Hands-Free Crutch Alternative

A Major Qualifying Project Report

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Abstract

The goal of this project was to design an assistive device that would serve as an alternative to crutches without requiring use of the patient's hands. The crutch body is a vertical series of concentric tubes that can be adjusted to fit patients of different heights. It is attached to the bottom of the thigh by tightening velcro that runs through a thigh support. The thigh attachment and the crutch body are connected with a pin joint, allowing for rotation along the same axis as the knee. Pinned to the crutch body is a short rod that attaches to the calf, enabling users to control where the crutch comes into contact with the ground while walking. Future research could improve on the device's balance, as that was one issue during testing.

Background

The National Electronic Injury Surveillance System (NEISS) is used to monitor injuries that are treated at emergency rooms throughout the US. According to the NEISS, 51.8% of all leg injuries occurred below the knee at locations classified as the toe, foot, ankle, and lower leg [1]. This means that a little over one-million fractures, dislocations, and sprains/strains to the lower leg are treated in hospitals each year [2].

The recovery time of these injuries can vary depending on their location and severity. Mild ankle sprains only require ice and rest to treat and are healed within a couple of weeks, but fractures and dislocations can take between four to six months to heal [3]. For many patients, this means that they will need an assistive device of some kind to help them get around. Crutches are one of the most common assistive devices used in the US since they are relatively cheap and easy to produce.

Crutches aren't perfect however, and prolonged use of axillary crutches (Fig. 1) can cause muscular soreness in the patient's back/neck and pain in their wrists. In some more rare situations, nerve endings in the armpit can be damaged and make it difficult for patients to move their arms [4]. Forearm crutches (Fig. 1) alleviate some of these issues, but still remove the patient's ability to use their hands, which can be inhibitive in daily life. By freeing up their hands, patients will be able to live a more routine and comfortable life.

Fig. 1. An Axillary Crutch and a Forearm Crutch [5]

Commercially Available Solutions

Forward Mobility Freedom Leg Brace (Fig. 2.) [6]

Fig. 2. Forward Mobility Freedom Leg Brace [6]

The Forward Mobility Freedom Leg Brace, pictured above, is available in a variety of sizes. The device attaches to the patient's thigh with a velcro thigh brace and is supported by a pair of "composite" supports that meet below where the foot rests. This design is relatively simple, removing all weight from below the patient's knee and diverting the forces to the patient's thigh instead. This is a common method of force redistribution, as other popular market-ready designs follow this pattern.

One of the drawbacks from this design comes from the angle that the thigh makes with the ground while the patient is moving. The device is strapped around the patient's thigh in a way that pushes it up the leg while it's supporting weight. Unless the thigh straps are set very tight, the brace would likely try to push up the patient's thigh in an uncomfortable way while the device is being used.

Sit & Stand Walking Assistance (Fig. 3) [7]

The Sit & Stand is a concept made by a student in a design contest back in 2014. While this design isn't commercially available, it is unique and worth discussing for some of the ideas that it brings forward. Firstly, the large thigh pad for support is a great concept. Distributing the force over a wider area reduces the pressure that's being applied on the thigh, which would make it more comfortable for the patient. Additionally, the rotating joint that connects the thigh pad to the rest of the device is important since it allows the patient an option to change to the most comfortable angle for their movement.

Fig. 3. Sit & Stand Walking Assistance [7]

IWalk 2.0 (Fig. 4.)[8]

Fig. 4. IWalk 2.0 [8]

Visually, the IWalk 2.0 is the most unique design found in our background research. Rather than having the support attach to the thigh, the patient would rest their weight on their knee. The device secures itself around the patient's calf, to deter any movement in the lower leg from walking. This device uses the knee for support and would not cause any riding up to occur on the thigh, eliminating one of the flaws shown in the previous two designs. However, this design cannot be used by patients with leg injuries above the ankle, which account for approximately 27% of all lower limb injuries. [1].

Functional Requirements

In order to better define the problem, we decided on a short list of functional requirements that would guide project design moving forward. For these requirements, we thought about common problems with existing crutches on the market, and what specific problems we were trying to address. The first ideas we thought of were about the sizes of the patients that would be wearing this crutch. We want the crutch to function with the majority of adults, so we decided to shoot for a large range in patient height and weight.

Next, we decided to take some ADA specifications into account when it came to the different types of terrain that a patient would be traversing while using the crutch. We consulted their specifications for indoor and outdoor stair sizes and slope steepness. We also wanted the patient to be able to walk on gentler natural terrain, like what would be commonplace in someone's front yard.

Finally, we didn't want this device to be a step back from crutches in any meaningful way. Patient walking speed should be at least as fast as it would be if they were using a normal crutch. We also want to make sure that putting on and taking off the device is easy and quick. We also imposed a weight limit for the device to ensure ease of use based on the weight of one single axillary crutch.

Final Device Functional Requirements

1. The device can support patients ranging from 110-225lbs (49.9-102.1). Patient height range is from 5'2" to 6' (157.4cm – 182.9cm).

2. The device will be usable on many different types of terrain, including up and down stairs with a height of 7in (17.8), inclined planes with a grade of up to 8.3%, and uneven terrain such as gravel walkways and dirt paths.
3. Patients will be able to travel comfortably at a speed of 2mph (3.2 kmh).
4. The device will be designed so it can be removable in under 20 seconds without another person's assistance.
5. The device will weigh a maximum of 2.5lbs (1.1kg).

Final Device Functional Requirements: MQP Goals

The goal of this project is to design a device that assists people who have lower leg injuries with walking hands that allows for free use of their hands.

Design Decisions

There are several decisions that were made in order to determine the final design of the project. The first was to assume that this device would only support patients with injuries that occurred below the knee. This is because it was thought that the crutch would operate best if the patient's knee were functional. The next decision made was to assume that the patient's other leg was functional. Regular axillary crutches are used when one of a patient's legs is still functional as well, so this is a fair comparison.

Methods

Several general design concepts and areas of importance were recognized from the background research. In no particular order, these focal points were general design shape, body attachment, foot design, modularity, compliance, and walking gait. Each of these points in the design were progressing simultaneously, with new ideas for one design aspect influencing ideas for other aspects.

Since the purpose of this project is to design a suitable replacement for underarm crutches that leave the hands free for use, most of these general designs are focused on the lower body. One of the first ideas considered was altering a standard knee brace. Where knee braces are meant to help give some structural support to the leg, this design would extend farther down to below the foot, supporting the patient's full weight. Shown to the right is an extender knee brace [9], which gives a rough idea of this concept.

Fig. 5. Extender Knee Brace

Another concept was to have the patient "sitting" on a stilt-like bar. It would be attached at the thigh, and extend straight down to the ground. There would be no rotation of any part of the device while it was in use, but the user could adjust the angle that their thigh was resting at. Patients would walk normally with their uninjured leg and rock on the stilt.

Overall Design

Under Leg Design

The first idea that came up during brainstorming was fairly simple, shown in two different configurations (Fig. 6). The concept here was to attach to the patient's thigh near the knee with a sort of brace or strap. The thigh support is located close to the knee in these designs to allow for maximum mobility. If the device is located that far down the leg, it would be easier to clear stairs and other simple obstacles. This design is supposed to function like an analog leg, with a similar gait pattern to normal walking.

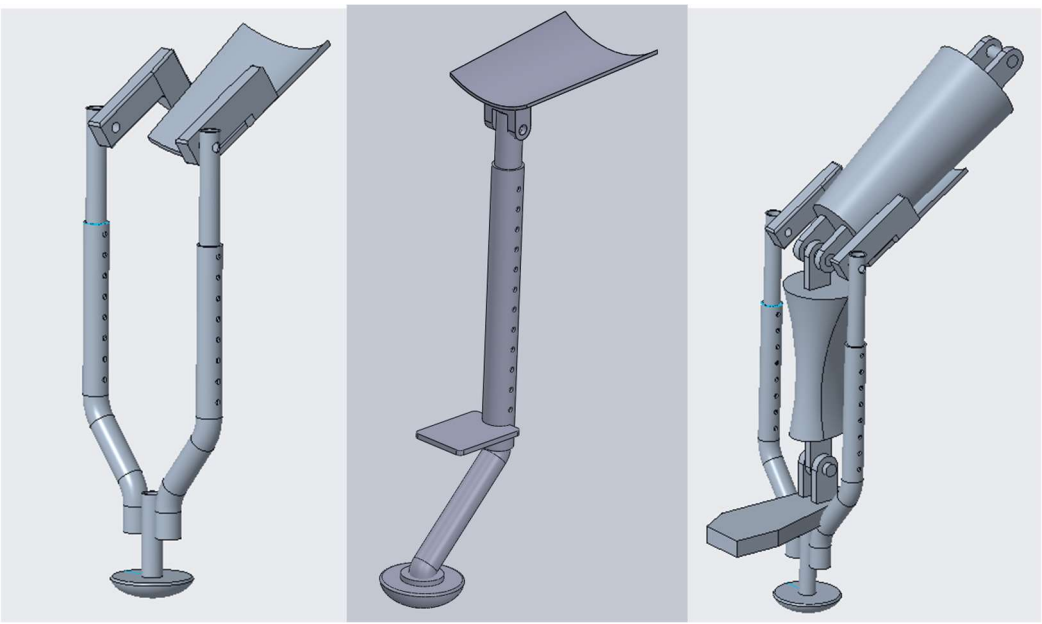

Fig. 6. Previous Device Design Iterations

The first design (left) was designed with a similar shape to a standard axillary crutch, with the two tubes converging on the foot. The second design (middle) considered adding a foot rest for the patient, as opposed to leaving the foot to swing freely. A view with the patient's leg in the first design is included (right); as shown the knee is the pivot point for the design.

The problem with these designs is similar to the ones found in the background research. The thigh support angle with the ground is problematic, and could cause discomfort for the patient. The ground reaction forces are shown in figure 7. The reaction force, F_n , would start at the point of contact the foot makes with the ground and be directed towards the patient's center of gravity (here shown at the hip, although it's actually slightly higher [10]). This vector can be broken down into two components, shown as F_{nx} and F_{ny}. F_{ny} is the force the patient would feel pushing into their thigh, and F_{nx} is the force the patient would feel pushing up their thigh. F_{nx} is the more concerning force in this situation, as that force needs to be supported by the softer tissue in a patient's thigh. This design would want to push up the patient's leg, resulting in a very uncomfortable experience.

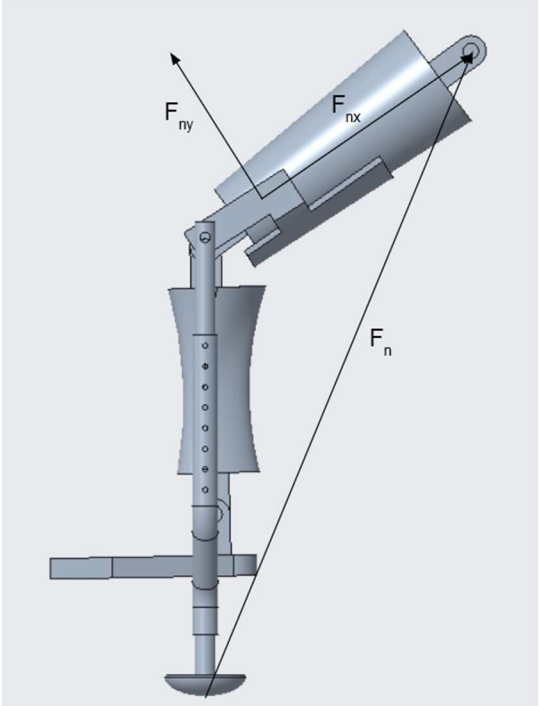

Fig. 7. Initial Idea Force Diagram

"**Dog-Leg" Design**

The "Dog-Leg" design iteration was a potential solution to the problems found in the under-leg design section above. Instead of functioning like an analog human leg, this design would attach to the thigh and stick out perpendicularly before bending forward at a "knee," like a dog's leg. Compliance in this design would be built into this knee joint in some capacity, whether with a spring or a dampening system. The patient's lower leg would be bound to the upper link on the design, keeping it from swinging freely.

Fig. 8. "Dog-Leg" Design

There were some issues with this design, the largest being that it would be very difficult for this design to walk down stairs. The lower part of the leg would run into the stairs above where the patient was trying to step, which is extremely unsafe. Another issue is that control of the device's foot would be very awkward. In uninjured walking, a person has three joints to control where their steps land: their hip, knee and ankle. Each joint is important in controlling how the leg moves. In this design, since the patient is left only with their hip joint, so fine control over where the device's foot would land would be difficult.

