# +ReinFORCEment

Prepared for:
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Shirley Ryan AbilityLab, Chicago, IL
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## Executive Summary

Ms. Erin Walaszek from the Shirley Ryan AbilityLab noticed that currently there is no effective way for physical therapists like herself to monitor the force patients with sternal precautions exert on to the walker while using the walker to recover from extreme weakness after open chest surgeries or other lower body injuries. Sternal precautions limit the force patients can exert through their arm to no more than 10 lbs, which could facilitate the healing of their sternum after open chest surgery.

We worked with our client to design a walker attachment that could measure the force patients exert onto the handle of the walker through their upper body and provide physical therapists with live readings of the force. This device would allow physical therapists to monitor the force exerted by their patients and make sure that it does not exceed the limited posed by the sternal precaution of their patients.

We did background research and observed our client, Ms. Walaszek, helping with one of her patients with sternal precautions to walk with a Guardian walker. We then built four mockups with the information collected and conducted mockup, user, and performance testing to select one design. Furthermore, to ensure the accuracy of our measurement, we conducted a rigorous theoretical analysis of the mechanical system accuracy. After creating a design review and with helpful insights from prototyping specialists, we used all the information we gathered to design and build our prototype.

Our design, the +reinFORCEment (see Figure 1), features a new handle that is removable and lightweight, which is very easy to use since it does not change the way patients interact with walkers. The removability allows our design to be used on different models of walkers and the light weight allows the patients to lift up the walker since the total weight of a normal Guardian walker plus our design is still within the limited posed by sternal precautions. The +reinFORCEment offers solutions to four aspects of our design challenge:

- Safety: Our design is sturdy and the structural integrity will not be compromised even though excessive force is applied, which will guarantee the safety of the patients. This conclusion is drawn based on the safety tests we did during the testing phase and the load case simulation with finite element analysis (FEA).
- Accuracy: Our design provides accurate measurements up to two decimal places of the downward force applied through the arms of the patients. We also provide Arduino custom coding with calibration information and the device will be automatically calibrated every time it is turned on. The data collected will be saved on the SD card. The handle design reduces the force applied through the whole area of the patient's hand into a point force, which further increases the accuracy of the measurement.
- Ease of use: Our design provides automatic calibration and adjustable display. It is also intuitive to use since the handle design does not change the way patients interact with the walker.

- Mobility: +ReinFORCEment is lightweight and does not hinder the activities of the physical therapists and patients.

Figure 1: +ReinFORCEment

## Introduction

Our team was asked to design a solution to a problem given by Ms. Erin Walaszek, a physical therapist from the Shirley Ryan AbilityLab (see Appendix A: Project Definition). She asked us to design a walker attachment to measure the force exerted by the patients onto the handle of the walker while they were using the walker (see Appendix B: Client Interview Summary). For patients who are recovering from open-chest surgery, they often have sternal precautions which limits the amount of force they can exert through their arms to less than 10 pounds (lbs). When the patients are also recovering from a lower body injury or weakness, they need to use a walker to recover their walking abilities. However, currently, the physical therapists do not have a way to monitor the force patients exert on the handle of the walker while using the walker. Thus, we were asked by a physical therapist to design a walker attachment that could measure the force patients exert on the walker.

Our design, +reinFORCEment (see Figure 1), solves these problems by providing a force measurement without affecting the way patients interact with the walker. The design is made out of a handle attachment, a set of load cells, a load cell bed, an Arduino nano chip, and a digital display. The handle is attached to the load cell bed and has a load cell force applicator that translates the force patients put on the handle into force on the load cell. The load cell bed is connected to the front part of the handle using screws, which provides a secure attachment. When a patient holds the handles and uses the walker, the force signal on the load cell will be processed by Arduino nano chip and the reading of force on the handle will be displayed on the digital display.

To use our design, the patients put their hands on the +reinFORCEment cushion handles and hold them in the same way they do the normal walker handles. They should then use the walker as usual. Our design will automatically display the force exerted by the user on the handles. The physical therapist can then monitor the force by looking at the digital display (see Appendix C: Instruction for Use).

This report explains the users, requirements, and specifications for the design, accompanied by a detailed explanation of the design and its rationale. We also discuss testing and additional research considerations for the design along with potential future developments.

## **Users and Requirements**

Users

➢ Patients in the Shirley Ryan AbilityLab who are recovering from lower body injuries or extreme weakness in their lower body after an open chest surgery. These individuals have sternal precautions, which limits the amount of force they can exert through their arms, which is less than 10 lbs (see Appendix B: Client Interview Summary).

➢ Ms. Erin Walaszek, who is a physical therapist in the Shirley Ryan AbilityLab and works with patients described above. She will operate the device to monitor the force the patients exert onto the walker so that she can better help them in the rehabilitation process and ensure that the patient does not breach the force limit set by their sternal precautions (see Appendix C: Instruction for Use).

Requirements

➢ Safety: the design must ensure the safety of patients while using. The design should not affect the way patients interact with a walker nor should it cause the user pain or discomfort (see Appendix D: User Observation Summary).

➢ The design should provide reliable force measurements (see Appendix E: Statistical Analysis of Lever Arm Length on Mechanical System Accuracy).

➢ The readings of force should be easy to interpret and visible to the physical therapists, which means that the physical therapists should be able to see the display without having to move from a standard position during physical therapy sessions (see Appendix D: User Observation Summary).

➢ The design cannot be too heavy and that lifting the walker exceeds the eternal precautions. Left and right side of walker must remain balanced after being installed with the design (see Appendix B: Client Interview Summary).

➢ The design must be able to withstand repeated use during physical therapy sessions. Each of the handles should withstand more than 150 lbs of force (see Appendix B: Client Interview Summary).

➢ The power source must be easily replenished (i.e. replaceable batteries or charging cable) (see Appendix F: Ethical and Sustainability Considerations).

## **Design Concept and Rationale**

### Overview

The purpose of our design is to measure the force exerted by a patient on their walker so that physical therapists can monitor the force and help the patient keep the force within the safe threshold imposed by their sternal precautions. Specifically, this is for patients at the Shirley Ryan AbilityLab who are recovering from an open chest surgery. Some patients under sternal precautions also have lower body injuries or extreme weakness after surgery that requires recovery activities with a walker. This design is an attachment to the Guardian walker currently used in Shirley Ryan AbilityLab. The attachment provides live readings of the force exerted by the patient onto the handle of the walker.

The design is composed of a handle, a bed for the load cell, two connecting screws, and the electronics unit, as shown in Figure 2. The electronic components of the design are two load cells, an Arduino Nano board, and a digital display. The patient will exert force on the handle, and the bending of the handle will cause the load cell force applicator on the handle to press down onto the load cell. The load cell will then convert the force reading into digital signals, which will be processed by the Arduino nano chip. The force reading from the load cells will be displayed on the digital display.

Figure 2: Final Design

The following sections describe the handle, the load cell bed, the connection method, and the electrical unit. The primary users are the patient and physical therapist; the patient will interact with our handle in the same way they do with a normal walker handle and the physical therapist will monitor the force on the handle through the digital display.

Handle

*Use and Specifications*

The patients will use our handle in the place of the regular handle when walking with a walker. The handle design is shown in Figure 3. The handle has a load cell force applicator, which is a small nub on the bottom of the handle. It is able to bend and thus allows the load cell force applicator to press down onto the load cell. The handle is screwed onto the load cell bed. A cushion is placed on the end of the handle to indicate where the patients should place their hands.

Figure 3: The handle

The handle will be 9.5 inches long, one inch tall, and a quarter of an inch thick. The cushion will be placed on the end of the handle and be 4 inches long. The load cell force applicator is 1.25 inch long and a quarter inch wide. The bottom of the handle will be two inches above the actual handle of the walker to ensure the patient has room to place their hands. The curve of the handle starts one inch to the end and the width of the handle after the curve will remain 1 inch. (see Appendix G: Dimensioned Graphics Sketches)

*Rationale*

The handle is fixed onto the load cell with threaded fasteners in order to restrict rotational motion. Initially, we planned on having the handle rotate about an axis, but we realized that without a way to stop the handle from rotating up, it would be difficult for patients to move the walker forward when lifted (see Appendix H: Performance Testing Report & Appendix I: Design Review Summary). In our final design, we removed the hinge. Aluminum is able to bend under force and a slight displacement will be able to be measured by the load cell while maintaining the functionality of the walker. Since the patient will always be applying force from the position of the grip on the handle, the readings of torque will always be normalized, in regards to distance having an effect on torque (see Appendix E: Statistical Analysis of Lever Arm Length on Mechanical System Accuracy).

Load cell bed

*Use and Specifications*
The load cell bed is used to hold the load cell, which is an electronic device that can measure the force applied on it (see Figure 4). Moreover, the bed also serves as a way to connect the design together and attach it to the walker. The top part of the load cell bed features two half-circle protrusions on each side, each with two holes, which are used to secure the handle by screwing screws through the handle and those holes. The bottom of the load cell bed also has two threaded holes, which will be used to connect the load cell bed onto the handle of the walker. The bottom of the bed is also geometrically matched to the curvature of the walker so that the bed will fit snugly onto the aluminum tubing of the walker (see Figure 5).

