wanted to consider using materials that would be easily reusable or recycled, as well as padding that could be biodegradable.

Reflecting on our goals for the social, ethical, and environmental improvements from our spring junior year presentation, we are satisfied with our results. We wanted to use environmentally responsible materials, have our product be widely available to all, regardless of social class, and be able to test ethically. In the construction of our crutch prototype, we used materials that could easily be recycled and reused. If we were to market these crutches, we would propose the use of aluminum, which is one of the most recycled materials. Therefore, we are satisfied with the environmental impact of our design.

We estimated our construction costs to be a little over $100 for the amount of material we used on our final prototype. Therefore, we believe our product would be inexpensive enough to allow all classes to be able to purchase it, especially as mass manufacturing will enable the price to decrease. As far as our testing process is concerned, we did not get our testing process IRB (International Review Board) approved. Instead, we created legally correct waivers that we had participants sign to allow use at their own risk and nothing would fall back on our group and the college. This allowed us to move to the testing phase quicker as there was no need to wait for approval with any changes we made.

Design

This project started with us wanting to make the lives of those with leg injuries easier. People who have leg injuries have many struggles they must face during their daily life, crutches being a considerable inconvenience. While we had a few ideas of problems we could solve through the engineering design process, by the end of Junior Project, we decided that we wanted to focus on redesigning the standard axillary crutch. To do this, we tried to take features from higher-end crutches and combine some of those features with a few of our ideas to create a crutch that fell in the middle of the price range, ideally around $75. We had the goal of designing a crutch that is suitable for multiple body types whether the person has wider hips or a disproportionate arm length to height. Most common crutches cause pain from either prolonged use or improper use. They also tend to be awkward and jerk when in use both of which can increase user discomfort. To narrow down our project, we decided to focus on college-aged users who will only use crutches for a relatively short period, several weeks to a few months, and will then keep the crutches for younger siblings or in case of reinjury.

When deciding what aspects of the crutch design that we wanted to focus on we created the House of Quality (see Appendix H, Figure 1). The House of Quality helped us to see what aspects went together and therefore could be solved by the same design change or modification. This helped to simplify the list of things that we wanted to achieve. With all this in mind, we tried to base decisions off what would have the most significant impact first and then focus on the little things, such as appearance once the more significant decisions were made.

During Junior Project, we created a massive Pugh Table (see Appendix H). This table broke down the crutch into its various parts from the arm piece to the method of shock absorption. Each of these sections was then broken down into the different ideas we could pursue. We then compared these based-on things like ergonomics and product lifespan. After all the comparisons were complete, we were able to see which ideas seemed to be better than others. For the most part, we did follow the results of the Pugh Table. The one significant way we varied from the results is that the results suggested that we a hand crutch style. As a group, we decided that we wanted to focus on the axillary crutch style as this is the style most common in the U.S. and is what people in our demographic tend to use. Therefore when it came time for testing, we would not have that much difficulty finding people who had used a similar style crutch in the past.

Starting senior year, we began with prototyping crutches out of scrap material we found lying around at our houses. Appendix C contains all the relevant photos for our first prototype. With each prototype, we compared our thoughts about them to the current design and made improvements where we thought necessary. The most significant changes we made were to the shape of the crutch. Figure 1 shows the evolution of the prototypes. This image shows how the design became more complicated in Prototype II, with two different bends. Then in Prototype III, we simplified our design to make it curve more naturally with the body.

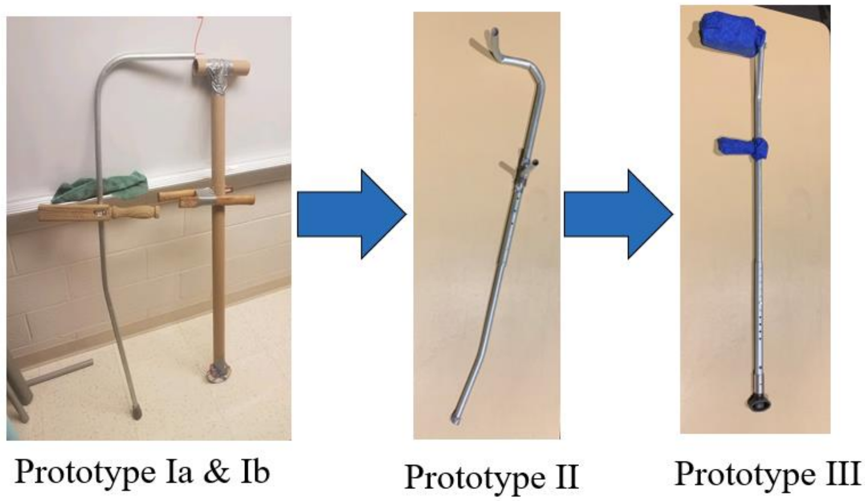

Figure 1: Evolution of Prototypes
The figure above shows the evolution of prototypes. Prototype Ia was made out of cardboard tubing while the rest were made from EMT