Mechanism Design

This next design was actually inspired by a desk lamp, like the one shown in figure 9. If the middle or bottom joints are bent, the orientation of the lamp head can remain unchanged. The idea was to replicate this into a crutch design, maintaining the orientation of the patient's lower leg while walking. If the patient's lower leg was perpendicular to the ground, then it would remain perpendicular to the ground even if the patient rotated their hip. This would make it easier for patients to traverse staircases, since their leg would be able to clear the individual steps more easily.

The biggest problem with this design is its complexity. The mechanism itself would require many individual moving parts. These parts would also need to be different depending on the patient's size, introducing a modularity issue. This mechanism would likely need to be used in tandem with some other weight bearing component.

Fig. 9 . Desk Lamp and Mechanism Design [11]

Extended Thigh Pad with Fine Adjustment

For this final design, the general idea was to make the thigh attachment pad larger, since more surface area would disperse pressure along the leg. This concept also pushed the device's leg farther up the patient's thigh in order to adjust the angle of the ground reaction forces. Lastly, the patient's leg needed to be secured, so a "connecting rod" was added between the device leg and the patient's leg. Shown in figure 10 is a picture of this first concept.

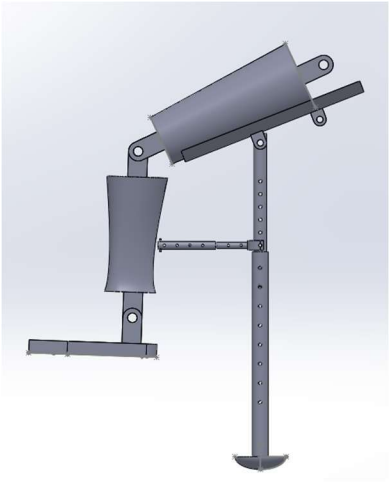

Fig. 10. Extended Thigh Pad With Fine Adjustment Design

While modelling this design, it became apparent that including a pin joint between the thigh pad and the crutch body would allow the patient to make fine adjustments of the device's foot by rotating their knee. This would increase patient mobility while using the device since it allows for more deliberate motion. One caveat introduced with this design is that patients who have injured their knee cannot utilize the fine adjustment. In cases like this, it would be best for these patients if the joint below the thigh attachment could lock. Shown in figure 11 is a joint that can rotate freely, and if pinned, could lock in a position that was most comfortable for each individual patient.

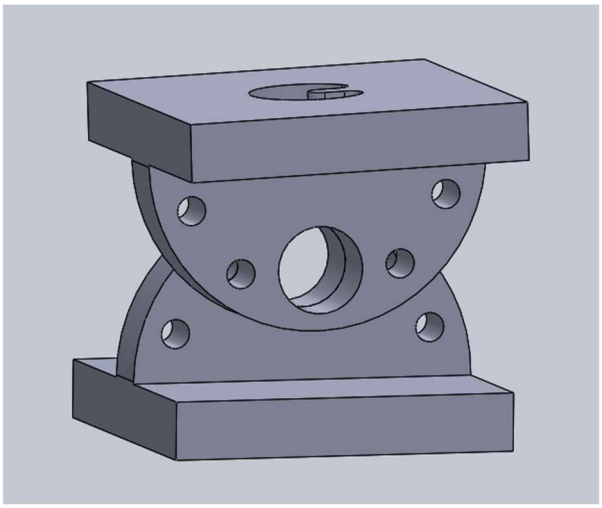

Fig. 11. Joint Design

Component Designs

Thigh Attachment

This part of the device is what is used as the main connection point to the patient's body, and will support the weight of the patient's body. There were a number of ideas for how to design for this attachment point, but it was agreed upon that no matter the design, the patient's upper thigh would be where the device attached to the user's body.

Small Knee Attachment

The method of our first major idea shown previously (fig. 6) was to have a small brace or set of velcro straps affix around the knee. This would be sewn or glued to the device along with the under leg support. It would be very similar to a regular knee brace, but it would have modifications that allowed the brace to connect to the rest of the device. This method would allow most of the support in the device to come from the under leg support plate. There would be minimal support through the brace/straps in order to minimize any forces on any injured portions of the patient's leg. However, after identifying the disadvantages of the first Under Leg design outlined above, it was decided to move forward with a different attachment method.

Freedom Mobility Design

Through background research, the idea to mimic the attachment method that the Forward Mobility Free Leg Brace (Fig. 2) used was considered. The attachment method is to have the crutch bars extend along the length of the thigh and connect to a brace wrapped around the thigh with velcro straps. While this design would support the patient well in the Forward Mobility Freedom Leg Brace's design, implementation of the design would be flawed here on this device. The device would be strapped around the patient's thigh in a way that pushes it up the leg unless it were tightened to an uncomfortable degree.

Pressurized Tube

Another idea was to create a brace with similar functionality to a standard blood pressure cuff, shown in figure 12. This attachment method would have a brace that would velcro shut around the patient's thigh, then be pumped up with air using an attached inflation valve so that the brace is secured and won't slip off. There would also be a quick release valve so the air could be released from the brace to take off. This method is quite simple since it doesn't include many parts. However there were some issues that make this design impractical. While the brace would fit snuggly immediately after the patient pumped it up, it is more than likely that the brace would slowly depressurize over time. This would require the patient to frequently reinflate the device to keep it comfortable and stable on their leg. The other issue is that the patient could unknowingly pump the brace up too much, which could damage the patient's already injured leg by decreasing or even cutting off blood flow to the leg.

Fig. 12. Blood Pressure Cuff [12]

Larger Thigh Support

Another idea for the thigh attachment of the device was to have a support underneath the patient's thigh like in the under-leg support, but it would be slightly wider and would extend further backwards towards the patient's rear. The attachment would stay affixed to the patient through the use of velcro straps wrapped around their thigh and through the device. The advantage of having the attachment be larger and longer was to increase the support for the patient's body by increasing the thigh pad's surface area, decreasing the pressure being applied to the leg. Due to the increased size the device would be slightly heavier, but the tradeoff was worthwhile.

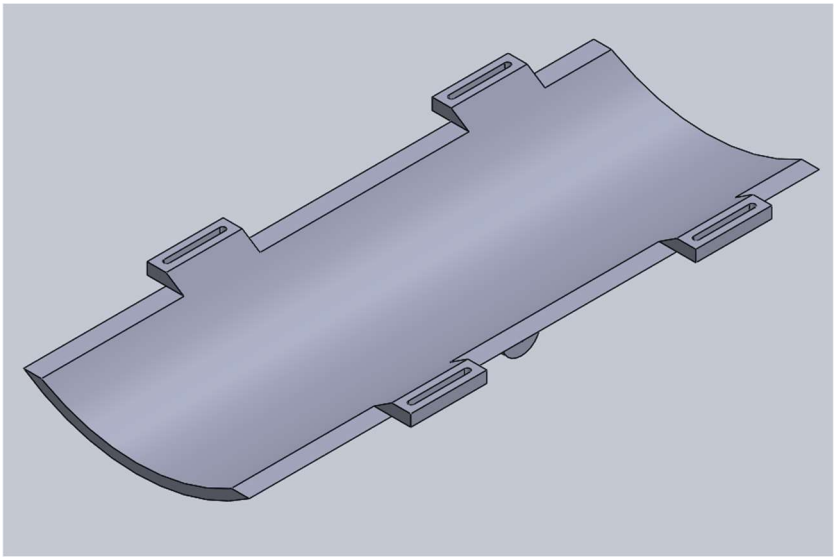

Fig. 13. Larger Thigh Pad Design

Leg and Leg Compliance

The basic design for the crutch leg hasn't changed significantly since its initial conception. One of the most important functions of this assistive device is that it's length is adjustable for those with varying heights. Axillary crutches, canes, and other assistive devices solve this problem by using two concentric tubes with spaced pin holes. Pinning the holes prevents the tubes from sliding, locking them at a certain length. As this method has proven to be effective, this design replicates the methodology.

For this design however, it was felt that a system allowing the patient to change the device's length while walking would be beneficial. By observing crutch motion in a SolidWorks assembly, it was determined that the patient may have difficulty walking up or down stairs. While going upstairs, the device's foot has clearance issues on steep stairs, so it would be prudent to allow the

patient to shorten the device on the fly. Similarly, if the patient was having a hard time going down stairs, they could lengthen the device, if they found that necessary.

Two potential systems were considered. The first system was found through research, where a group of students from the University of Pittsburgh designed a mechanism that allows for quick height adjustment of axillary crutches [13]. In this device, the patient would be able to pull on a "hand lever" that contracts two pins that prevent the two concentric tubes from sliding (Figure 14). The design works well in concept, but for this project it would be difficult to integrate and manufacture.

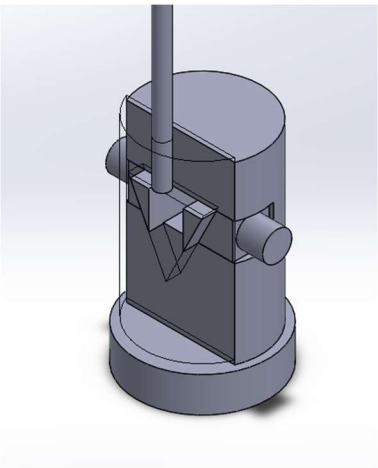

Fig. 14. University of Pittsburgh Student Device

The second design is much simpler. The mechanism is a lever that would latch onto the exterior of the crutch and pin it from the outside. By compressing the lever, the pin is pulled out of the holes in the crutch, releasing the two concentric tubes. The device is held in place with a pin hole that is drilled on the side of the crutch leg. The pin will be held in the locked configuration by a spring that attaches near where the patient would compress the lever.

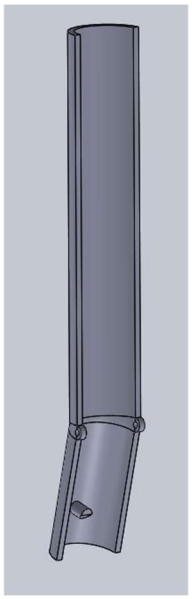

Fig. 15. Outer Length Adjuster

The next aspect to be addressed will be referred to as compliance. One of the functional requirements of this design is that patients are able to move "comfortably," and one way to help ensure this would be to integrate some amount of shock absorbance in the device's leg. If the leg has some amount of built in elasticity, then the repeated impact force of the device leg on the patient's leg will be lowered.

Initially, research was put into having some kind of damped spring system, like a typical shock absorber one would find in a car. One of the earliest ideas was to integrate a mountain bike shock absorber into the device leg, but this would be too expensive and too complicated to successfully complete. Another idea was to use the pneumatic cylinder one would find on the bottom of an office chair. These cylinders have a certain springiness and could even be used to modulate the overall length of the leg if need be. However, pneumatic cylinders are too heavy for our design, since their design does not account for the weight restrictions being imposed on this design. An appropriately sized cylinder for this design would on its own almost exceed the weight limit of 2.5lbs that is stated in the functional requirements, so another direction must be taken. The design of these cylinders is also extremely complex, so it would be very difficult to recreate another one made with lighter materials.

One of the more unique ideas found during research was a design made by four Stanford University students [14]. Their design aimed to make it easier for people using forearm crutches

to get around and focused on crutch compliance. They wanted to make the crutch as light as possible while retaining high strength, so they decided to make their crutch out of a composite material. Using a composite allowed them to integrate compliance "directly into the body of the crutch itself," saving both weight and complexity in the design.

Fig. 16. Stanford Compliant Composite Crutch

The problem with this design is that each of these crutches have to be custom made to fit the patient. The stiffness of the "spring" and the crutch heights would have to change from person to person. This goes against this project's functional requirements to design a device that can accommodate many different people.

The design that was implemented was an adjustable spring system. In this design, the patient can set the stiffness of the spring to whatever is most comfortable to them. The basis of this design is the equation:

$$k = \frac{Gd^4}{8D^3n} \text{ [15]}$$

where k is the spring constant, G is the shear modulus of the material, d is the wire diameter, D is the coil diameter, and n is the number of active coils in the spring. By lowering the number of active coils, the spring constant increases, and the spring becomes more stiff. Shown in figure 16, the patient would be able to change the number of active coils by changing where the spring is pinned. The spring would sit between pins A and B, in its least stiff position. The vertical pinholes are how the patient would adjust spring stiffness.