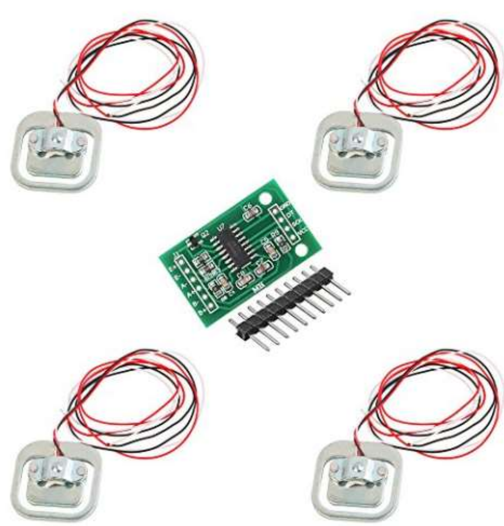


Figure 4: The load cell

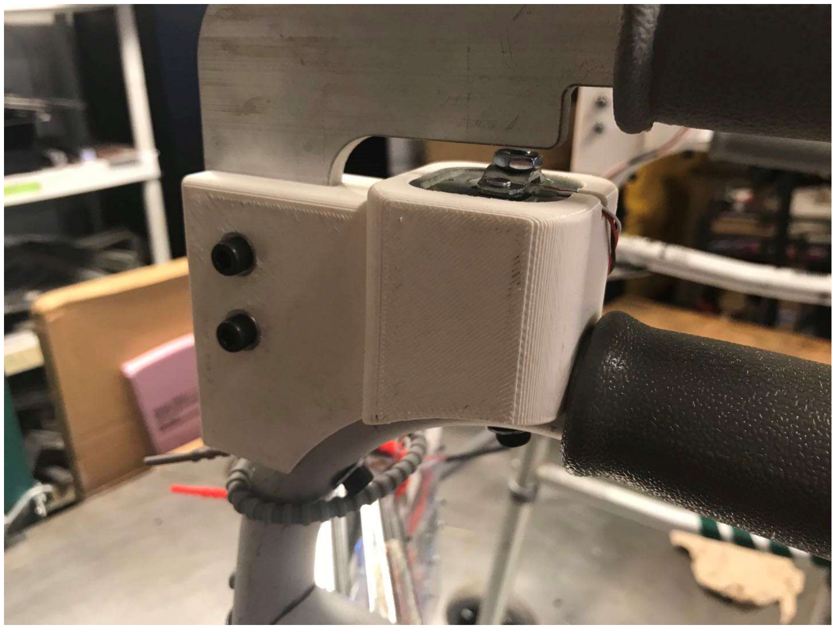


Figure 5: The load cell bed

The load cell bed is 4.5 inches long and 0.65 inches wide. The bed has identical dimensions to the load cell, 0.34 x 0.34 x .25 inches. The thickness of the wall of the load cell bed is 0.2 inches. The protrusion on the front that will be used to connect to the handle is a semicircle with a diameter of 1 inch. The top part of the load cell bed, which will actually contain the cell, is 0.75 inches thick. The bottom part of the load cell bed will be designed to fit the curvature of the walker handle. The bottom part will be 2.25 inches long. The front end of the bottom part will be 1.25 inch tall and the rear part will be 0.25 inch tall (see Appendix G: Dimensioned Graphics Sketches).

*Rationale*

The load cell bed is the ideal way to connect the design together. The load cell (see Appendix J: Background Research Summary) is placed on the front part of the handle of the walker because of two reasons. First, we need to create 2 inches of clearance between the handle of our design and the original handle of the walker, which prevents us from mounting the load cell bed in the middle of the walker handle. From our conversation with shop specialist Scott Simpson, we learned that drilling a threaded hole to the bottom of the load cell bed and screwing the bed unto the walker handle with a screw will be the best option to connect the design with the handle of the walker (see Appendix K: Conversation with Prototype Specialists).

Our material selection of 3D printed ABS is a special type of plastic using a fused filament deposition (FDM) printer that provides an extremely rigid mounting option and is able to precisely conform to the bent aluminum tubes on the sides of the walker.

Connecting screws

*Use and Specifications*
Two screws will be used to connect the load cell bed to the walker. We will drill two holes into the handle of the walker, push the screws through the two holes, and then screw into the threaded holes on the bottom of the load cell bed, as shown in Figure 6. This structure is important because it prevents the load cell bed from moving in all six directions and thus ensures the stability of our design.

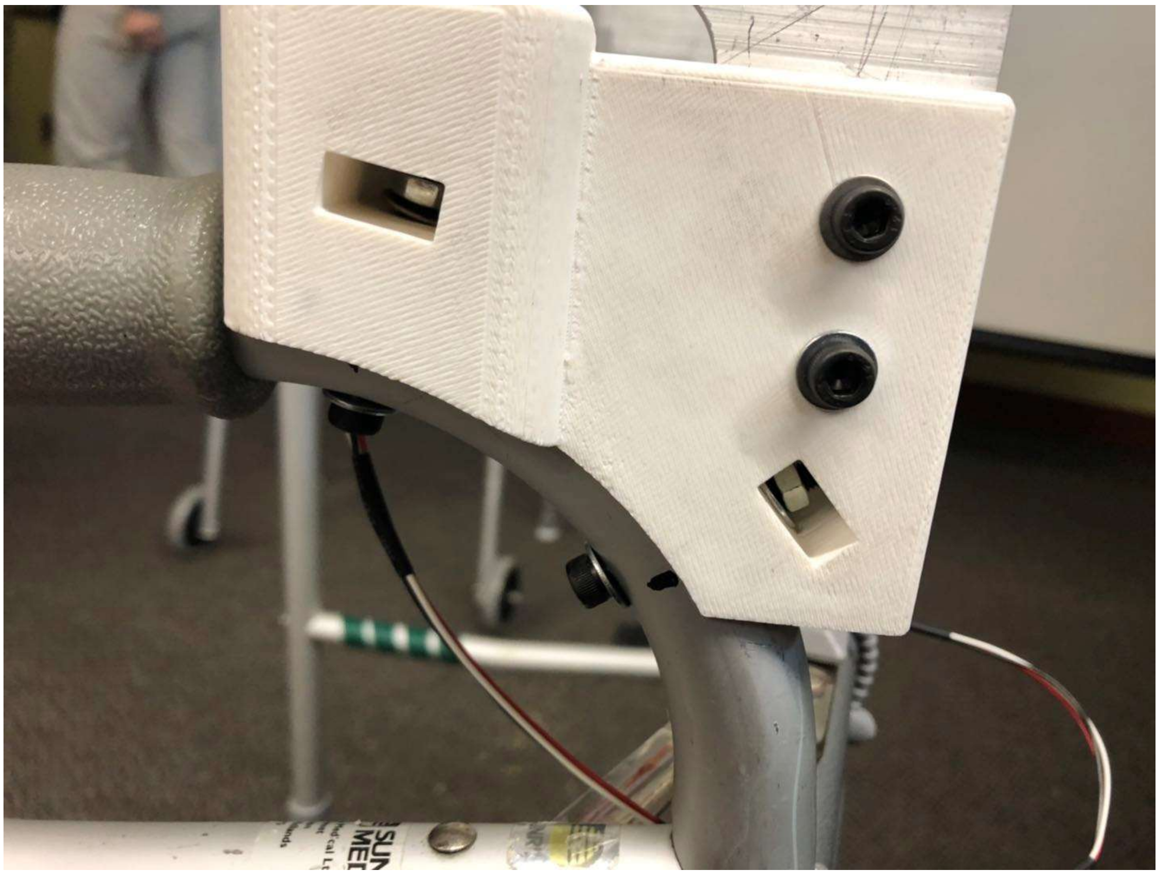


Figure 6: The connecting method

The screw, the holes on the handle of the walker, and the threaded holes on the bottom of the load cell bed are all a quarter inch in diameter (see Appendix G: Dimensioned Graphics Sketches).

*Rationale*
We tested different ways of attaching our design onto the handle of the walker during performance testing (see Appendix H: Performance Testing Report). However, the method we used in our mockup was not very reliable and extremely difficult to install. During the design review (see Appendix I: Design Review Summary) and interview with

shop specialist, we narrowed down our options to either using a screw or using a clamp. Shop specialist, Scott, suggested that using a screw will be more convenient and aesthetically sound compared to a clumsy clamp. Moreover, the clamp would add extra weight which might make the walker too heavy for the patients to lift up. Thus, we decided to use this screwing method to connect our design to the handle of the walker.

<u>Electronic unit</u>

*Use and Specifications*

The electrical component of the design consists of two load cells, an Arduino nano chip, a battery charger, and a digital display, as shown in Figure 7. The load cell will convert the force signal into electric signal and send it to the Arduino nano chip. The chip would then process the information and feed the data to the display, allowing the display to give live data of the force exerted on the handle of the walker. The physical therapist will then be able to monitor the force applied by the patient onto the handle of the walker and make sure that the force does not exceed the limit imposed by the sternal precautions of the patient. The Arduino nano chip will be programmed and calibrated using known weights.

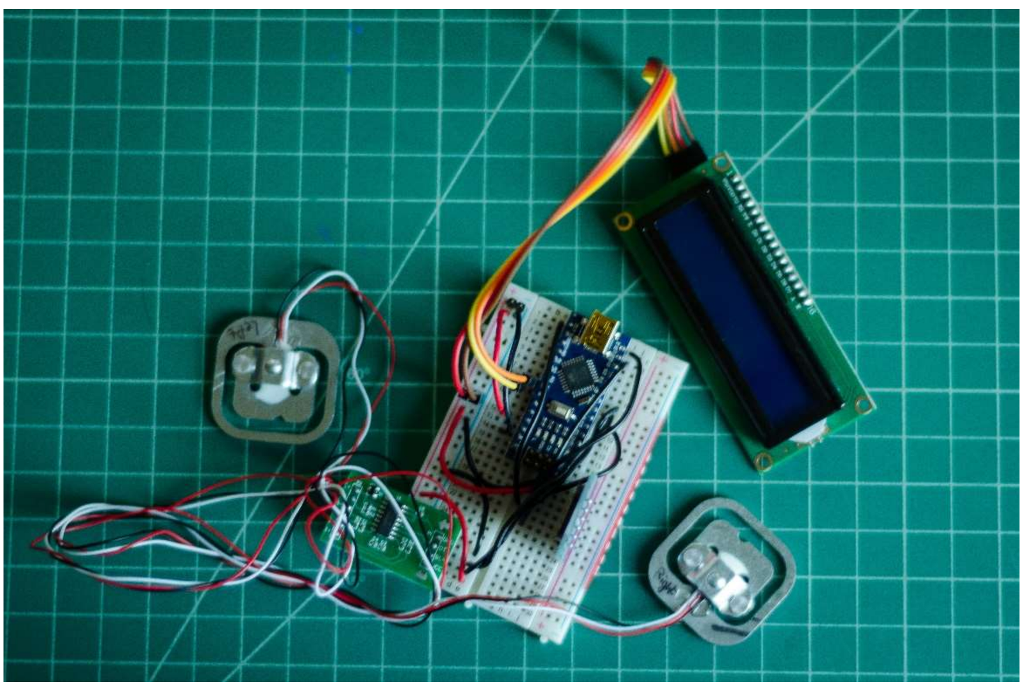


Figure 7: The electronic circuit

The dimensions of the load cell are 0.34 x 0.34 x .25 inches, and they weigh 0.32 ounces combined. The dimensions of the Arduino nano are 18 x 45 mm, and it weighs 7 grams. The dimension of the display is 24mm x 69mm. They will be attached to a clamp and then clamped onto the front bar of the walker (see Appendix G: Dimensioned Graphics Sketches).