While our first prototype was a simple cardboard tube with a handle duct-taped to it (Prototype Ia), we quickly moved onto a simple piece of conduit that we put a ninety-degree bend in for the shoulder rest (Prototype Ib). From there we moved onto what can only be described as an overcomplicated bend for Prototype II (also see Appendix B). After testing, we found that with how complicated the curve was not only was it too large but would also be more difficult to manufacture on a large scale. At this phase all the testing we did ourselves as these were not intended for serious use but more as a proof of concept to see if we wanted to pursue that particular design any further.

After the complicated design of Prototype II, we scaled it back to a more elegant single bend that brought the crutch out away from the user's body in Prototype III (also see Appendix A). While the shape of the crutch was the most notable change from one prototype to another, we also made changes to the foot, handle, and padding with each iteration. The foot started as nothing, just the bare tubing. As we got more confident in our prototypes, we began to spend more resources on foot. We started by adding the regular crutch foot to the bottom and found that this was a less than ideal situation as it seemed to limit the user's mobility. With that in mind, we looked into building our own foot and adding a spring into the crutch to soften the impact of hitting the floor with each step. This resulted in the PVC design pictured in Appendix C Part III and Appendix D Figure 4. After some testing we found that while the PVC worked great initially however after repeated use, the PVC no longer returned to its original shape, so we moved on from these designs and continued with more research.

During our research, we discovered the MD Crutch's foot (see Appendix A Part V). This foot had everything we wanted already built in and ready to be attached. While these feet would be the most expensive part of the crutch, the benefits outweighed the actual cost. These feet have an internal spring that helps to cushion the impact of the foot, and they are curved in such a way so that they allow for a longer stride while still providing plenty of traction. These aspects along with several others were significant factors that we wanted the foot to provide. We had looked at using Belleville Washers (see Appendix D Figure 7), but the MD foot provided a more straightforward option.

While prototyping did start with scrap material, we obviously could not use that forever and needed a way to decide what materials to use for the future prototypes and final design. We had experimented with curved wood (see Appendix D Figure 2) but found this to be impractical as the process of curving it also severely weakened it. This was when we created the Materials Pugh Table (refer to Appendix H Figure 2). On this Pugh table, we listed several different materials from pure aluminum to self-healing plastics. Some of these materials were impractical for our circumstances, but they served as a comparison for more practical materials. From this table, we narrowed it down to materials like aluminum and steel as some of the better choices from the table. We finally decided to purchase steel EMT as it was readily available, cheap, and easy to work. This material could also be easily mass produced at a reasonable cost to the shape of the final design. If our crutch were to be mass produced it would be made from aluminum which would allow stretching for the right-angle bends and tighter tolerances to our specified dimensions to eliminate the need for shims and ease the handle's adjustability.

The handle adjustability also went through several iterations during this time as well. It started as a hammer handle duct taped to a cardboard tube and shortly moved onto a piece of conduit sticking out from a tee joint. Taking inspiration from how bike seats adjust we looked into if that concept could be applied to our project. After some testing and 3D printing prototypes, we found that this concept could indeed not only add the adjustability we desired but also provide a secure way of holding the handles in place. Appendix A Part III contains a more detailed explanation as well as photos of this aspect of our project. The handle does slide reasonably well along the length; however, it does get stuck occasionally. This is due to the loose tolerances kept on the outer diameter of the EMT which is a problem that could be quickly eliminated during the manufacturing process.

Even though the handle started as scrap material, we researched possibly purchasing a pre-made handle. Appendix D Part III has a listing of all the various handle types we considered. After some deliberation, we decided that we would use the padding we had purchased for the shoulder pads on the handles. We reached this decision not only to keep the list of materials as simple as possible but also to keep the design simple. If we were to purchase a handle, there was a good chance the inner diameter of the handle would be different than that of the materials we were already planning to use. This way we could not only get the exact handle padding we wanted but also eliminate waste by using the remaining padding we had.

Once we settled on the shape and handles for the crutch, it was time to focus on how exactly we were going to cushion the otherwise uncomfortable metal rods. While researching online, we came across a website that sold various kinds of foams intended for mattress toppers or seat cushions. Once we had three different types of foam come in, we started experimenting with multiple wrapping styles, and layering of the foams. Over several weeks, we cut, taped, and wrapped the foam to the handles. Each time we would grab and rest on the padding to see how it felt. We found that if we made the shoulder padding too wide it cut off circulation to the user's arms. So, with that in mind, we focused on tall and thin padding for the shoulders.