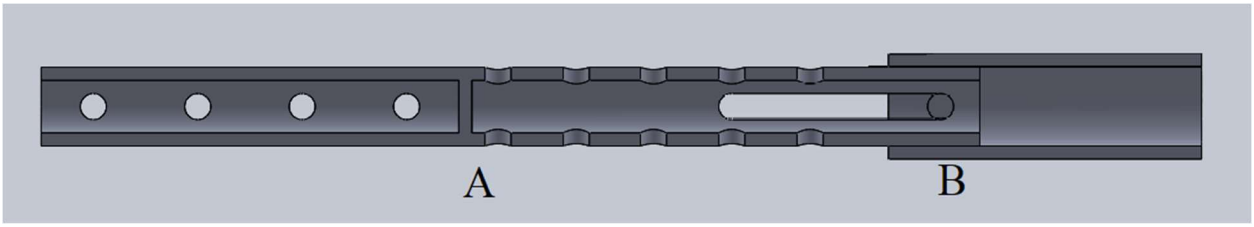

Fig. 17. Adjustable Spring System

Lastly, the leg material needed to be chosen. Since there were several competing factors that were necessary to consider, a design matrix was made. The four functional requirements for the leg material were weight, strength, cost, and manufacturability. Weight consideration is extremely important because the leg is the largest component of the device, so saving weight here goes a long way. Strength is also very important because the device needs to be able to support the patient's weight without failing. Cost is an issue here as well, since this project was operating on a limited budget. Manufacturability was also considered, as access to on-campus facilities was limited during this project. Shown in table 1, aluminum crutch tubes scored the highest, so they were chosen as the main body material.

Table 1. Material Design Matrix

Leg Material						
	Functional Req.	Weight (5)	Strength (5)	Cost (4)	Manufacturability (3.5)	**Score**
Material						
Carbon Fiber		5	4	2	3	63.5
Aluminum		4	4	5	4	74
Titanium		4	5	1	2	56
Stainless		2	5	3	3.5	59.25
Aluminum Crutch Tubes		4	4	5	5	77.5

Connecting Rod

The connecting rod of the device was designed with a similar function to the main body leg of the device. It began with the concept of standard telescoping tubes held together at a length with pins, similar to a typical underarm crutch leg. However, since this component is not load bearing, material strength was not as important a consideration as weight. The two materials considered for this component were 3D printed PLA and aluminum tubing. PLA was chosen as the original prototype since it was lighter.

The connecting rod was improved from this original design by adding a compliance system integrated within the length adjustment mechanism. It was advised that compliance would be useful within the connecting rod for user comfort. Originally, the connecting rod design had a compression spring within the smaller of the two telescoping rods that could compress when force was applied. However, it was felt that more customization was necessary to allow all users to adjust this component to their desired length and stiffness settings. The length adjustment and compliance mechanisms were then separated within the rod, with both individually controlled with separate pins. The spring concept was kept for the compliance mechanism, however a pin was added to control the number of active coils within said spring. This mechanism functions similarly to the one shown in figure 18, which describes the compliance in the crutch leg. The connecting rod is shown in figure 18.

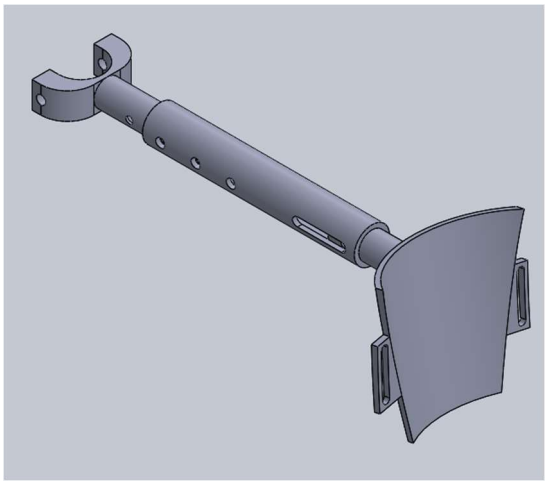

Fig. 18. Connecting Rod CAD Drawing

Eventually, after testing, the PLA components in this design all failed. These components were replaced with machined aluminum and aluminum tubing. The calf pad remained 3D printed, though its design was changed so it could interface with the new machined component. Shown in figure 19 is the final version of the connecting rod.

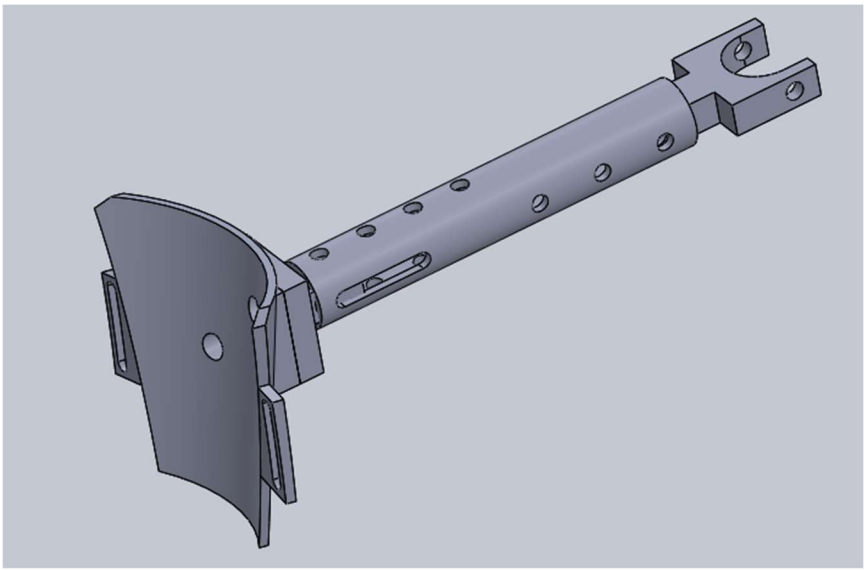

Fig. 19. Final Connecting Rod CAD Drawing

Foot

Originally, the rubber foot found on a standard under-arm crutch was considered for the design. However, with some research a few new ideas were thought up that could improve the standard crutch foot on this design.

The first design iteration was to create a hemispherical foot with a rubber ball material on the bottom. This concept came from the understanding that a circle would allow for the most surface area to keep contact with the ground. This would allow for the patient to have a large range of motion in their walking gait while retaining a safe amount of contact with the ground. The rubber material was desired to have a strong adherence to the ground while maintaining a comfortable level of compliance in the patient's step. This compliance would act like the natural spring in a normal step, as an attempt to allow for the patient to have a walking gait as close to normal as possible.

Walking gait was considered further, and the shape moved onto a semi-ellipsoid, shown in figure 20. This shape would more mimic the user's foot and would still allow for an increased surface area to keep in contact with the ground in lateral motion. This increased surface contact would also improve the traction of the user's foot, reducing the possibility of slipping. The curve of the bottom of the would have a radius equal to the length of a person's hip to their foot.

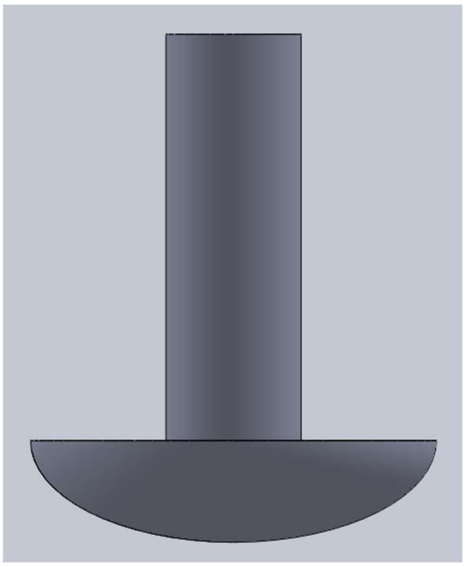

Fig. 20. Semi-Elliptical Foot CAD Drawing

Another similar idea was to make a rectangular foot but with an elliptical rocking motion, similar to that of a walking boot for people with foot injuries, as shown in figures x and y. The thought process of this was to create a wider stepping area for the user laterally. Additionally, this shape would allow for more stable rocking in the walking motion for the user, reducing the fall risk. Also, it helps to better match the center of pressure on the user's foot while moving.

Fig. 21. Rectangular semi-ellipsoid design based off of a walking boot

Another concept was to attach a shoe stretcher to the leg of the crutch, allowing the patient to wear their own shoe with the crutch. Doing so would give the patient's more natural comfort with their own shoe, which could reduce the time it takes for the user to adjust to the device. Additionally, the use of one's own shoe has been proven effective in prosthetic uses before.

Eventually, due to time and manufacturing limitations, it was decided to use a regular crutch foot on the device. Designing a new foot was not a top priority, as most of the project focus was spent ensuring the device functioned properly.

Thigh Joint

One component of the device that needed to be designed was a joint that would connect the thigh attachment to the crutch leg (the location of the joint is shown in figure 22). This is a critical component, since it needs to be strong enough to support the patient's full weight. As such, these components were machined out of aluminum for a good combination of low weight and high strength. The original joint design can be seen in figure 11.

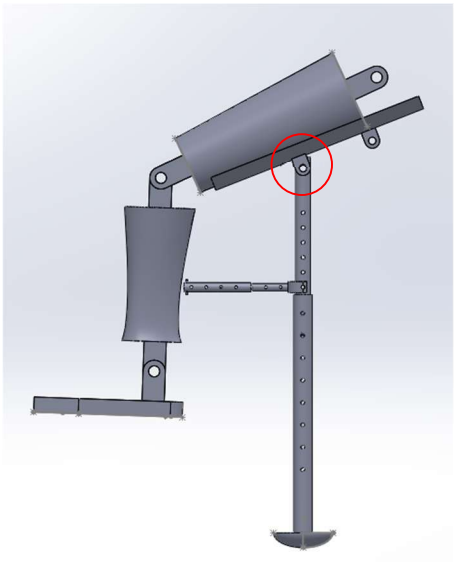

Fig. 22. Thigh Joint Location

This joint also went through several iterations since there was no easy way to attach the joint shown in figure 11 to the rest of the device. The parts in the joint were changed to the ones shown in figure 23 so that the parts could attach to the rest of the device mechanically.

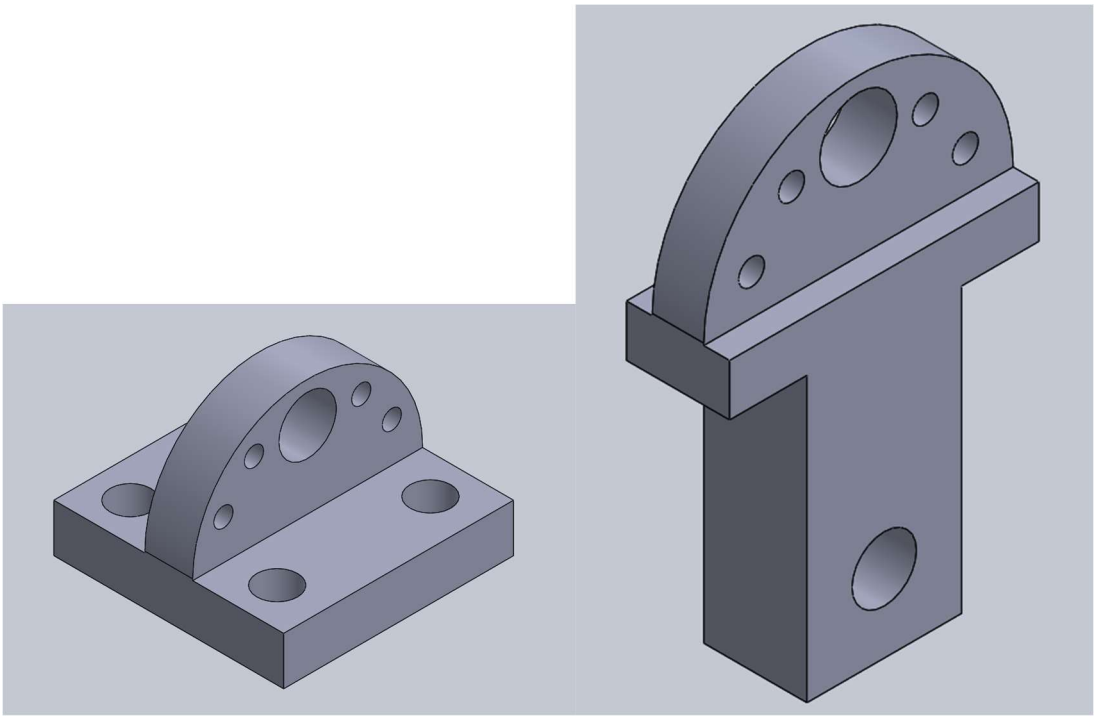

Fig. 23. Thigh Joint Redesigns

The addition of the holes on the upper half of the joint means that it can be bolted to the thigh attachment. The protrusion on the bottom joint allows for it to be pinned to the device leg. These changes allow the joint to be more easily and more securely attached to the rest of the device.