*Rationale*

We decided to use load cells to measure the force because they can provide an accurate measurement and do not add a lot of weight to the walker. Compared to resistive sensors, load cells can provide force readings with a smaller standard deviation and thus a better accuracy (see Appendix J: Background Research Summary). The decision of using an Arduino nano is also based on similar arguments. The Arduino nano chip is lightweight and computationally capable of processing the data from the load cells. The display is also lightweight and compatible with the Arduino chip.

## Future Development

The following are the design future development areas accompanied with potential ways to address them.

### Testing

*User testing*: During user testing, we relied on the advice given to us by our client, Ms. Erin Walaszek. Since we were unable to bring working prototypes to user testing, most of our questions were conceptual, which limited the amount of information we were able to gather. Feedback from our client on the final prototype would certainly provide insight on how to improve the accuracy, the ease of use and safety of our design. Another important aspect our user testing lacked was feedback from patients. Since the mockups we brought to the user testing did not go through safety testing, our client understandably did not allow any patient participate in user testing (see Appendix L: User Testing Report). In the future, it will be helpful if we could iterate on working mockups to allow patients to operate our design features and collect feedback. The feedback from patients will be very helpful for us to improve the design since they are the ones who are directly interacting with it.

*Performance Testing*: In the current calibration method, we assumed that the force on the load cell only depends on the force on our handle. Though the assumption is mostly valid (see Appendix E: Statistical Analysis of Lever Arm Length on Mechanical System Accuracy), the force on the load cell might still vary slightly depending on the weight of the patients or the way patients grab the handle. In the future, we will need to do additional performance testing to address the dependence of the force on the load cell on other factors and use the data to improve our calibration methods.

### Features of the Design

The attachment method of the design onto the walker is far from perfect. In the current design, we secured our device on the handle of the walker by drilling two holes on the handle of the walker and putting a screw through the holes. The screw will then be screwed into two other threaded holes in the load cell bed. Though this attachment method is reliable, it is not very convenient, since it requires the user (physical therapist) to align the holes accurately and tighten the screws from below with a screwdriver. Moreover, this attachment required us to drill holes in the handle of the walker and perfectly align the holes on the walker handle with the holes in the load cell bed, which can be challenging. In the future, we hope that we can keep brainstorming other possible attachment methods that are easy to use, easy to build, do not require impacting the original handle of the walker, and also keep the attachment removable.

## Conclusion

Our design exceeds the key requirements of Shirley Ryan AbilityLab patients who will use the walker and physical therapists who will operate it.

Our client requires the device to be lightweight and safe to use. Our design fulfills this requirement by ensuring that the walker weighs less than 10 lbs and has a balanced center of mass after being installed with the device. Also, our design will not cause discomfort to the patients since it does not change the way patients interact with a walker.

Our client needs a device that could measure the force patients exert onto the handle of the walker through their arms. Our design meets this requirement by accurately measuring the force on the handle (see Appendix E: Statistical Analysis of Lever Arm Length on Mechanical System Accuracy) and providing live readings of the force for physical therapists to monitor.

Moreover, +reinFORCEment can be used for research purposes because of the its data logging capabilities and sensor accuracy.

## Appendix A: Project Definition

Project name: Walking with Force
Client: Ms. Erin Walaszek, Shirley Ryan AbilityLab
Team members: Shane Dolan, Rossoneri Jing, Davis Miller, Aimee van den Berg
Date: May 20, 2019
Version: Four

**Mission Statement:** To design a device that measures the force exerted by a patient on their walker so that physical therapists can monitor the force and help the patient keep the force within the safety limit imposed by their sternal precautions.

**Project deliverables:** A final prototype, a final report, and a PowerPoint presentation to the client.

**Constraints:**

- ➢ Must be built at a minimal cost (Maximum of $100)
- ➢ All project deliverables must be completed by June 13th, 2019

**Users/Stakeholders:**

Primary users:

- ➢ Physical therapists (PTs) who need the device to monitor the force their patients (see secondary users below) exert onto the walker so that they can better help them in the rehabilitation process and ensure that the patient does not breach the force limit set by their sternal precautions.

Secondary users:

- ➢ Patients in the Shirley Ryan AbilityLab who are undergoing sternal reconstruction after open chest surgery. These individuals have sternal precautions, which limit the weight-bearing ability of their upper extremities and restrict the force the patient can exert on the walker to less than 10 lbs. The patients are mostly males from the ages of 20 to 60 and are of varying ethnicity. All of them have undergone heart surgery, and afterward experienced complications that hindered their ability to walk.

Stakeholders:

- ➢ Shirley Ryan AbilityLab, where the patients are undergoing physical therapy.

Table 1: Requirements and specifications of the project

| Requirements | Specifications |
| --- | --- |
| Safety<br>- Does not cause the user pain or discomfort | - Aluminum and plastic will be used for construction, as they are nonporous and can |

| | |
|---|---|
| - Must be able to be wiped down/sterilized | withstand the necessary weight.<br>- The device must place the grip in the same position as the original grip so that the patient's experience using the walker will not be greatly altered. |
| Accuracy<br>- Gives reliable force measurements | - The measured force is within a standard deviation of 0.6 pounds from the true force as measured statically using a ground scale. |
| Ease of Use<br>- User can use it in a way that does not detrimentally affect their usual use of a walker<br>- The display showing the readings of force is easy to interpret and is visible to the physical therapists.<br>- The physical therapists are able to see the display showing the force exerted by the patients without having to move from a standard position during physical therapy sessions. | -The design should be able to be moved around and attach to all three sides of the walker to allow the PT to see it regardless of which side they are on. Attachment and removal should take 1 minute or less.<br>- The force display must be in pounds |
| Mobility<br>- Can be used while the user is walking (aka not static)<br>- Must be removable | - The prototype is able to attach to a walker and remain attached while the walker is in motion (5-15 meters of walking as in a normal therapy session) |
| Weight/Size<br>- Cannot be too heavy that lifting the walker exceeds the eternal precautions<br>- Left and right side of walker must remain balanced | - Added weight from the prototype cannot cause the walker to weigh 10 or more pounds.<br>- The left and right sides of the walker cannot have a weight difference of more than 0.25 pounds when the prototype is attached (as measured by placing the left and right sides of the walker on different force plates). |
| Maintenance and Durability<br>- Must withstand repeated use during physical therapy sessions.<br>- The power source must be easily replenished (i.e. replaceable batteries or charging cable). | - Must not show visible signs of wear after less than 10 uses.<br>- Must work for at least 50 uses.<br>- The power source must last through at least one session of use.<br>- The power source must be able to be charged/replaced through the use of a Phillips head screwdriver and/or no additional tools. |

## Appendix B: Client Interview Summary

Our first meeting was with our client Ms. Erin Walaszek, a physical therapist from Shirley Ryan AbilityLab (SRAL). The meeting was an online meeting held on BlueJeans, at 9:00 am on April 12th, in the ISP house, 616 Noyes Street, Evanston. Team members Rossoneri Jing and Davis Miller were present for the meeting, as well as Team 13.3 members Alex Manka and Kevin Wu. The purpose of the meeting was to learn more about the background of the design problem and the specific requirements that the client wants for our design. This appendix summarizes what we learned about the current design problems, desired requirements, users, and current/competitive equipment.

Problems

Our client emphasized two main problems:

- Patients tend to put excessive weight onto the walker while walking
    - Patients are usually recovering from an open chest surgery and with additional complications, such as other injuries on their lower extremities or extreme weakness after surgery.
    - While walking with a walker, there is a risk that patients will lean forward and push their body weight unto the walker. However, in Shirley Ryan AbilityLab, the sternal precautions limited the weight patients can push through their arms to less than 10 lbs.
    - Though patients might be able to keep the force through their arms lower than 10 lbs at the beginning of the training, they might lean forward and increase the force as they fatigue through the training.
- There is no current solution to the problem
    - Currently, there is no way for the physical therapists to monitor the force patients put on to the walker and the physical therapists at Shirley Ryan AbilityLab do not have any device to measure the force.
    - Physical therapists can only determine the force patients exert onto the walker by observing their postures and guess the force based on their experience. This is always inaccurate and put a lot of pressure on the physical therapist.

Requirements:

Our client identified these as the requirements for the design:

- Safety
    - The device should not weigh more than a few pounds. This is because the sternal precaution limited the amount of weight a patient can lift to 10 lbs

and the weight of the walker is less than the limit, which means that currently the patients can lift the walker and carry them around. If the device is too heavy and the total weight of the device and the walker exceeds the sternal precaution limit, the patients can no longer lift the walker, which can cause inconvenience.
    - The device should not cause unbalance of the walker. That is, if the device is not installed symmetrically on both sides of the walker, the weight on one side should not be more than a few pounds larger than that of the other side.
- Sanitation
    - The device must be able to be sanitized just like other equipment used at the Shirley Ryan AbilityLab. The client more specifically requested that we make a prototype that can be wiped down using Clorox or Lysol brand disinfecting wipes. This means that the prototype cannot have any porous surfaces or exposed electronics that could break after being wiped down.
- Accuracy of measurement
    - The device that is constructed should be able to accurately measure the force applied by a user to a walker, and this force measurement should be delivered in units of pounds.
    - Force sensing devices should be installed on both sides of the walker to generate a bilateral result and hence ensure accuracy.
- Display
    - The device must contain a display that provides real-time readings from the sensor.
    - Physical therapists are prioritized in the positioning of the display. It is advised that the display be installed on the front bar of the walker, where it will be clearly visible to the physical therapists.
    - There is no preference for whether the display should be digital or mechanical. However, the client mentioned that a digital display might cause complications such as zeroing and delay. If the above-mentioned difficulties cannot be overcome, a mechanical display is suggested.
    - It would be helpful if we can add an audible alarm that goes off when the force exceeds the sternal precaution limit. However, the client has concerns that the alarm might need zeroing and adjusting for different patients, which can cause unnecessary complications, so it is not a requirement.
- Adjustability
    - Our client would like to have us design a removable device that can be fitted on different types of walkers that are available at SRAL.
- Other

- ○ There is no requirement on whether the device should be on the top part of the walker or the bottom part.
- ○ There is no requirement on the size of the walker.