As for the handles, we found that wrapping the foam tightly to the handle provided sufficient padding. Too much padding on the handles made them challenging to hang on too. Not only did we test each padding style personally, but we commonly asked whoever was around at the time to give us their feedback and to hear what they recommended. In the end, we came up with a succession of layers that we felt was as good as we could get with the little time left and the materials we had. While the cost of foam is low, the ability to recreate this exact wrapping technique is not feasible. Instead, for mass manufacturing, we would need to spend more time and resources searching for a foam that could replace the multiple layers of different layers with either a few or a single layer.

With the padding decided the final step was to make the crutch more visually appealing. We did this by wrapping the pads in cloth and securing them in place with drawstrings. The drawstrings would allow the end user to wash the covers or change them out to personalize the crutch a little. The last part of the project involved doing a simple cleaning of the crutch to make sure all the chips and dust were cleaned off for our SCAD presentation.

Fabrication Report

Fabrication methods and processes were considered when creating the design of the crutches, which greatly simplified the fabrication of our prototype. Early in the project, we used shop time to get familiar with the pipe bender and how it handles various sizes of conduit. We found the strengths and limitations of both the bender and the material and used that information in our design. To be agile with our design changes, we chose to fabricate Prototype II with two sizes of conduit and their fittings. This allowed us to replace parts quickly, and try out potential designs, speeding up the design process. Our prototypes often shared numerous parts with previous prototypes.

Once we decided upon crucial individual design specifications, we began replacing the conduit fittings with more robust, permanent parts. Based on our feedback on Prototype II, we decided to use ¾ inch conduit for Prototype III. With the conduit sizing known, the handle assembly and foot adapter were drawn up and machined. The CNC capability of the fabrication shop was taken advantage of for certain complicated features on both parts. The mill and lathe provided accuracy that allowed us to machine to tight tolerances and reduced stack up errors, particularly on the sliding leg mechanism. The machining processes took more time than we had expected, but the final results were worth the time invested. Additionally, we took advantage of the 3D printer for the bushings, as the plastic bushings would reduce noise and require less time to fabricate.

Fabrication of the padding on the handles and under the arm was an evolution throughout the entire semester. Since the padding was secured with tape and spray adhesive, it was easy enough to tweak the padding to get the desired result. Much of the fabrication process for the padding was experimental, as it is difficult to predict how the foam will feel.

Throughout the project, our design was driven by the fabrication methods available to us. We did reach a point where future design changes would require specialized machinery that is not available to us. Particularly a pipe bender that pulls the pipe though as it bends to reduce the buildup of stress on the inside radius, and the ability to form and anneal the metal to make a tool-free replacement for the through bolt.

Testing Results and Analyses

In the beginning, we tested our prototypes. Especially with our first prototype, Prototype Ia, we merely wanted to see how it felt. In this case, we did not walk around with it; we just messed with its height, handle, and how much cushion the foot added. Even the second variant of the first prototype, Prototype Ib, did not receive much testing as that one was for more of a shape comparison. We wanted to see how the bend affected the way the crutch felt. For example, did it put the handle too far forward? Was the curve too large of a radius to be comfortable? It was not until Prototype II that we started to test. We designed this prototype to be easily adjustable so that we could modify and test multiple variations in a short amount of time.

It was this part where we decided that the complicated bend was impractical. One of the reasons being that it made the crutch too large and moved the handle too far out. With the limited tools at our disposal, we would not be able to modify the current design to bring the handle in any further. So, we came up with a plan that became our final design, an idea that would lead to the next prototype. The beauty of Prototype II was that we could create the different top and bottom halves and interchange them to see what bends worked best together. This allowed us to quickly and easily change things we did not like and see if our ideas improved or worsened the crutch.

Prototype III was the design on which we spent the most time working. With this design, we created the testing parameters (see Appendix E for the testing survey). These parameters had a participant use the standard crutches first to establish a baseline. They would complete tasks like walking, standing in place, and getting in and out of chairs. Once they were comfortable with those crutches and activities, we had them do the same thing with our prototype. After they had completed all the events, we had them rate their experience compared to the traditional crutches on a scale to 5 for each action and overall experience. All participants were also required to sign the waiver (listed in Appendix E) for legal purposes.

At this stage, we were also comparing various padding techniques, so we also had them pick their favorite shoulder and handle padding. With all the results from multiple participants, we then looked at what they said and made some minor adjustments. Based on their responses we made a final decision on how to finalize the padding for the should and handle pads. On SCAD day we did have several people try out the crutches and give us their feedback. Almost everyone said that they were considerably more comfortable than a standard crutch. They also commented on how the foot made it easier to walk and how the shape of the crutch was more convenient, with the handles being farther out. Overall, we felt that our final prototype had met our aspirations and we were proud of it.