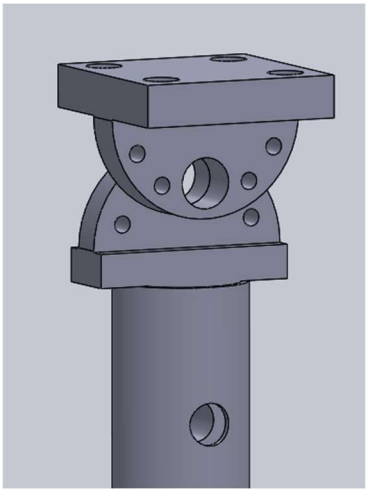

Fig. 24. Assembled Thigh Joint Redesign

Final Design

Each of the parts outlined above went through changes during manufacturing and testing. Figure 25 shows the final assembled CAD model, and figure 26 shows the finished design. Drawings for each of the CAD models can be found in appendix A.

Fig. 25. Final Design CAD

Figure 26. Final Design

Analysis

Most of this project was design based, meaning that the focus was on the device's motion and whether or not it would accomplish the requirements set out at the beginning of this project. One of the requirements was for patient weight, which was capped at 225lbs. Once the general design of the device and on the materials being used was decided, a buckling calculation was run to determine whether or not the device would be able to support the maximum weight. This tube buckling equation can be expressed as:

$$F = n\pi^2 EI \,/\, L^2 \text{ [16]}$$

In this equation, E is the elastic modulus, I is the moment of inertia, n is a geometry factor, and L is the length of the length of the tube. E, I, n, and L are all known variables, so this equation can be solved directly. Here, the length is given as 24in (60.9cm), which was the longest configuration that was initially planned to be used on the device.

$$F = 2\pi^2(10^6 psi)(.0169in^4) \,/\, (24in)^2$$

$$F = 579.2lbs \text{ (262.7 kg)}$$

As can be seen, this device poses very little risk of buckling under use.

Next, a shear analysis was run to make sure that the pins being used to hold the device together would be able to support a patient weight of 225lbs (102.1kg). The shear stress equation is

$$\tau = F/A$$

where F is force and A is cross sectional area. Since the force is being applied on each pin in two places, the effective shear force on the pins will be halved. The equation can be rewritten as

$$\tau = F/2A$$

The force being applied and the cross-sectional area of the pins are known, so the equation can be solved.

$$\tau = 225lbs/2(0.077in^2)$$

$$\tau = 1466.75psi \text{ (10.1 Mpa)}$$

The yield strength of low carbon steel is ~50,000psi, so there is no risk of the pins shearing under the patient's weight [17].

Additionally, a kinematic analysis of the device was prepared so that the dynamic forces of the device could be analyzed at different times across the device's expected motion cycle. The analysis was conducted in Mathcad, and can be found in appendix B.

Finally, analysis was performed to determine the necessary height of the device to fit the required patient height range. This analysis was performed through the use of Winter's Anthropometric Tables [18] based on the equation for total leg height, measured distally. This was chosen as the distal height would be approximately at the end of the hip bone, where the patient's thigh would likely be sitting. Therefore, the equation to determine the device height is:

$$Device\ Height = 0.533 \times (Patient\ Height)$$

$$Device\ Height_{Shortest} = 0.533 \times (62'') = 33.046''\ (83.93\text{cm})$$

$$Device\ Height_{Tallet} = 0.533 \times (72'') = 38.376''\ (97.47\text{cm})$$

As shown in the equations above, the device height must be between approximately 33" (84cm) and 38.5" (98cm) tall to support the required patient height range. This was then used to adjust the device height, requiring the team to cut the main body shorter to fit within this range.

Testing

Once initial manufacturing of the device was concluded, it was necessary to test its functionality. A significant amount of testing occurred prior to official testing to ensure the device would be fully functional when the design was complete. These tests often consisted of walking on the device, determining any flaws that could be found, and making adjustments to improve those areas. For example, the main crutch body showed some bowing in a previous iteration, as the concentric tubes were not a flush fit. These gaps between the tubes caused some rattling while walking as the tubes bounced against one another, and when the device was at its maximum height, there was significant bowing in the tubes. The device was then completely remade with crutches that had rubber tips at the ends of each tube to stop this rattling and reduce any bowing.

After the device passed unofficial testing and seemed to be in the best position for success, official testing protocols were created (Appendices C-F). These testing protocols were based upon the functional requirements set at the beginning of the project. The device's performance on these tests showcases what it does well and how it could be improved in future iterations. These testing protocols determine the successfulness of the device's ability to pass the six functional requirements. This testing did not include any subjects outside of those immediately involved in its design.

The first test performed was determining the total weight of the device. The functional requirements state that the device must weigh no more than 2.5lbs (1.1kg). If the device is too heavy, it could be too labor intensive. Additionally, one crutch is approximately 2.5lbs (1.1kg) heavy, so this was chosen as a weight goal. To test this, a scale was zeroed, and the device was placed on the scale, with one user holding the device straight up so as to hold as little weight as possible.

The second test measured how easy it was for patients to remove the device. The functional requirements state that a patient must be able to remove the device from their leg in under 20 seconds without the assistance of another person. This test, while simple, is important to prove that the device is not overly complicated or difficult to maneuver on one's own. In order to pass this test, the patient first must have the device on to their functional comfort with a period for adjustments once standing. Once the device is on, the tester is required to sit down in a chair, and is asked to take off the device while sitting.

The third test determined the comfort of the device for the user after a normal period of use. This test does not directly apply to the functional requirements of the device, however patient comfort is a priority so a test was made. In this testing, the user was asked to stand using the device for thirty seconds, and then rate their comfort level on a scale of 1-10, one being the worst. After this test and one minute of rest, the tester was asked to walk in a straight line down a measured 100 ft. length in Higgins Laboratory, and rate their comfort level.

The fourth test determined the device's ability to perform on a variety of different terrains and inclines. This test showcases patients' abilities to return to more normal activities, like going on walks and other recreational activities while recovering from injury. This test was performed by firstly having the tester put on the device to their functional comfort, with a period of readjustment as necessary. Once this was situated, the tester walked from one end of Higgins Laboratory level 2 hallway to the end, down a set of stairs, outside, across Earl Bridge, and down the ramp next to it, as shown on the map below. This test would require the user to walk both up and down stairs, up and down multiple inclines, measured greater than 8%, as well as on several different types of terrain. The device would pass the test as long as the patient can complete the test without serious need for readjustment or discomfort that required stoppage of the test.

Fig. 27. Testing Route

Lastly, a test was performed that compared the amount of energy patients would use with this device and with standard axillary crutches. A Pnoē metabolism mask can be used to measure a patient's oxygen use levels, allowing for a reasonable estimate of energy use. For this test, a subject would wear the mask and stand for five minutes in order to get a baseline for their metabolic use. Next, the subject would move on normal crutches for five minutes. The subject would then be allowed to rest until they had completely caught their breath. Lastly, the subject would walk on the device for five minutes. This test would be repeated at least three times for a more accurate baseline.

Results

The device was able to pass all but one test, the weight test. The device with all components attached weighed approximately 2.6 pounds (1.2 kg) (Appendix C), which is .1lbs (50g) heavier than the maximum allowance for the functional requirements. Additionally, during testing, the user stated that the device did not feel heavy at all, and felt that the device weight was not an issue during use.

As for the requirements that were passed, the first was the patient limits that the device could handle. The patient height limits were determined through the use of Winter's Anthropometric Tables, as explained previously. The patient weight limit was found through a kinematic analysis of the pins used throughout the device, which proved the device could handle patients at or above 225lbs (102.1kg).

Next, the testing for device removal was extremely successful. Through the use of the Velcro straps on the thigh attachment and connecting rod, putting on and taking off the device is fast and easy for the user. The functional requirements stated the user must be able to take off the device completely in 20 seconds or less. In official testing, the device was able to be taken off in approximately 6.77 seconds, and put on in 17.71 seconds on average (Appendix D). This means that on average, a user can take the device off in approximately ⅓ of the time that was originally considered the maximum. Timing how long the device would take to put on was also measured, simply because taking the device off was so fast, this information could be useful as well.

The next test, designed to test comfort, also showed positive results. On average, when the user was asked to measure their comfort level from 1-10, with one being the lowest and ten the highest, the user rated it at an 8/10. The primary comments made regarding comfort included that balance was difficult while walking, as it was the main focus while walking.

The speed test, where the user walked one hundred feet in a straight line while being timed, showed significantly improved results compared to unofficial testing. In unofficial testing, the user was measured walking approximately 1.2 mph (1.93 kmh), well below the functional requirement of at least 2mph (3.2kmh). After further improvements were made to the design and the final iteration was tested, the device had an average walking speed of 2.269mph (3.65kmh). The final iteration had a walking speed of nearly double of the original test.

The next test of the device's traversal ability throughout several different terrains showed promise, but not perfection. The device was able to complete the course (Fig. 27) in approximately four minutes and twelve seconds, with no device failure or user falling or injury. After the course was complete, comments made about the test included that walking upstairs was difficult and the traction while walking across the bridge was questionable. The user also stated that while walking, "balance was the only focus," and that the spring in the main body was not stiff enough. However, the user also stated there were no forces felt below the knee and they were able to open and walk through doorways unassisted. Additionally, it was seen that the foot of the device had significant wear to it, due to dragging (Fig 28). This has been attributed to the user having the device set at a height too tall, which caused the device to scrape across the ground while walking.

Fig. 28. Device Foot After Official Testing

The final test, the metabolic test, showed solid results. Although this test was not required for the functional requirements, it still shows important data about the difficulty of using the device. When compared to the oxygen usage and heart rate while walking on standard axillary crutches, the device had nearly the same numbers, though it varied by test subject. This test was performed three times, with three individuals with varying levels of experience with the device. The data is shown in figure 29. The flat section at the beginning of each test was with the patient standing still, the first data spike was with the patient using standard crutches, and the second data spike was the patient using the device. This data was compiled in table 2. The results showed one individual worked harder on the standard crutches, one individual worked approximately the same, and one individual worked harder on the device. Therefore, it can be concluded that the device is similar to the level of difficulty when using standard axillary crutches.

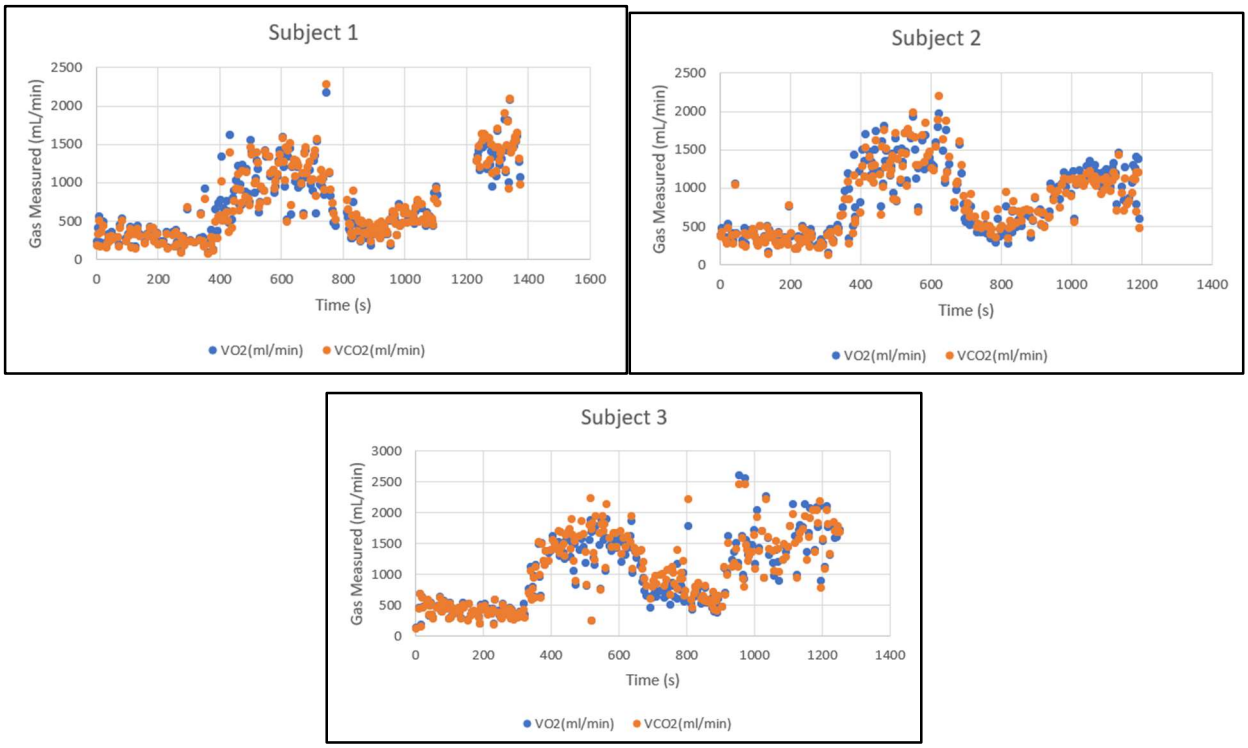

Fig. 29. Metabolic Cost of Standard Crutches vs. The Device

Table 2. Metabolic Testing Data

		VO2 (mL/min)	VCO2 (mL/min)
Standing	Subject 1	304.05	280.35
	Subject 2	373.96	352.85
	Subject 3	415.84	407.21
	Average	364.62	346.80
Using Crutch	Subject 1	1101.59	1152.14
	Subject 2	1382.70	1359.86
	Subject 3	1413.98	1530.17
	Average	1299.42	1347.39
Using Device	Subject 1	1443.99	1440.73
	Subject 2	1110.23	1016.15
	Subject 3	1570.43	1562.34
	Average	1374.88	1339.74

Discussion & Recommendations

The following section discusses some of the main issues with the final design and goes into some potential improvements for components.