Users

- ➢ Sternal precautions are employed for patients recovering from open chest surgery.
- ➢ Walkers are used to help patients with sternal precautions and lower extremity movement restrictions, which are normally caused by injuries or weakness after surgery.
- ➢ Patients use their pec muscle when pushing weight through their upper extremities, and pec muscle pulls on the sternum.
- ➢ Patients are normally allowed to walk with a walker 6-8 weeks after the surgery. Training normally includes walking for 50(household distance)-150(community distance) feet.
- ➢ Patients with sternal precautions also have movement restrictions. These include: 1) arm lifting is restricted to shoulder height; 2) arms are not allowed to be behind the body at the same time.
- ➢ The age group is typically 45-65 years old. The risk of open chest surgery for patients above 65 years old is too high.
- ➢ The height and weight of patients vary.
- ➢ Patients sometimes squeeze the handles of the walker, but that is not concerned by sternal precautions.

Equipment

- ➢ The walker that is most widely used by the physical therapists at SRAL is the Guardian walker, which has 2 wheels in the front and 2 pegs in the back. The weight limit of the walker is 250 lbs. The weight of the walk is light enough to be allowed to be lifted by patients with sternal precautions.
- ➢ The physical therapists also use Guardian heavy duty walkers for patients that weigh more than 250 lbs.

The interview provided crucial information for understanding the problem, users, and client requirements. When we do our user observation at SRAL, we will observe how current models of walkers are used to help our users walk, how the physical therapist ensures the force on the walker is within the sternal precaution limit, and the difficulties our users encounter when using the current walkers.

## Appendix C: Instruction for Use

### The Design

The purpose of our design is to measure the force exerted by a patient on their walker so that physical therapists can monitor the force and help the patient keep the force within the safety threshold imposed by their sternal precautions. Specifically, this is for patients at the Shirley Ryan AbilityLab who are both recovering from an open chest surgery. Some patients under sternal precautions also have lower body injuries or extreme weakness after surgery that requires recovery activities with a walker. This design is an attachment to the Guardian walker currently used in Shirley Ryan AbilityLab (see Figure 8). The attachment gives live readings of the force exerted by the patient onto the handle of the walker. The design is composed of a handle, a bed for the load cell, two connecting screws, and the electronics unit. The electronic components of the design are two load cells, an Arduino Nano board, and a digital display.

Figure 8: +ReinFORCEment

### Introduction

These instructions will lead you through the process of safely and efficiently attaching and setting up the force sensing handles. The instructions for the physical therapist are broken into the following sections: attachment and setup, using electronics, cleaning, and disassembly. “Attachment and setup” is for the very first time using the device, while the “using electronics” and “cleaning” sections are for each use between assembly and disassembly. The physical therapist should not disassemble to the whole device after each use. Instead, they should only follow the “disassembly” section’s instructions when they decide they no longer want to use the device on the walker in the future. There is only one section of instructions for the patient, which details how to use the walker with the force sensing handles attached. Only one person, the physical therapist, is necessary to assemble and prepare the device for use by the patient as well as for disassembly. The whole process of setup or disassembly should take less than five minutes each. When setting up the device one must make sure to secure the handles very tightly and to calibrate the sensors well so as not to endanger the safety of the patient when the device is in use.

**Materials and Equipment**

Allen Wrench
Zip Ties

**Theory of Operation**

The primary users are the patient and physical therapist; the patient will interact with our handle in the same way they do with a normal walker handle and the physical therapist will monitor the force on the handle through the digital display. The physical therapist will follow the below steps to secure our design to the walker and set up the electronics. The therapist will then calibrate the sensors to prepare for the physical therapy session. During the session, the patient will walk with the walker as they normally would while holding our handles instead of the walker’s handles. This will exert a force on the handle, and the bending of the handle will cause the load cell force applicator on the handle to press down onto the load cell. The load cell will then convert the force reading into digital signals, which will be processed by the Arduino nano chip. The force reading from the load cells will be displayed on the digital display. The physical therapist can then view this reading from their position at the side of the walker. Between each session, the physical therapist will turn off the electronics, wipe down the handles, and charge the battery pack when necessary. If the physical therapist no longer wants the design on the walker, they will follow the detachment steps below to take the design off the walker.

**Instructions for Physical Therapist**

<u>Attachment and Setup</u>

1. Attach the handles
    a. Take one of the handles and align the holes on the underside of the handle to the corresponding holes on the arch of the walker handle so that the handle device’s grip is above the walker’s grip
    b. Slide one screw into one of the walker holes through the underside of the walker handle and push it through the walker handle until it is aligned with the handle device’s hole

Figure 9: Screwing in the screw

   c. Use an Allen Wrench to thread the screw into the handle device and screw it in very tightly, until the head of the screw is pressed to the walker handle the device cannot be screwed in any more (see Figure 9).
   d. Repeat b and c for the other hole on that handle
   e. Repeat a-d for the other handle on opposite side of walker
2. Attach the electronics
   a. Make sure the rechargeable battery pack is sufficiently charged
   b. Place the battery pack in the designated spot in the electronics box and plug it in
   c. Decide where to place the electronics box on the walker to allow you to see it from your position during the therapy session
   d. Hold the box to the chosen bar on the walker and wrap the Velcro around the bar to secure the box to the walker (see Figure 10)

Figure 10: Securing electronics using Velcro

e. Secure loose wires to the walker with Zip Ties (see Figure 11)

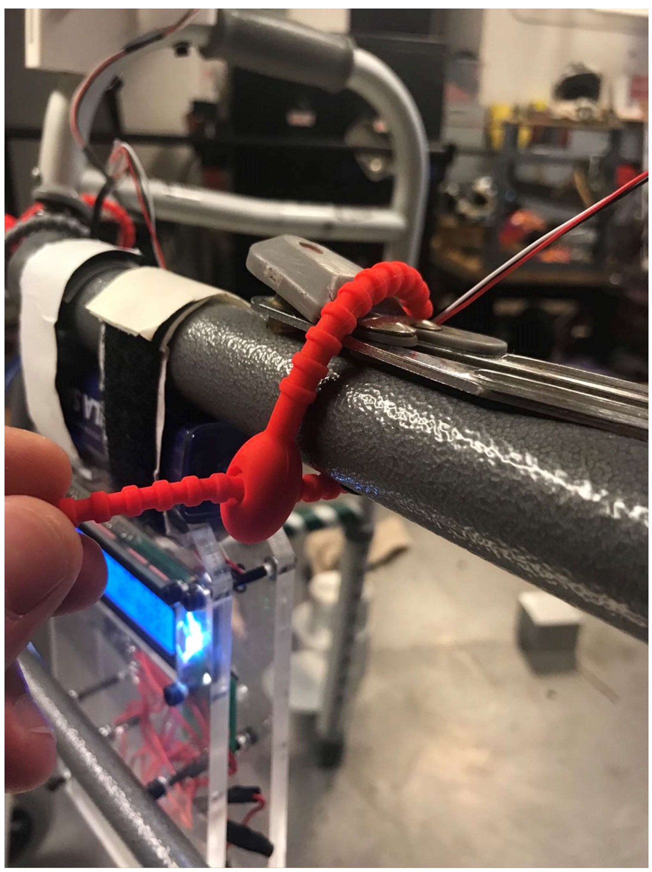


Figure 11: Securing loose wires

Using electronics

1. Make sure the electronics box is in a visible position for the session and move it if not
2. If not plugged in already, plug in the battery pack (doing so will turn on all the electronics)
3. The device will automatically calibrate and zero. Wait until calibration is completed. (see Figure 12-13)


Figure 12: Auto-calibration

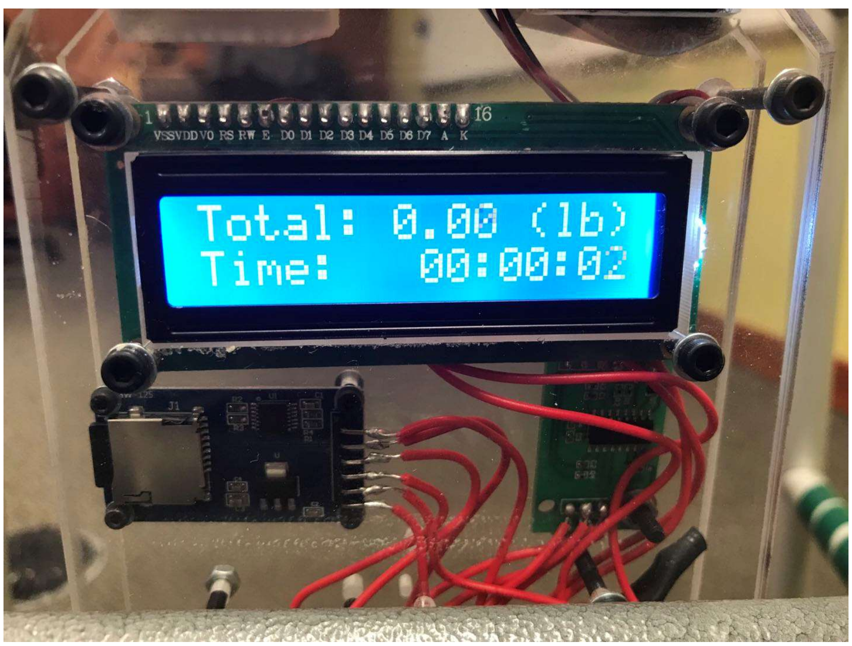



Figure 13: Zeroing the device

4. Lower or raise the walker height so the device's handles are at the height the walker's handles would usually be
5. Have the patient follow the "Instructions for Patient" to use the walker during the session
6. While the patient is using the walker with the device, look at the screen to see the downward force they are exerting on the walker (keep in mind any negative force measurements while lifting the walker are not actual measurements of the force used to lift the walker, disregard them)
7. After the session is over, turn off the device by unplugging the battery pack
8. Charge the battery pack if necessary

<u>Cleaning</u>

1. Simply take any type of wet wipe that would usually be used to clean equipment and wipe down the grip part of the handle (avoid getting wires and electronics wet)

<u>Disassembly</u>

1. Disassemble electronics
   a. Make sure the battery pack is unplugged
   b. Cut all Zip Ties securing wires
   c. Undo Velcro securing electronics box
2. Use an Allen Wrench to unscrew each screw from the device handle base, then pull the screws out of the walker handles

**Instructions for Patient**

<u>Using the walker with force sensing handles</u>

1. Hold the grips of device's handles as you would the walker's handles. Do not grip the handles anywhere else or the reading will not be accurate. (see Figure 14)

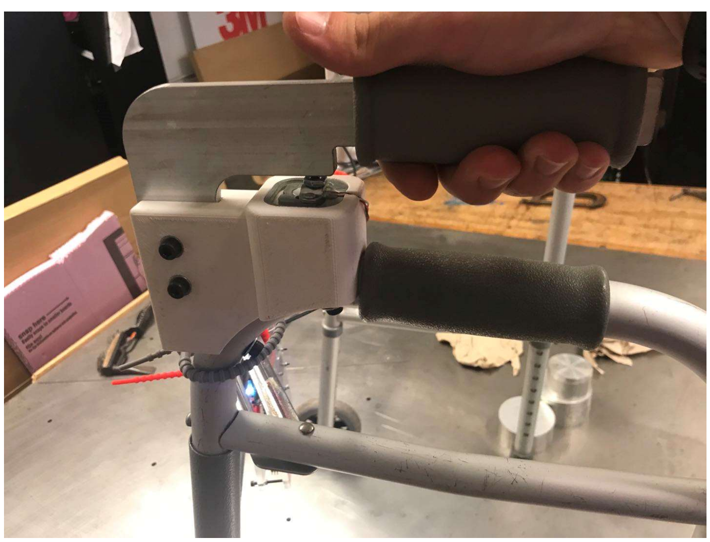


Figure 14: Holding the handle

2. Use the walker as you normally would.
3. Pay attention to the instruction from the physical therapist as the therapist might warn the patients if the force on the handle reaches the maximum of the sternal precaution.