Manufacturing

To manufacture these crutches, there are numerous process changes that would reduce cost, and taking advantage of specialized tooling would improve the functionality of certain parts of the design (see Appendix G). We chose the conduit for the prototype for its selection of fittings, but in a production model, aluminum tubing can replace the conduit. Aluminum will weigh less, have a better surface finish, and will be sizable. We could reduce the gap in the slide mechanism can by specifying the inner and outer diameter of the tubing, which will reduce the size of the bushings needed to fill the gap. Industrial tubing benders found in manufacturing settings will be able to bend the tubing into a tight radius, which was not possible with a lesser bender. Replacing the ninety-degree elbow with a continuous bend which would save money and improve strength and appearance.

Instead of machining the handle assembly and foot adapter, they could become cast parts instead to save time and money. The four-part handle assembly could ideally become just two parts, the cast handle, and the bolt. The foot adapter could be cast to reduce the complexity of milling the shape of the tapered ellipse foot adapter, or a similar foot could be designed with a circular post that would be sized to fit into the lower leg. This would eliminate the need for an adapter altogether.

Leveraging the machinery that performs draw forming would allow us to replace the through bolt with a simple part that acts as a spring detent, to hold the crutches at a given setting (see Appendix G). These parts rely on bending jigs and heat treatment to create spring-like properties and draw press to form a pin that will extend through both tubes on the crutch. Unlike a fabrication lab, creating these in a manufacturing setting is feasible and inexpensive, which is why they are so widely used in crutches on the market.

Discussion

Overall, this redesign was a success. We were able to successfully create a prototype design that solved all of the problems associated with the common axillary crutch as detailed above. We were able to solve the problem of pinched nerves by identifying its cause and creating a new design to fix it. The padding on our design is larger than that found on a store-bought crutch, allowing for more surface area of contact to reduce the pressure on the underarm nerves.

It is also more comfortable to rest on and has a slight dip in the middle to keep the arm in place while moving to prevent chafing. The infinitely adjustable handle also helps with the problem of pinched nerves as well as improving posture. These problems are often caused by misuse of a crutch as they are designed to distribute your weight between your hands and underarms. If the handles are in the wrong spot for the user, they can rely too heavily on the shoulder padding which can cause discomfort. This also tends to happen as the user begins to tire as they use the crutch.

To prevent exhaustion, we researched various methods of energy return such as the Belleville Washers and springs. In the end, we bought replacement crutch feet from the MD Crutch—which we identified as one of our closest market competitors. This foot compresses and rolls with use allowing for energy return and a longer stride which reduces how much energy the user has to expend. One of the design aspects we ended up spending the most time on was the shape of the crutch. We knew that we wanted to bring the crutches away from the body slightly to allow for different body types, but we were unsure which direction or how to make it ergonomic for the user. After lots of sketching and a redesign, we found a shape that brought the body of the crutch out and away from the body slightly while still following the natural movements of the body. The infinitely adjustable handle was helpful here as well because it allows the user to rotate the handles to fit their grip best.

We were able to solve all of these problems while also keeping the crutch at an affordable cost and without wasting too many materials. As stated above, we almost wholly followed our PDS with a few exceptions that made them more practical. For example, we wanted our crutches to be able to be packed away easily. This goal was not attained as we kept our focus more on solving the problems above than those of convenience. We initially discussed creating a collapsible or foldable crutch, but that was not practical considering our time and fabrication constraints. Although there were a few features that didn't make it to the final design, we had all of the essential aspects that we wanted and were able to solve the problems with crutches that we identified at the beginning of this project. Therefore, we can call this project a complete success, and we are very proud of our work product as well as our overall teamwork.

References:

[1] "Incidence of Patients with Lower Extremity Injuries Presenting to US Emergency Departments by Anatomic Region, Disease Category, and Age," *US National Library of Medicine National Institute of Health.* [Online]. Available https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3237997/. [Accessed 19-Apr-2019]

[2] **"**How Many People Use Assistive Devices," *U.S. Department of Health and Human Services.* [Online]. Available: https://www.nichd.nih.gov/health/topics/rehabtech/conditioninfo/people [Accessed: 19-Apr-2019]

[3] "Emergency Department Visits," *Center for Disease Control and Prevention*. [Online]. Available: https://www.cdc.gov/nchs/fastats/emergency-department.htm. [Accessed: 19-Apr-2019]

[4] "Crutch Use," *Foot Health Facts*, 2018. [Online]. Available: https://www.foothealthfacts.org/conditions/crutch-use. [Accessed: 11-Dec-2018].

[5] "M D Crutches- Painfree, stylish and custom elbow crutches," *Kickstarter*. [Online]. Available: https://www.kickstarter.com/projects/682596326/m-d-crutches-painfree-stylish-and-custom-elbow-cru?ref=nav_search&result=project&term=walking aids. [Accessed: 14-Feb-2019].