Design Weaknesses

The major problem with this current design is user balance. Currently, it is difficult to balance while using the device, which makes just about every part of using the device harder. User speed is limited, user comfort is lower, and the device itself doesn't hold up well under the irregular motion caused by balance issues. The current thigh joint configuration is simply pinned, which allows the thigh pad and the crutch leg to rotate independently from one another. This was by design, though in practice it makes it hard for users to balance comfortably.

Another issue with the design is durability for some components. Every 3D printed component on this crutch broke at some point during testing, some more than once. By the end of testing, some of the aluminum holes had begun to stretch, a sign of wear.

The compliance system integrated into the crutch leg did not work as intended. As shown in figure 16, the original intent was that patients would be able to adjust the spring by changing where a pin was placed. In practice, the space in between the spring coils was too small to fit a pin, so the stiffness could not be altered. It may be necessary for different patients to use different springs with this device.

Recommendations for Improvement

The thigh joint should be redesigned to include a way that limits the rotation between the thigh pad and the crutch body. The method currently on the device can only lock the rotation at certain angles, which is not conducive to good balance. If the joint were dampened in a way that made rotation slower, this would make balance easier and more natural. One way to accomplish this could be to integrate a spring system that impedes rotation of the joint.

The foot should be redesigned so that it improves user balance. The normal crutch foot that is on the device in its final design is sufficient, but it could be used to make balance and traction better. A foot with more surface area could help improve balance. Additionally, the crutch foot

that was used for testing began to wear down, apparently from sliding on the ground while in use. The foot material would need to be changed somewhat in order to prevent this from happening.

Since each of the components that were 3D printed from PLA broke during testing, this is a material that should be removed from the design moving forward. Different plastic materials may work better when 3D printed. Additional consideration should be put into the use of non-3D printed plastic components in non-load bearing locations, mostly in the connecting rod. It may be necessary for the design to move on from plastic components and utilize an all metal design.

The method of attachment for the thigh pad to the user's thigh should be reconsidered. The thigh pad experienced some slipping on the user's thigh, leading to rotation from its original position. This would decrease user balance and make motion more difficult. Another potential solution would be to change the shape of the thigh pad so that it more closely fits the thigh.

The method of attachment to the calf pad should also be reconsidered for largely the same reasons. While in use, the connecting rod would sometimes slide down the patient's calf. There needs to be a way to prevent this slipping from happening, either by addressing the method of attachment or by including additional restraints that prevent the slipping.

An issue that was found during manufacturing of the crutch leg was that the tolerances between the concentric tubes had to be fairly tight in order to prevent rattling between them. This rattling made precise foot placement difficult, and as a result reduced balance. Integrating some kind of spacer between the concentric tubes to keep them from rattling would improve the overall design.

Broader Impacts

If the device is further developed to be produced commercially, there are a number of ethical considerations that must be made known in relation to engineering, society, the environment, standards, and economy. Throughout the project's duration all proprietary information and intellectual property was cited to their rightful owners and the safety of all included parties was taken into consideration whenever prompted, in compliance with the Mechanical Engineering Code of Ethics. In terms of its effect on individuals and groups of people, the device is intended to have a large beneficial impact. People who are always on the move working or around the house wouldn't have their daily lives hindered by having to occupy their arms and hands with regular axillary crutches, and instead be able to freely go about their day.

Groups like those that are unfortunately bound to assistive devices like crutches for longer periods or even indefinitely due to injury or complications will have the opportunity to perform regular activities.

When discussing how the device's material, construction, and outcome affect the environment, it can be seen that it would not be any more harmful in creation than regular crutches are, since it is made of the same materials. As for technical codes and standards governing the work related to the project and its construction, there were a number of safety regulations followed and size standards that were accounted for. When designing the length of the device the industry standard for maximum stair height and pitch was taken into consideration and planned for, as well as the highest grade of incline. All components of the device were machined while following the safety protocols for each process and the device itself is safe to wear, i.e., no dangerous materials, sharp edges, or hazardous protrusions. Finally, an important aspect of the project was to make the product financially available to the public, so that those who need it can afford to buy it. The cost would be almost identical to that of regular crutches, ranging from about twenty to fifty dollars.

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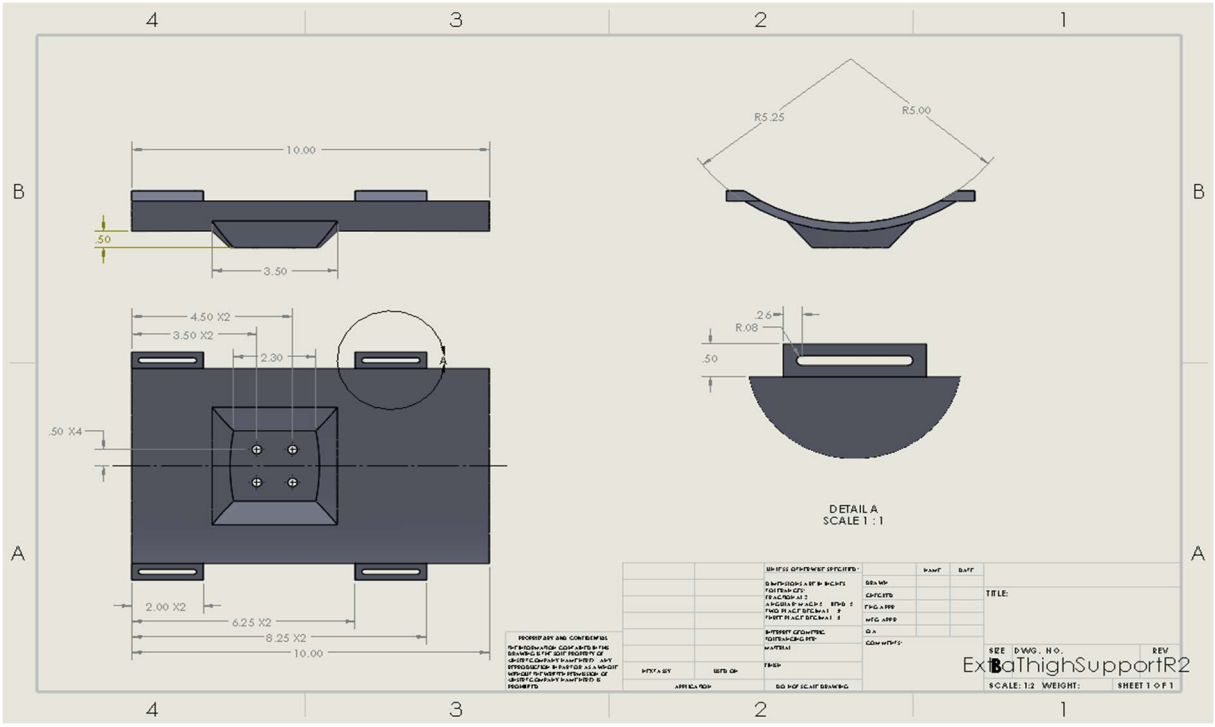
Appendices

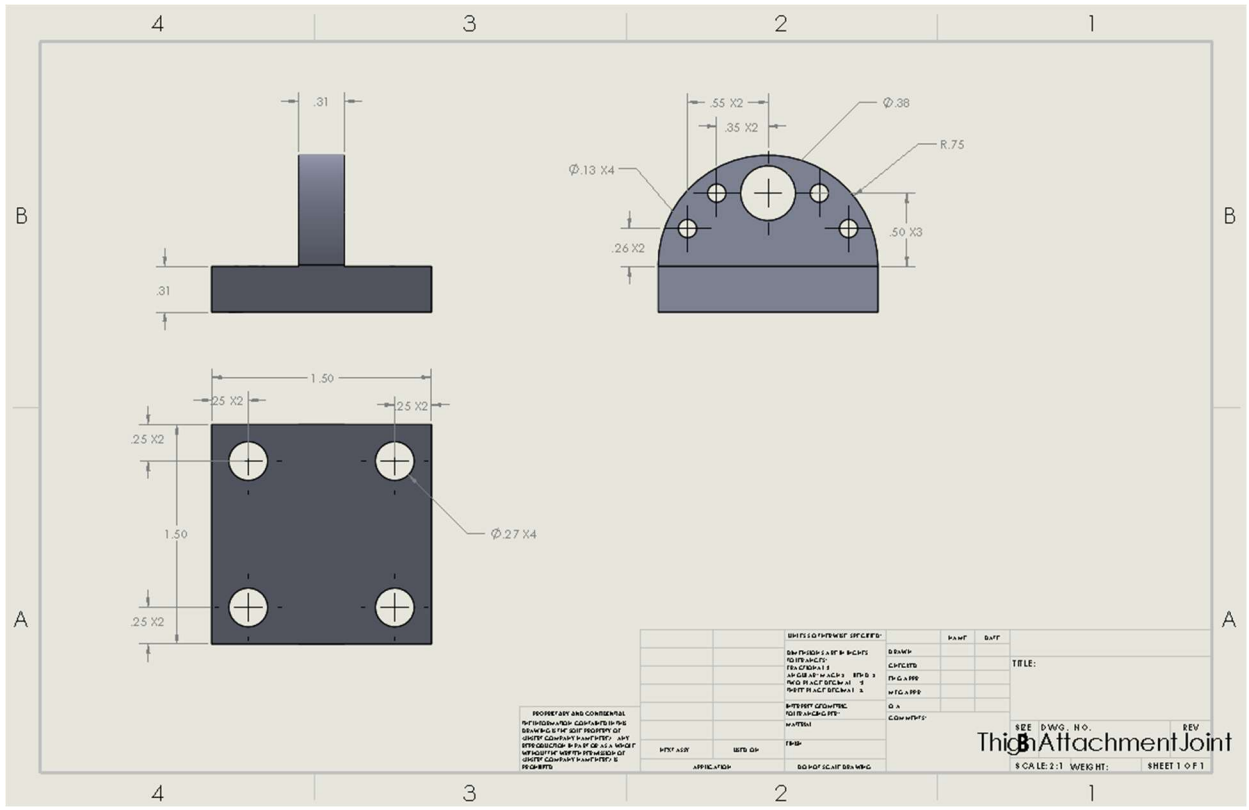
Appendix A

CAD Drawings

Each of the following drawings are those that were included in the final iteration of the design. They are shown below for anyone who may wish to replicate the design. Any part shown with an asterisk was made with materials from cutting up a store-bought pair of crutches. Dimensions not shown on these parts are not relevant to the design of the device.