## Appendix D: User Observation Summary

### Introduction

On April 4, 2019, we, Aimee van den Berg and Shane Dolan, observed the physical therapist Ms. Erin Walaszek and the patient Mohammed at the Shirley Ryan AbilityLab. We held the observation with Alex Manka, Malav Patel, and Kevin Wu from group 3. The purpose of this observation was to learn:

- The type of walkers that we will be designing the modification for
- What design would hypothetically be the most comfortable for the user
- How the way the patient interacts with the walker restricts the design space
- How the patient applies force to the walker, with regards to the directions

### Observations

During the observation, we watched as the PT assisted Mohammed in walking a few yards with the walker and afterward, the PT spoke to us about different types of walkers and what she was looking for in the design. The observation ended up lasting a little over an hour.

Mohammed is 46 years old and from the United Arab Emirates. He does not speak much English and requires a translator for every physical therapy session. He has sternal precautions due to his open heart surgery when doctors inserted a left ventricular assistance device on March 5, 2019, following his heart attack. Mohammed is confined to a wheelchair due to weakness in his left leg and cannot stand on his own. He needs a harness and pulley system, which is attached to the ceiling, in order to stand (Figure 15).

Figure 15: The harness system patients need to stand

Because of his weaker left leg and ankle, the therapist sits on the left side of him as he walks to observe and help him move his leg. She sits on different sides for different patients and as such the display would either need to be seen from all sides or it must be movable. Currently, they have no way of measuring force at all, not even statically as we had thought from the original project definition. The PT is simply going with her gut to tell him when to put less force. However, she is so busy trying to help him with other parts of his walking (lifting his left leg enough, posture, arm straightening, which leg to walk with first, etc.) that there is really not much attention paid by anyone to the force he exerts on the walker. She is very busy looking at him and it would be difficult for her to always have to direct her attention to a force display to see if he is going over his limit, so an auditory warning is very important.

While walking he needed to take a few breaks because walking is very difficult and tiring for him. While walking he showed a lot of physical discomfort in his facial expressions and body language. He says he feels he had to push down the most when he stands up from the chair and he often pushes down with his left hand more than the right. When holding onto the handles he says he squeezes them a lot and sometimes he is not grabbing exactly on the drip but in front of it on the bare bar. He was leaning back a lot while walking and did not have the correct walker posture yet. The steps he uses to walk are 1. Push walker forward, 2. Right leg forward, 3. Swing left leg forward, and repeat. As he goes through these steps his body posture drastically changes. After he has moved his right leg forward he straightens up, then swings his left leg, then collapses his body.

The standard walkers used at Shirley Ryan are Guardian or Medline walkers. They have a weight limit of 250 lb. Their handle grips are usually hard and non-rotating, which is very important for the safety of the patient. The handles must not rotate or the patient will be likely to hurt their wrists when they exert force to stand and walk.

**Client Requirements**

The Physical Therapist is looking for a device that is easily cleanable so that everything used in the Lab is sanitary. She also asks that the display be very easy to read as she will have to focus more on the patient and that the auditory notification of the weight limit is adjustable for different patients' weight limits. Lastly, she would like to be able to store the data on a computer for future research purposes.

## Appendix E: Statistical Analysis of Lever Arm Length on Mechanical System Accuracy

### I. Problem

Does there exist any advantage to placing applied force on a lever arm far away from force-sensing load cell?

### II. Parameters and Setup

A load cell is mounted two inches away from the rotational axis of a lever arm. A nonpoint-force is applied to the lever arm some distance, *dx* (between 0 and 15 inches from the load cell), across a specified length, *GL*.

A nonpoint-force is approximated as 1000 single point-forces applied over a certain area. In this simulation, the magnitude of each single point-force comprising the nonpoint-force was calculated in one two ways. (1) Initially, the magnitude of each point force is equal, summing to the *total force.* (2) As a random number between zero and the *total force* such that the sum of each single point-force in composing the nonpoint-force sums to the *total force* applied to the lever.

**In order to test the accuracy of this setup, we ought to compare a single point-force approximation of the *total force* to a nonpoint-force and analyze the difference between the two measurements.**

A single point-force approximation is calculated by placing a single point-force *dx + GL/2* away from the load cell. This the length of the lever arm plus the average of the nonpoint-force area.

### III. Hypothesis

Because lengthening of the lever arm results in the force application area becoming a smaller proportion of the total lever arm length, moving a nonpoint-force along lever arm away from rotational axis (and load cell) will result in a comparatively more predictable load cell reading that can be approximated accurately with a single point-force.

### III. Diagrams

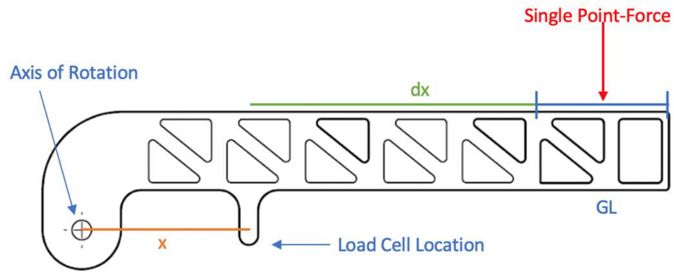



Figure 16: Variable Labels

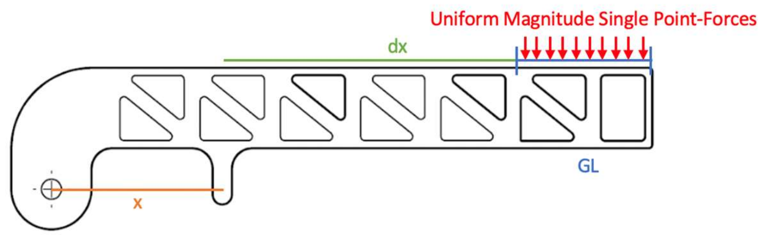



Figure 17: Uniform Magnitude Nonpoint-Force

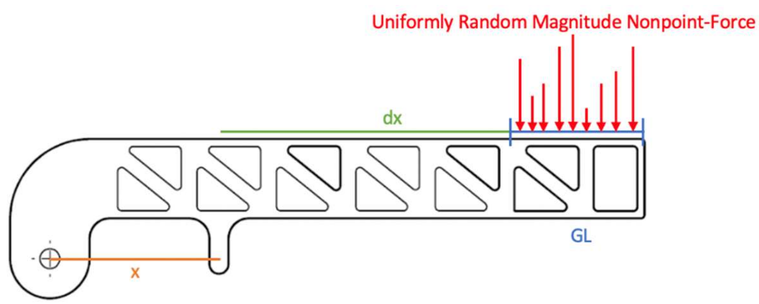



Figure 18: Uniformly Random Magnitude Nonpoint-Force

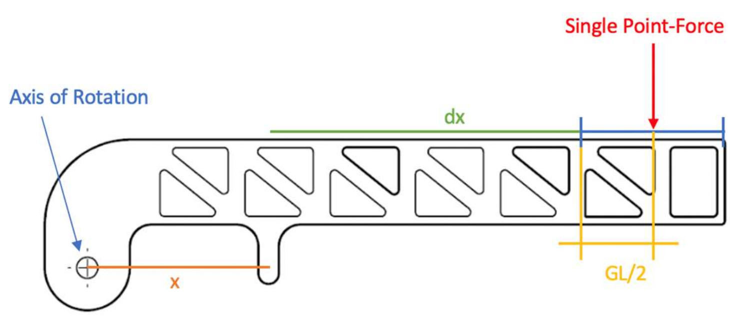



Figure 19: Single Point-Force Approximation

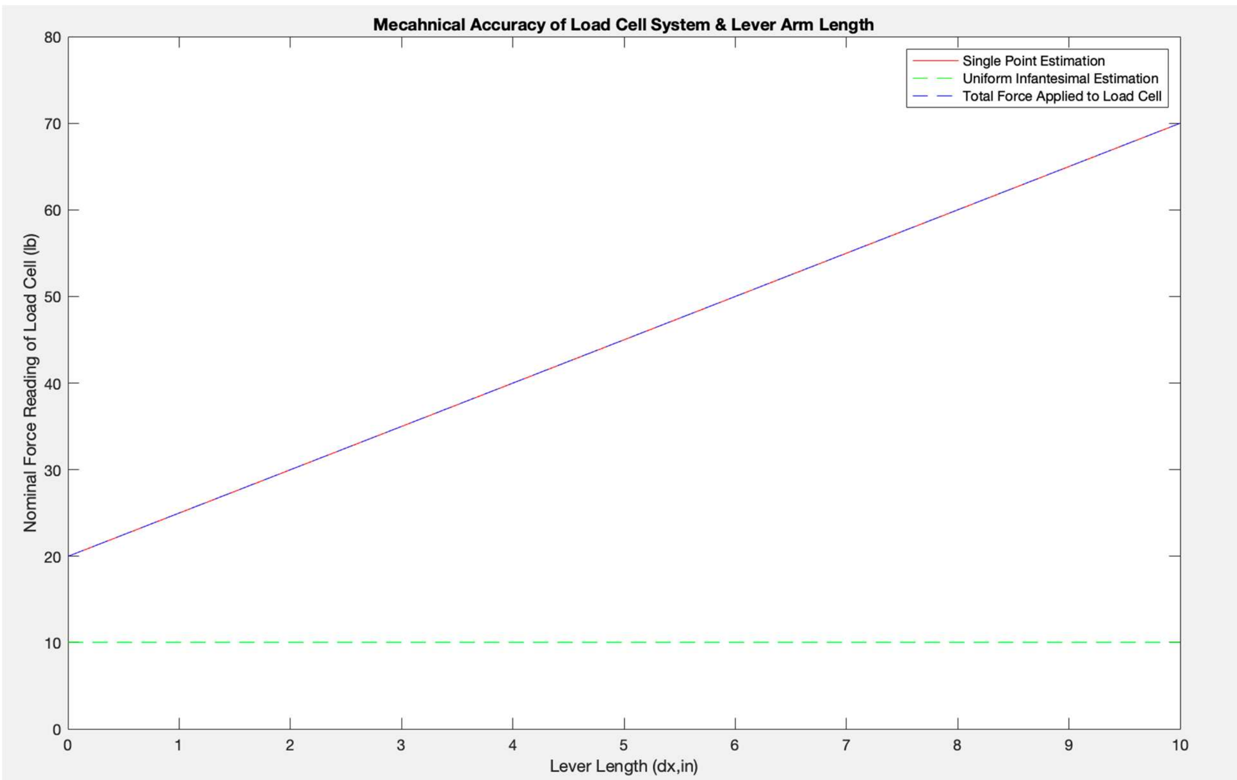
**IV. Method**

A MATLAB simulation was developed to run this simulation. The code simulates a nonpoint-force and calculates a solution force applied to the load cell as a result. The code iterates a similar function for *dx* ranging from 0 to 15 inches.

The results are reported by plotting the force applied to the load cell for the calculated nonpoint-force and the estimated single point-force on top of each other.

As mentioned previously, the method for determining the magnitude of each point force is one of two possibilities. The results of both simulations are found below.

**V. Results**




```
Mean Absolute Percent Error = -0.00 percent
Accuracy = 100.00 percent
>>
```

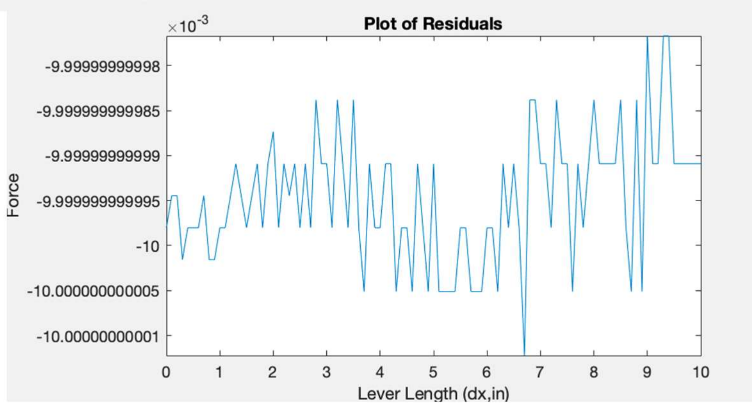



Figure 20: Uniform Magnitudes for Nonpoint-Force Composition

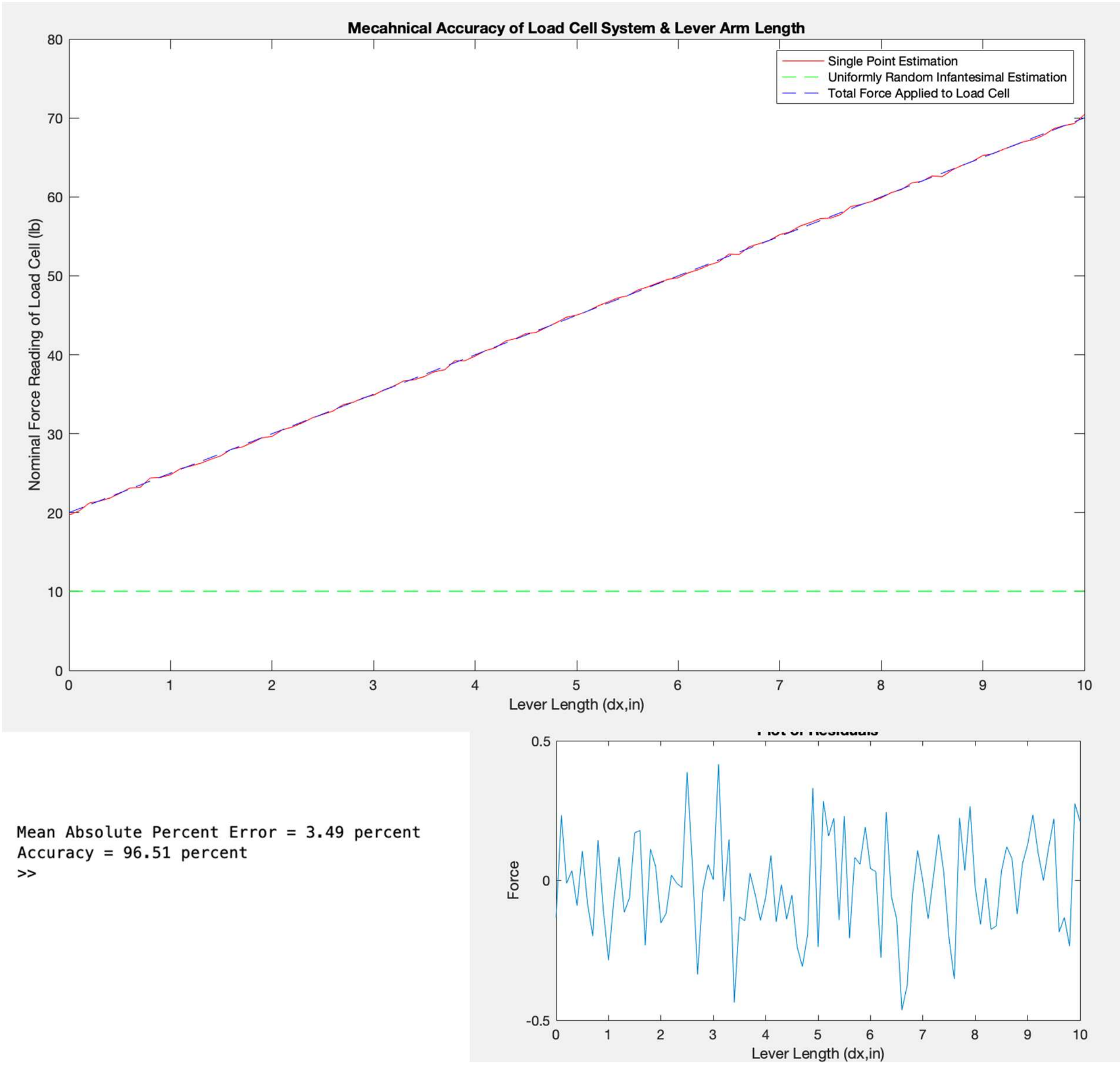



Figure 21: Random Magnitudes for Nonpoint-Force Composition

## VI. Conclusion

From our simulation, we can safely conclude that increasing the length of the lever arm will not improve the mechanical accuracy of the system.  From the first trial (Figure 20), we see that a uniform nonpoint-force applied over a given length of lever arm yields the *exact* same force as a single point-force approximation placed in the middle nonpoint-force area. From the second trial, it is clear that even a random distribution of force over the nonpoint-force area (Figure 21) has little to no impact on the force reported by the load cell. Any deviation from the estimated force is likely due to inadequate coverage of the normalized random force magnitudes. This conclusion was based on plot 4 which showed no obvious trends. The accuracy of the random distribution system hovered around 96% over 10,000 trials. This leads to the conclusion that the mechanical accuracy of the system is significantly greater than the load cell accuracy and that changing the length of the lever arm will have no statistically significant impact on the accuracy of the system.

A more visual comparison of the phenomenon can be found below (Figure 22).

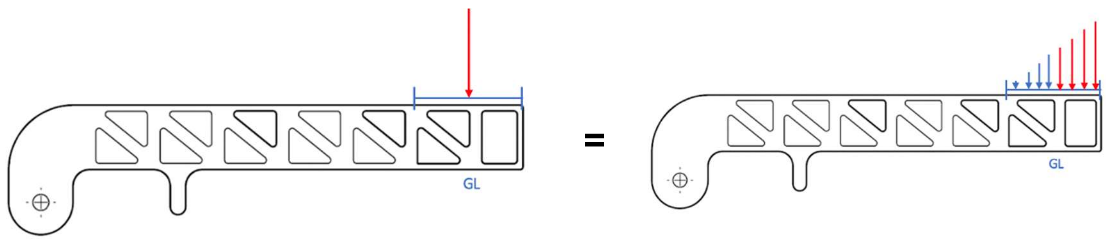



Figure 22: Result of statistical analysis

**VI. Code**

```
%%%%%Handle Parameters
n = 1000;        %number of point forces applied to the walker
gl = 4;          %length of grip where force will be applied (inches)
alpha = gl/n;     %distance between point forces applied by hand (inches)
x = 2;           distance between fulcrum and load cell (inches)
dx = [0:0.001:10];        %distance between first point load fulcrum
tf = 10;               %total magnitude of force applied to handle
pmag = tf/n
%%%%%Variable Initiation
TFA = [];         %total, real force applied
TMA=[];           %total moment applied keeper
ema = [];
efa = [];
load_cell_nom =[];     % force value read at load cell for given dx
                     %random point force generation
pm = randfixedsum(n,length(dx),tf,0,tf); %magnitude of point force

%%%%%Iteration Solve
for ii=1:length(dx)
    TM=0;
    for jj=0:n-1
       el = x+dx(ii)+jj*alpha; %Length of effective lever arm for a moment     component
       %mp = pmag * el; %uniform point force magnitude
       mp = pm(jj+1,ii) * el; %random point force magnitude moment piece is product of el and
force applied
       TM = TM + mp; %total moment is the sum of its components
```

```
    end
    TMA(ii) = TM; %indexing TMA
    ema(ii)=(x+dx(ii)+gl/2)*tf; %estimating single point force
    efa(ii) = ema(ii)/2; %single point force, used to calibrate load cell
    TFA(ii) = TMA(ii)/2; %total force applied to load cell
end
figure(1);
plot(dx,TFA,'red',dx,10*ones(1,length(dx)),'--g');
hold on
plot(dx,efa,'--b','LineWidth',.5)
hold off
title('Mecahnical Accuracy of Load Cell System & Lever Arm Length');
xlabel('Lever Length (dx,in)')
ylabel('Nominal Force Reading of Load Cell (lb)')
legend('Single Point Estimation','Uniform Infantesimal Estimation','Total Force Applied to Load
Cell')
ylim([0,80]);

%%%%%Accuracy Testing
sqd=TFA.^2-efa.^2;
percenter = sqrt(sqd)/TFA*100;
fprintf('Mean Absolute Percent Error = %.2f percent\n',percenter);
fprintf('Accuracy = %.2f percent\n',100-percenter);
figure(2)
plot(dx,TFA-efa)
title('Plot of Residuals')
xlabel('Lever Length (dx,in)')
ylabel('Force')
```

## Appendix F: Ethics and Sustainability Considerations

In this appendix, we evaluated potential ethical and sustainability consideration with regard to our final prototype. We mainly focused on safety concerns and sustainability issues regarding energy consumption and maintenance cost of our prototype.