1. Thigh pad
2. Thigh joint (upper)
3. Thigh joint (lower)
4. Crutch tubing (upper)*
5. Calf pad
6. Connecting rod tube*
7. Calf pad connector
8. Conrod connector
9. Crutch tubing (lower)*
10. Spring tube*
11. Crutch foot*

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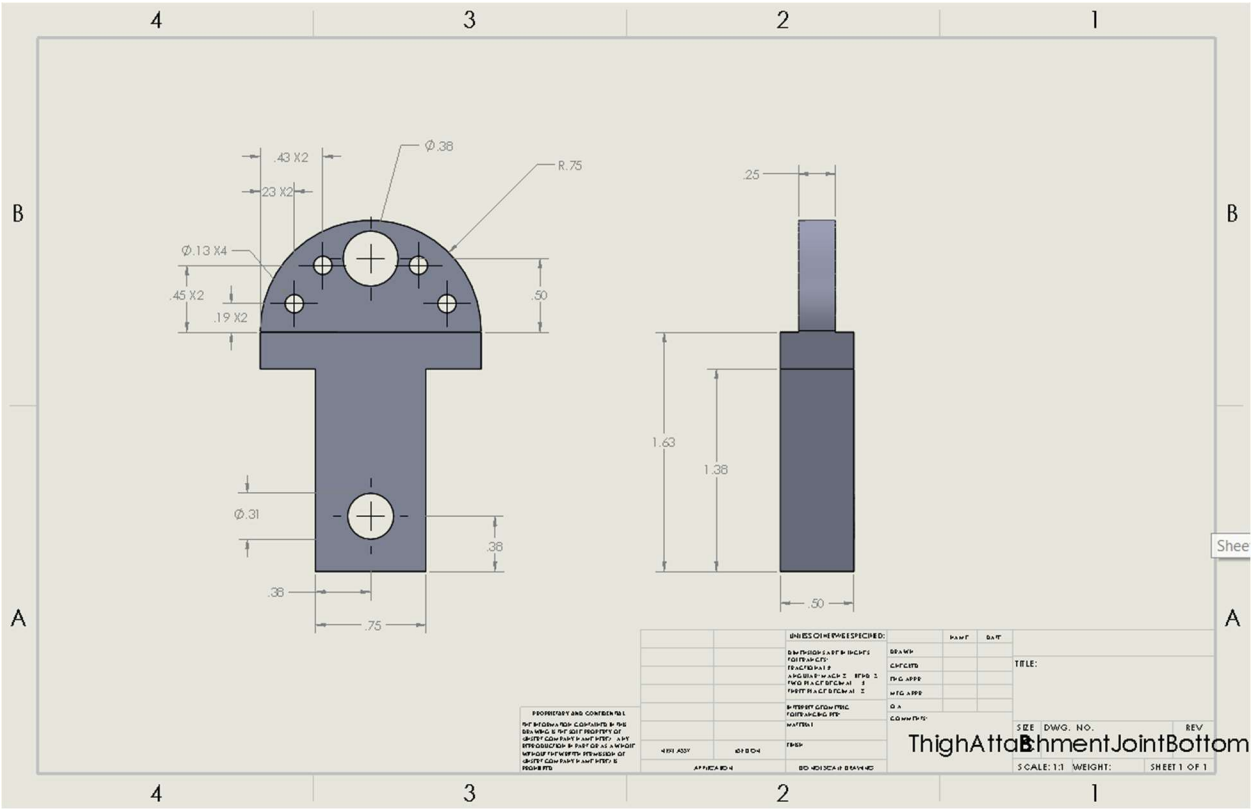
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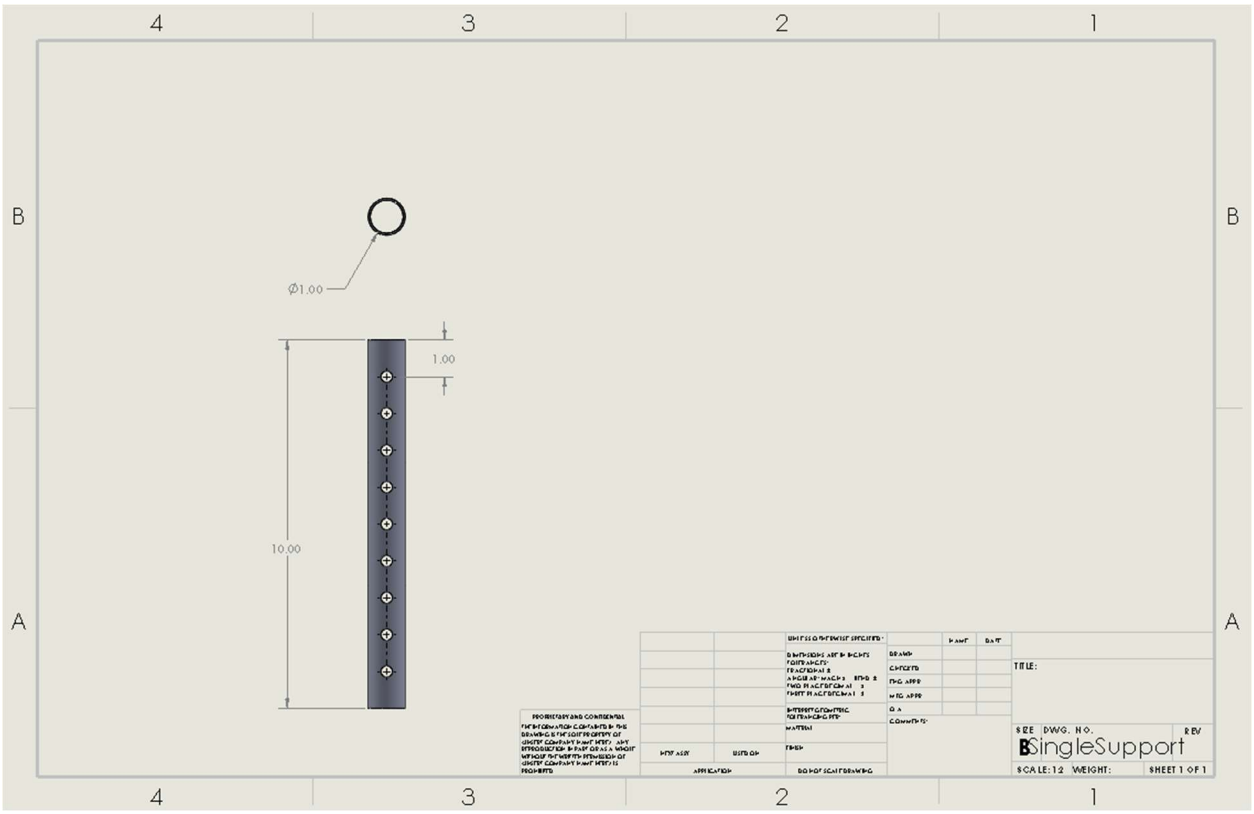
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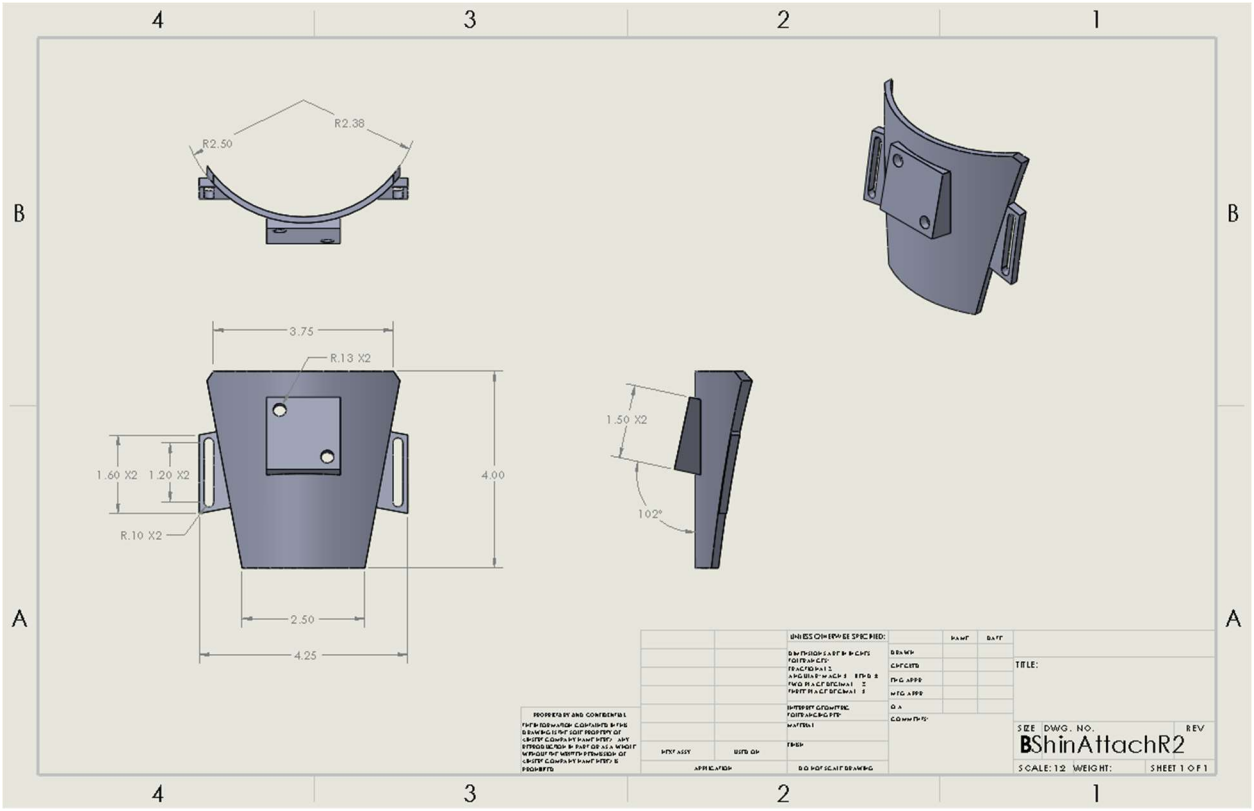