### User Safety

Something that was greatly emphasized by our client, Ms. Erin Walaszek, during our user testing session, was that the prototype that we will create must be able to withstand the weight of the patient's entire body. Should the user accidentally fall, they may push all of their weight onto the walker, creating the need for this requirement. Since we are using the program SolidWorks to design our prototype, we are able to perform virtual stress analysis for various materials through the program. Our current design has passed these stress tests for weight up to 100 pounds. Since we will create two identical models of the prototype, one for each side of the walker, the two combined will be able to withstand up to 200 pounds, satisfying the weight-bearing requirement for most cases. However, we will conduct additional performance testing after creating the prototype in order to make sure that the design works in reality, as well.

Another safety concern for the user is in regards to the accuracy of the force reading that is given by the prototype. Should the force reading be too low, the user may overexert themselves without knowing, while the physical therapist believes they are within their force limit due to the erroneous reading from the prototype. This puts them in danger of breaching their sternal precautions and hurting himself.

### Battery usage

Since our design utilizes electronics and must be able to be used on a moving walker, a battery is required for operation. Thus, a decision had to be made as to whether a rechargeable battery or a disposable one would be used. We found rechargeable batteries to be the obvious choice for both ethical and environmental reasons. According to studies conducted by Uniross and Professor David Parsons, rechargeable batteries have a much smaller environmental impact than disposable batteries, due to the fact that recharging the battery leads to a much smaller use of materials as the rechargeable battery is used over and over, as compared to frequently needing to replace disposable batteries. Additionally, the choice to use a rechargeable battery benefits the client. With disposable batteries, the Shirley Ryan AbilityLab would regularly have to purchase and replace the batteries of the prototype, and there is no guarantee that the client would properly recycle batteries to reduce their environmental impact. Thus, by using a rechargeable battery, we are providing a product to our client that has minimized environmental impact, and a lowered cost to maintain the product over time.

### Maintenance

Another ethical concern is that of making the design easy and inexpensive to maintain for the client. One requirement of the client was that our design would be able to be wiped down with a certain brand of sanitary wipes, and for this reason, we chose to make the design out of aluminum and plastic, and to house electronics within plastic, as aluminum and plastic were not corroded or damaged by the wipes during performance testing. As for accounting for the prototype breaking, all the electronics that will be used will be relatively inexpensive. The Aubrey branded load cells, Arduino nano board, and compatible display, and USB rechargeable battery all cost roughly $50 total. That cost includes a pack of 4 rechargeable batteries, meaning that the client will be supplied with extra batteries initially, somewhat reducing the cost of maintenance. Additionally, the code used to program the Arduino board will be sent to our client so that they will not need to recreate the code in the case of the board breaking. The other components of the design will be 3D printed or waterjetted, minus the clamps which are readily available, and a link to purchase them online will be supplied to the client. This way, the client can contact us if these parts of the design break, and we will have the digital models of these parts on hand so that we can easily replace, and potentially modify to improve, these aspects of the design.

## Appendix G: Dimensioned Graphics Sketches

Figures 23-30 illustrate isometric and orthographic perspectives of different parts of our prototype.