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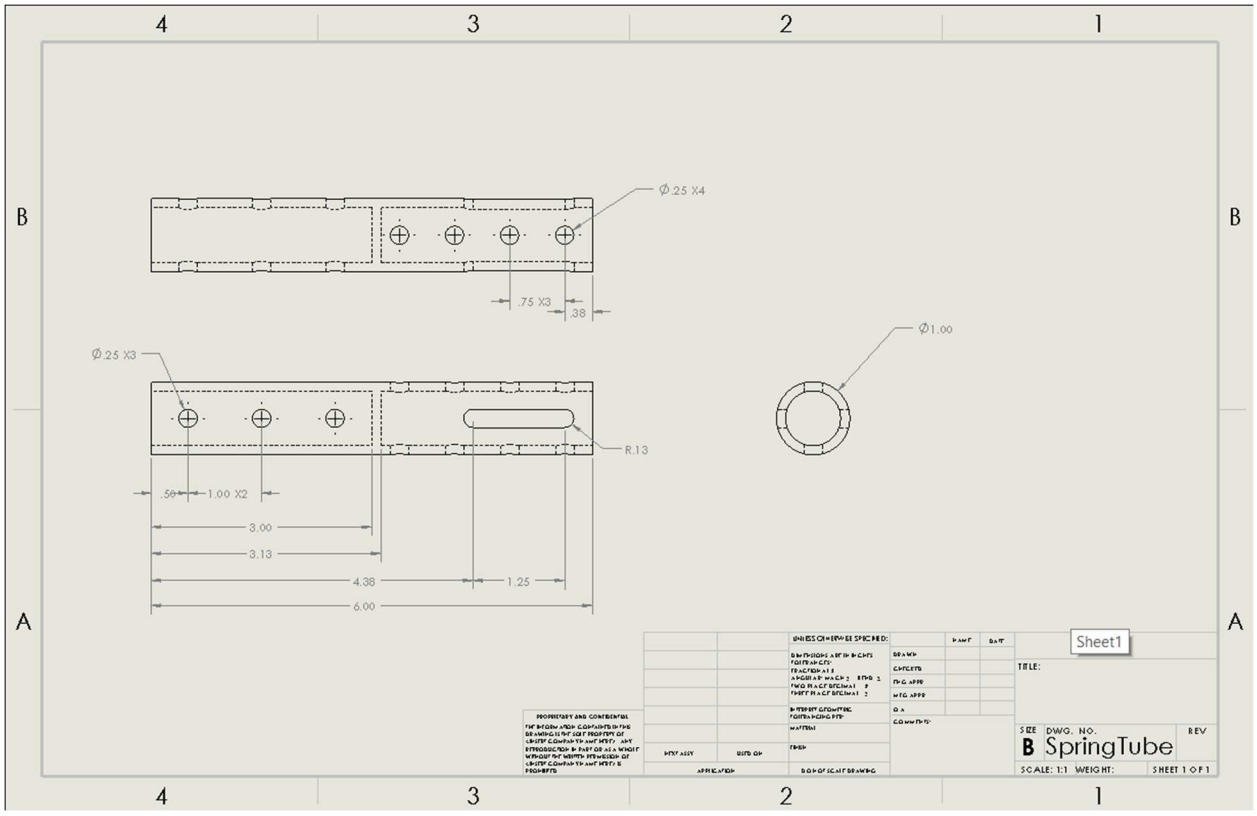
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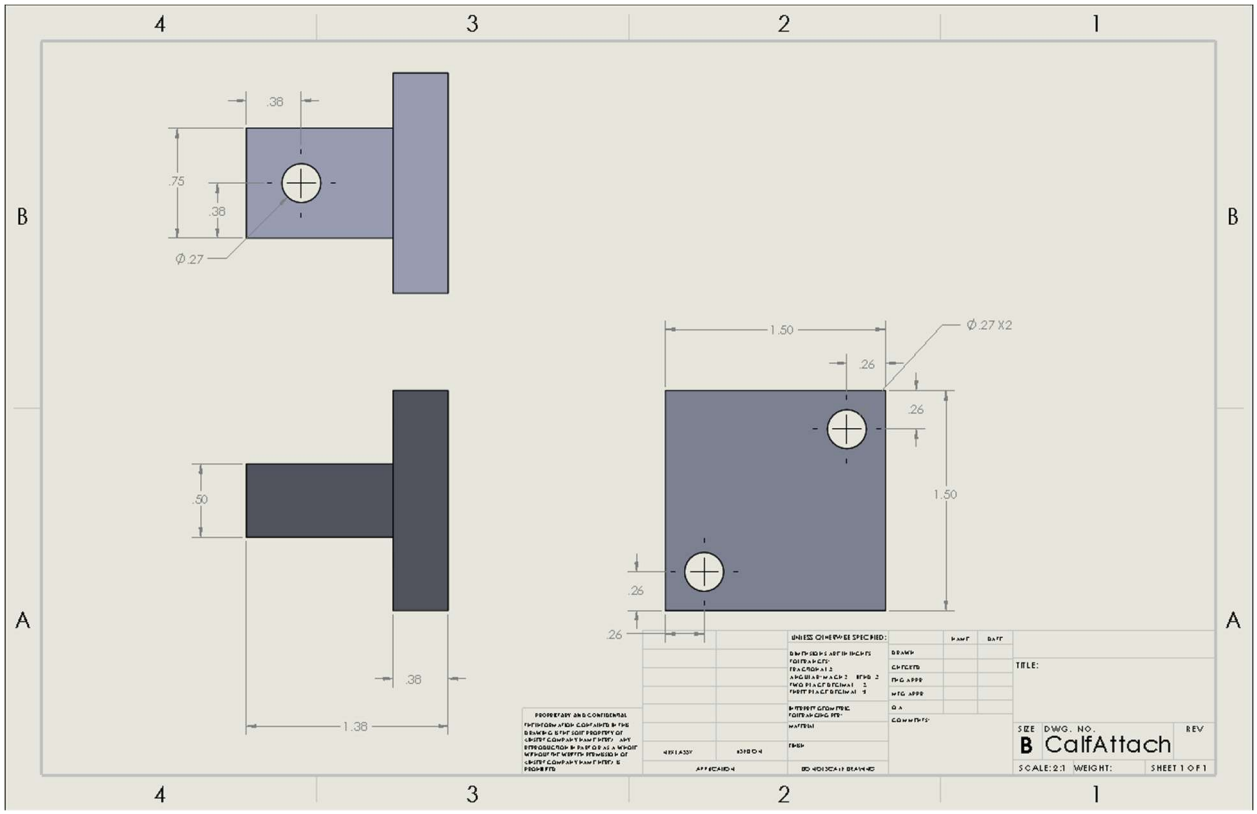
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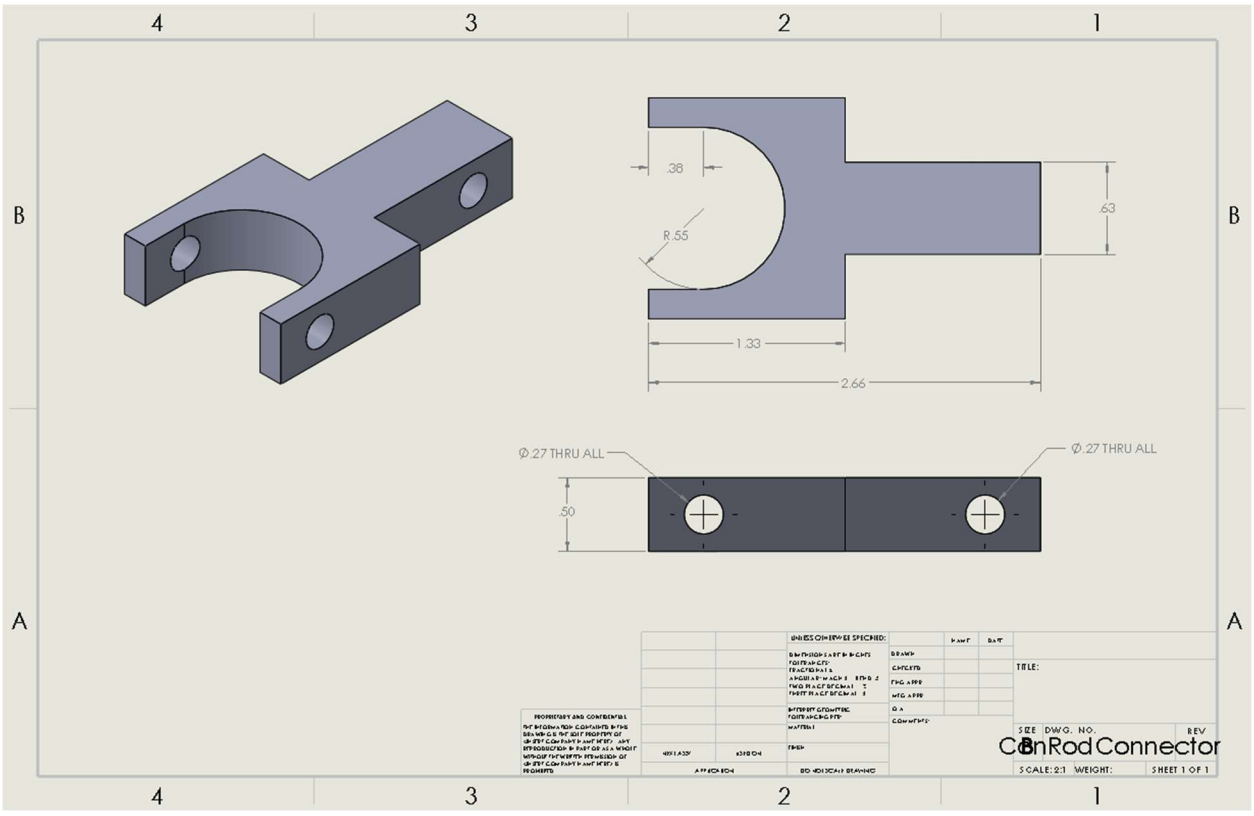
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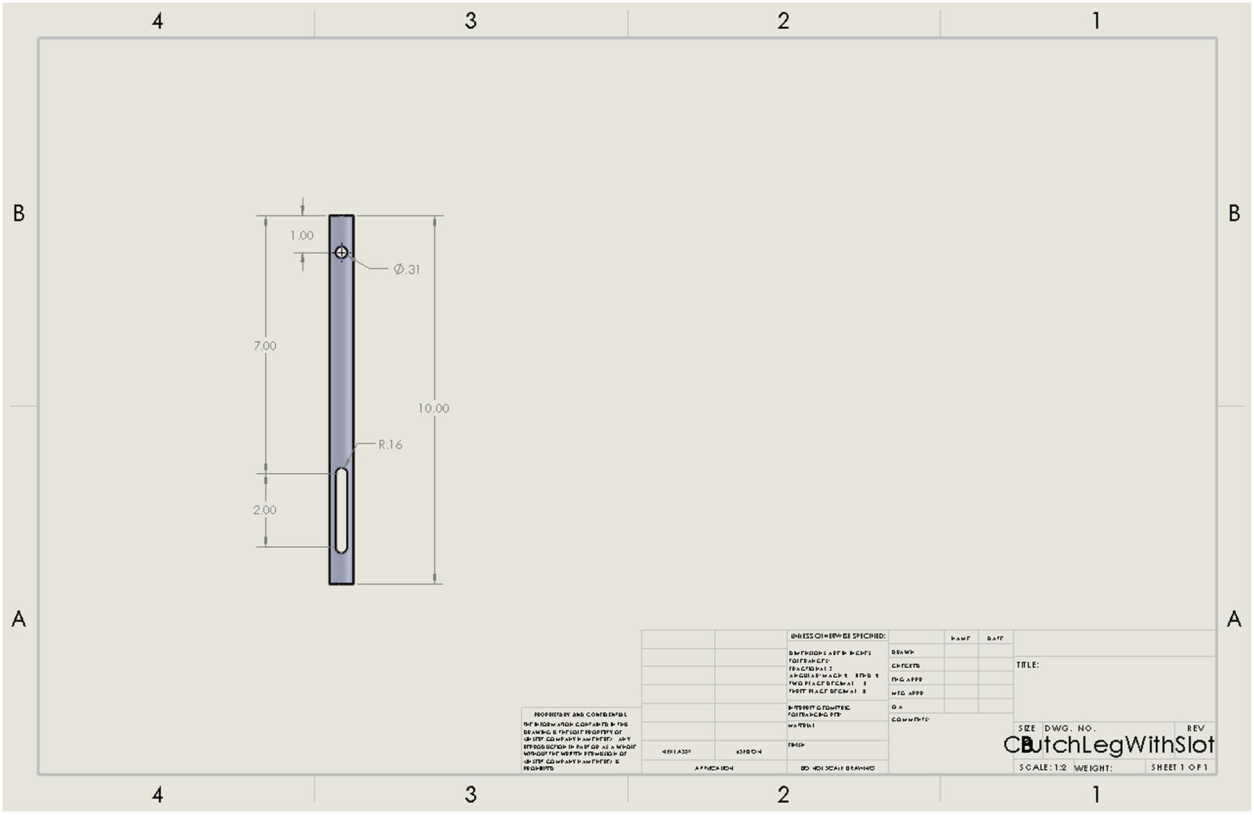
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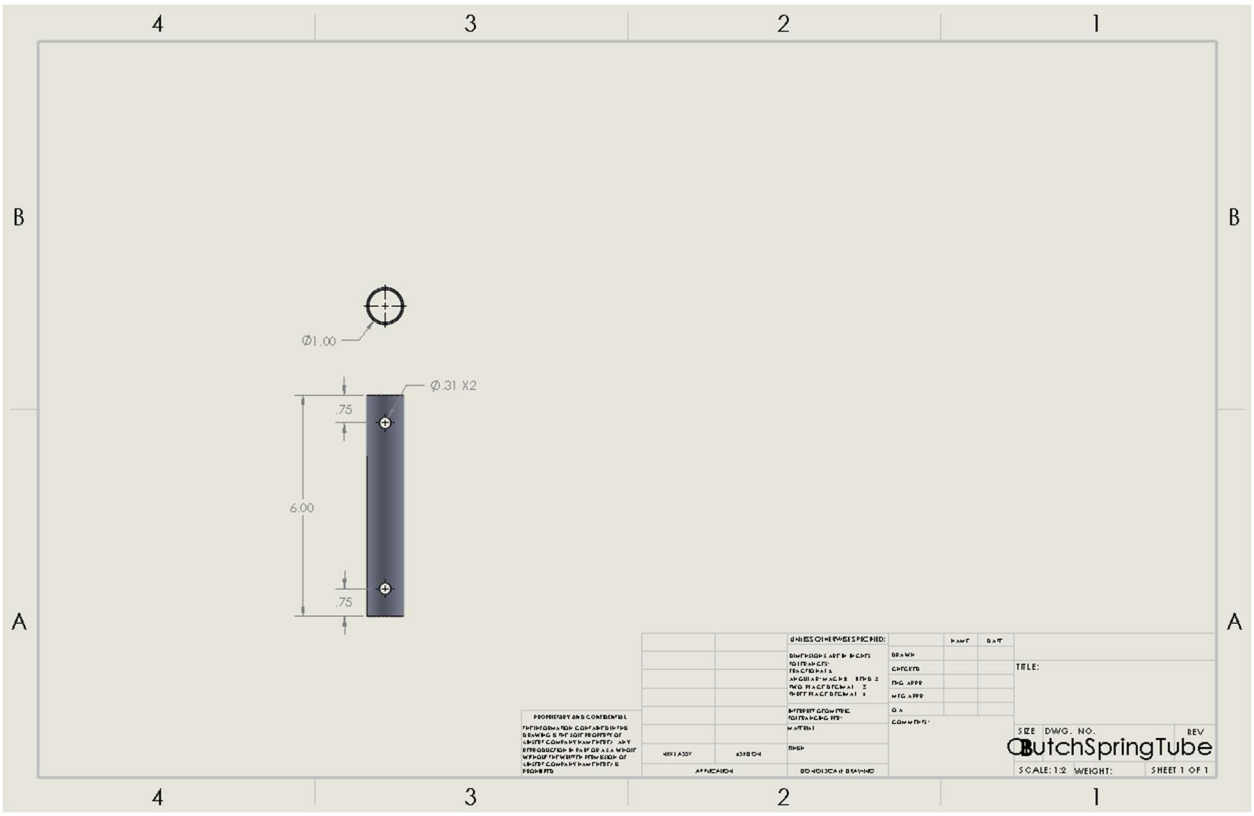
WEIGHT:
SHEET 1 OF 1


Ø1.00
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UNLESS OTHERWISE SPECIFIED:
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MFG APPR
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COMMENTS:
NAME
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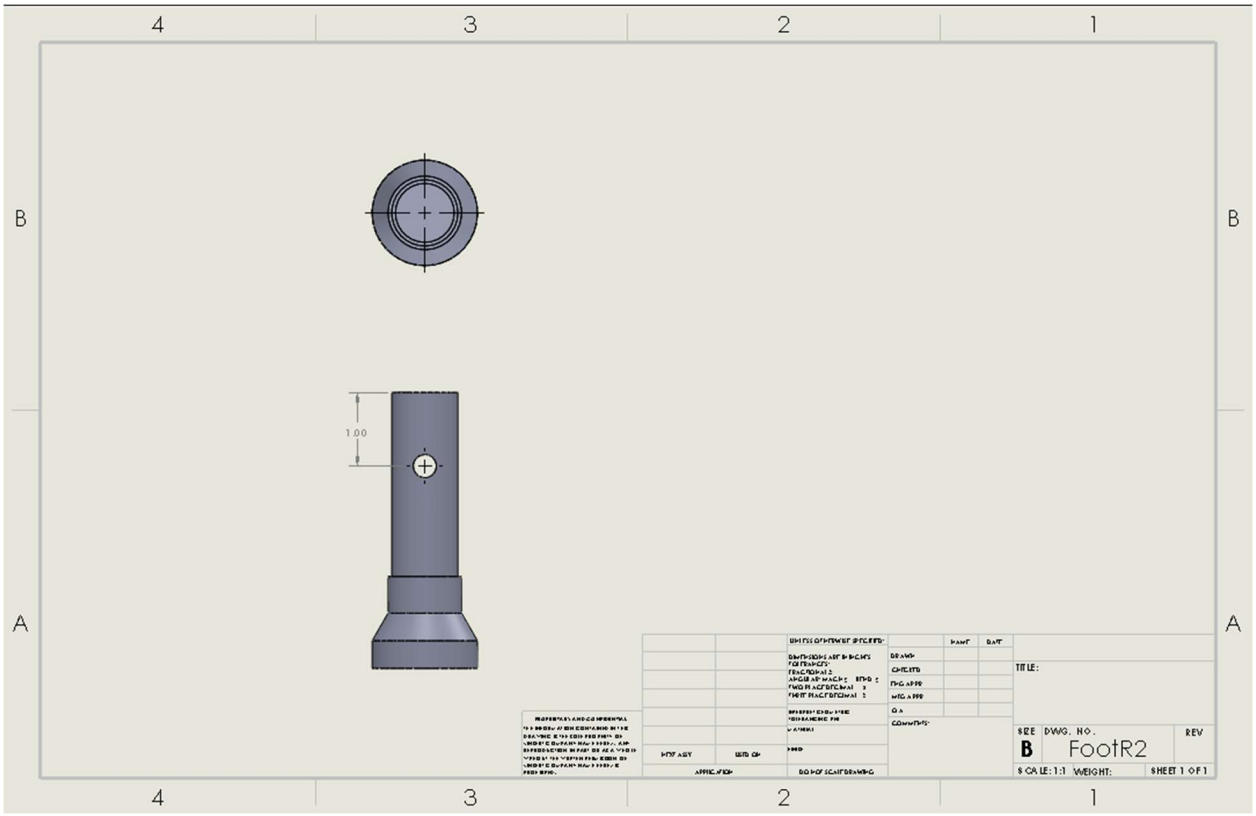
TITLE:
SIZE
DWG. NO.
REV
ButchSpringTube
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


1.00
UNLESS OTHERWISE SPECIFIED:
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REV
B
FootR2
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

Appendix B

Main Body Analysis Equations

$$P := link2 \cdot \sin(theta2) \cdot \sin(gamma) + (link2 \cdot \cos(theta2) - link1) \cdot \cos(gamma)$$

$$Q := -link2 \cdot \sin(theta2) \cdot \cos(gamma) + (link2 \cdot \cos(theta2) - link1) \sin(gamma)$$

$$r := -link4 \cdot \sin(gamma)$$

$$M := r - Q$$

$$n := 2 \cdot P$$

$$O := Q + R$$

$$theta4a := 2 \cdot \arctan\left(\left(-n + \frac{\operatorname{sqrt}\left(n^2 - 4 \cdot P \cdot r\right)}{2 \cdot M}\right)\right)$$

$$theta4a :=$$

$$theta4b := 2 \cdot \arctan\left(-n - \frac{\operatorname{sqrt}\left(n^2 - 4 \cdot P \cdot r\right)}{2 \cdot M}\right)$$

$$theta4b :=$$

$$link3 := \frac{(link2 \cdot \sin(theta2) - link4 \cdot \sin(theta4a))}{\sin(theta3)}$$

$$theta3 := theta4a + gamma$$

$$omega4 := \frac{(link2 \cdot omega2 \cdot \cos(theta2 - theta3))}{link3 + link4 \cdot \cos(gamma)}$$

$$omega3 := omega4$$

$$Vslip := \frac{[link2 \cdot omega2 \cdot \sin(theta2) + omega4 \cdot (link3 \cdot \sin(theta3) + link4 \cdot \sin(theta4))]}{\cos(theta3)}$$

$$alpha2 :=$$

$$alpha4a := \left[link2 \cdot (alpha2 \cdot \cos(theta3 - theta2)) + omega2^2 \cdot \sin(omega3 - omega2)\right] + link4 \cdot omega4^2 \cdot \sin(omega4 - omega3) - 2 \cdot Vslip \cdot omega3$$

$$alpha4 := \frac{alpha4a}{link3 + link4 \cdot \cos(theta3 - theta4)}$$

$$Aslip := \frac{\left[link2 \cdot omega2^2 \cdot (link3 \cdot \cos(theta3 - theta2) + link4 \cdot \cos(theta4 - theta2)) + link2 \cdot alpha2 \cdot [link3 \cdot \sin(theta2 - theta3) - link4 \cdot \sin(theta4 - theta2)] + 2 \cdot Vslip \cdot link4 \cdot omega4 \cdot \sin(theta4 - theta3) - omega4^2 \left(link3^2 + link4^2 + 2 \cdot link3 \cdot link4 \cdot \cos(theta4 - theta3)\right)\right]}{link2 + link3 \cdot \cos(theta3 - theta4)}$$

$$R12y := \quad R23y := \quad R32x := \quad R34x := \quad R43x := \quad R14x :=$$

$$R12x := \quad R23x := \quad R32y := \quad R34y := \quad R43y := \quad R14y :=$$

$$ux := \cos(theta3) \qquad uy := \sin(theta3)$$

$$m2 := \quad m3 := \quad m4 := \quad ag2x := \quad ag3x := \quad ag4x := \quad ig2 := \quad ig3 := \quad ig4 :=$$

$$ag2y := \quad ag3y := \quad ag4y :=$$

$$M := \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -1 \cdot R12y & R12x & -1 \cdot R32y & R32x & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & R23y & -1 \cdot R23x & (R34y - R43y) & (R43x - R34y) & -1 \cdot R14y & R14x & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & ux & uy & 0 & 0 & 0 \end{bmatrix}$$

$$X := \begin{bmatrix} m2 \cdot ag2x \\ m2 \cdot ag2y \\ ig2 \cdot alpha2 \\ m3 \cdot ag3x \\ m3 \cdot ag3y \\ (ig3 + ig4) \cdot alpha4 \\ m4 \cdot ag4x \\ m4 \cdot ag4y \\ 0 \end{bmatrix}$$

$$Vector := M^{-1} \cdot X$$

Appendix C

Device Weight Testing Protocols and Results

1. Zero the scale being used
2. Tester should step on the scale without the device and record their weight
3. Step off the scale
4. Tester should then step on the scale with the device, and record the displayed weight
5. Subtract the difference between the two weights to calculate the device weight
6. Repeat steps 1-5 for 3 trials

Trial	Displayed Weight (lbs.)	Remarks
1	202.82-200.21=2.61 lbs.	Slightly above requirement of 2.5
2	202.80-200.21=2.59 lbs.	Minor variation
3	202.82-200.21=2.61 lbs.	

Appendix D

Ease of Removal Testing Protocols and Results

1. Ask the subject to put on the device to their functional comfort
2. The subject should then stand up and test functionality of device
    a. If necessary, sit down once again and readjust device
3. Subject should sit down in a chair, with the device still attached to their thigh
4. Inform the subject that when the tester states begin, the subject should take off the device at a normal speed to take it off
5. When the tester states begin, the tester should start a timer, and the subject should unstrap all straps necessary and take the device off their leg.
6. The timer should stop only when the subject has successfully taken off the device and is completely detached from their leg.
7. Record findings and remarks

Trial	Time Elapsed (s)	Remarks
1	18.79 on, 7.26 off	Taking off too fast, chose to measure on and off as well
2	16.43 on, 6.22 off	2nd Trial
3	17.91 on, 6.85 off	3rd Trial

Average Speed: 17.71 on, 6.78 off

Appendix E

Comfort and Speed Testing Protocol and Results

1. Measure a 100 ft. length of Higgins Laboratory level 3 hallway
2. Mark the start and stop points for the subject
3. Ask the subject to put on the device to their comfort while sitting in a chair
4. The subject should then stand up and test functionality of device
    a. If necessary, sit down once again and readjust device
5. Ask the subject to stand using the device as their second leg for 30 seconds
    a. Subject can take a few steps if desired during the 30 seconds
6. Have the subject sit and rest for 1 minute
7. While they sit and rest, ask the subject on a scale of 1-10, 1 being the worst and 10 being the best, how comfortable they felt while standing on the device
8. Ask the subject to stand
9. When the tester states to begin, the tester should start the timer and the subject should walk in a straight line from the first marked point to the second marked point while wearing the device
10. The timer should stop only when the subject has passed the 100-foot mark
11. Have the subject sit and rest for 1 minute
12. While they sit and rest, ask the subject on a scale of 1-10 to rate their comfort in walking with the device on
13. Record findings and remarks

Trial	Distance Travelled/Time Elapsed (ft/s)	Speed (ft/s)	Speed (mph)	Comfort Level (1-10)
1	100 ft/35.78 ft	2.795	1.905	7
2	100 ft/27.62 ft	3.621	2.468	9
3	100 ft/27.99 ft	3.573	2.434	8

Average Speed: 2.269 feet per second

Appendix F

Testing Protocols and Results for Traversal Across Terrains Test

1. Mark a line 100 ft. from the southern doorway of the 2nd level of Higgins building
2. Ask the subject to put on the device to their comfort while sitting in a chair
3. The subject should then stand up and test functionality of device
    a. If necessary, sit down once again and readjust device
4. The subject should walk from the marked line straight to the other end of the hallway
5. They should continue through the doors of the hallway, down the stairs, and out the door to the outside of the building
6. They then should walk down the stairs in front of them, walk to the left of the large tree directly in front of them, and turn to walk towards Earl Bridge
7. The subject should then cross the bridge, and immediately turn left to walk down the sloped walkway
8. Once they have successfully completed this, the subject can sit down in a chair provided to them by the testing team and rest

Trial	Pass/Fail	Remarks
1	Pass	Walking upstairs proved difficult, the painted bridge surface caused traction issues, and the device foot showed serious loss of material over time. Total time elapsed- 4:11.91