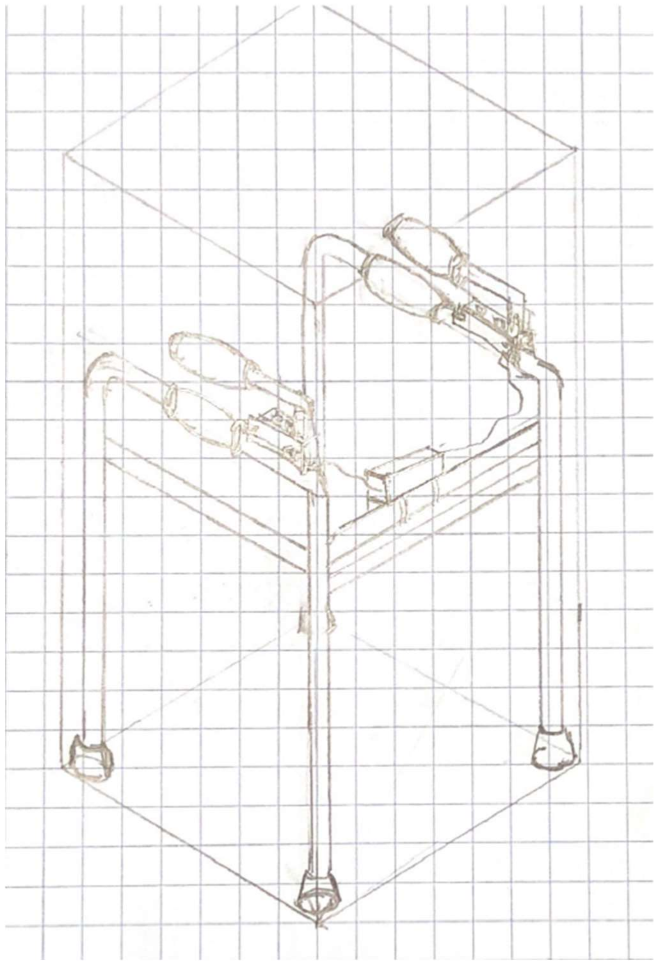


Figure 23: Isometric view of the entire assembly

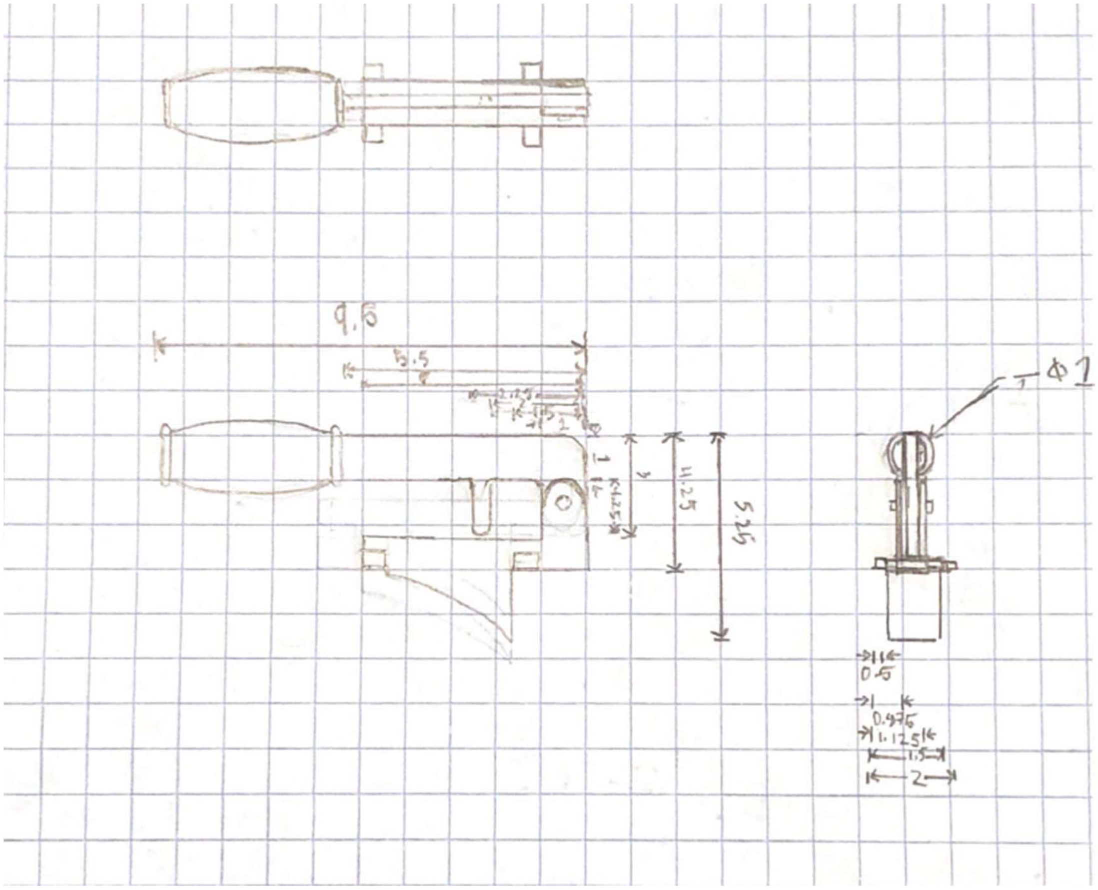


Figure 24: Dimensioned orthographic view of the handle attachment

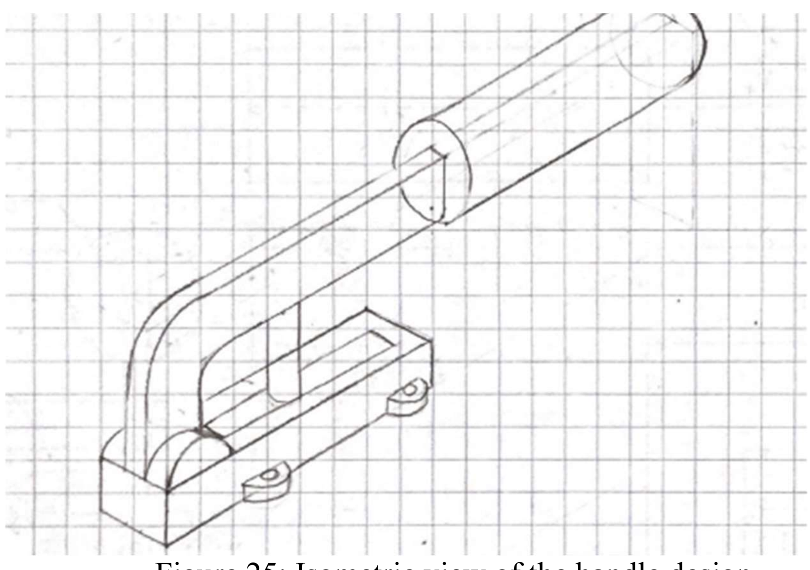


Figure 25: Isometric view of the handle design

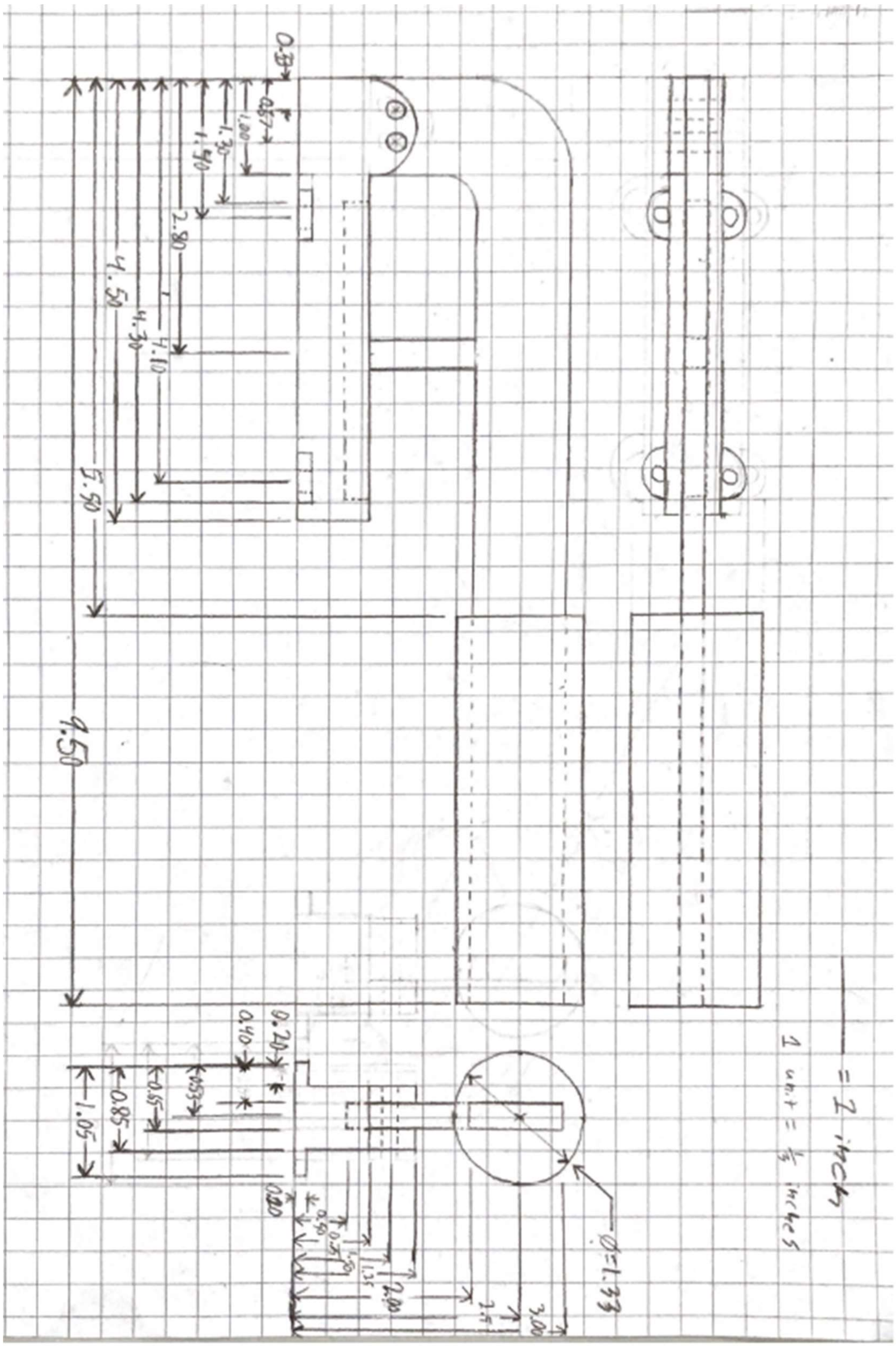


Figure 26: Dimensioned orthographic view of the handle design

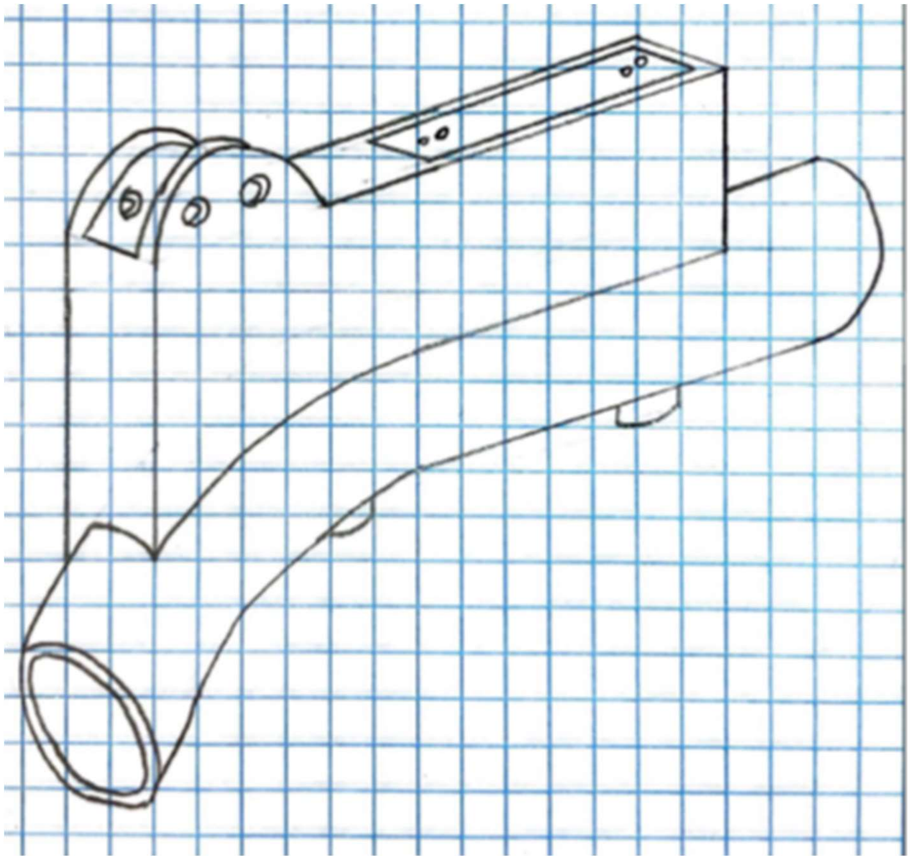


Figure 27: Isometric view of the connection method

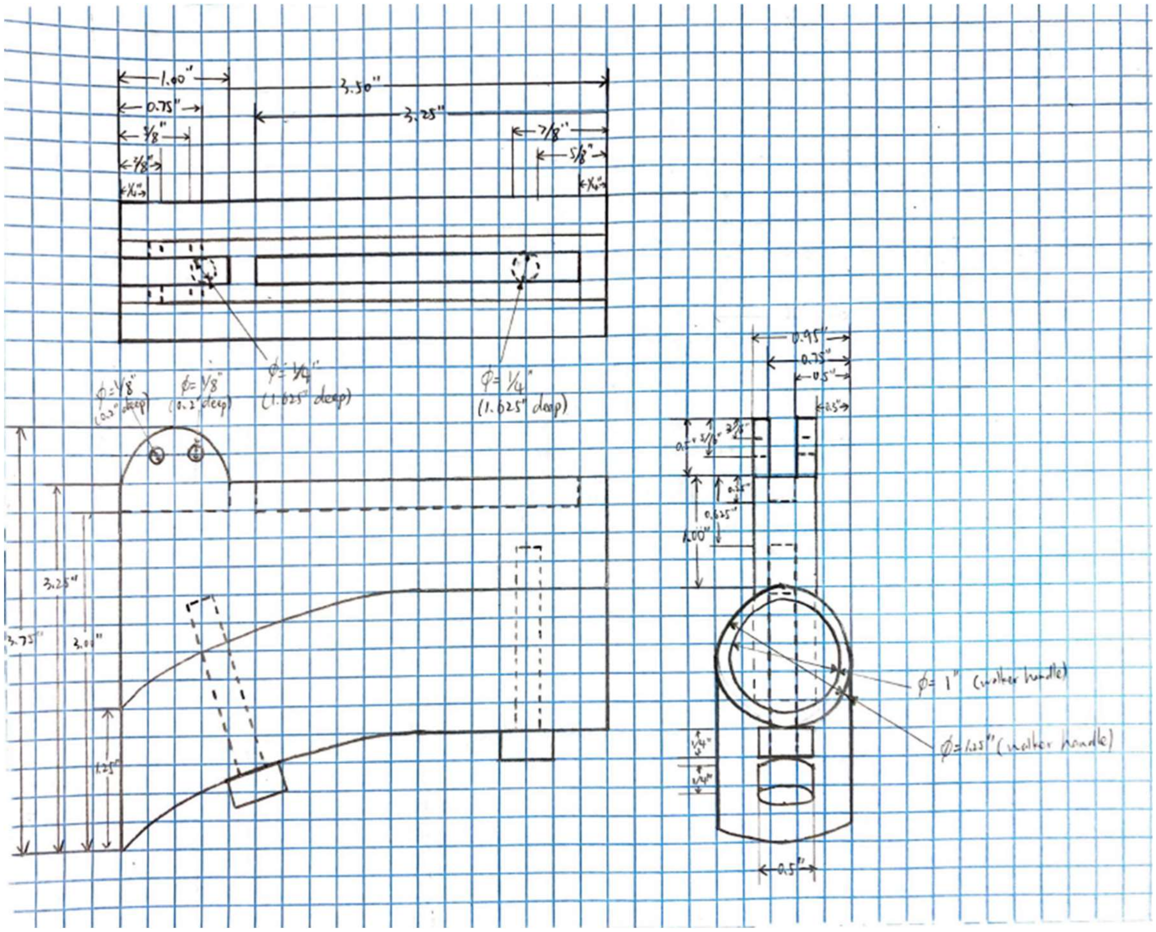


Figure 28: Dimensioned orthographic view of the connection method

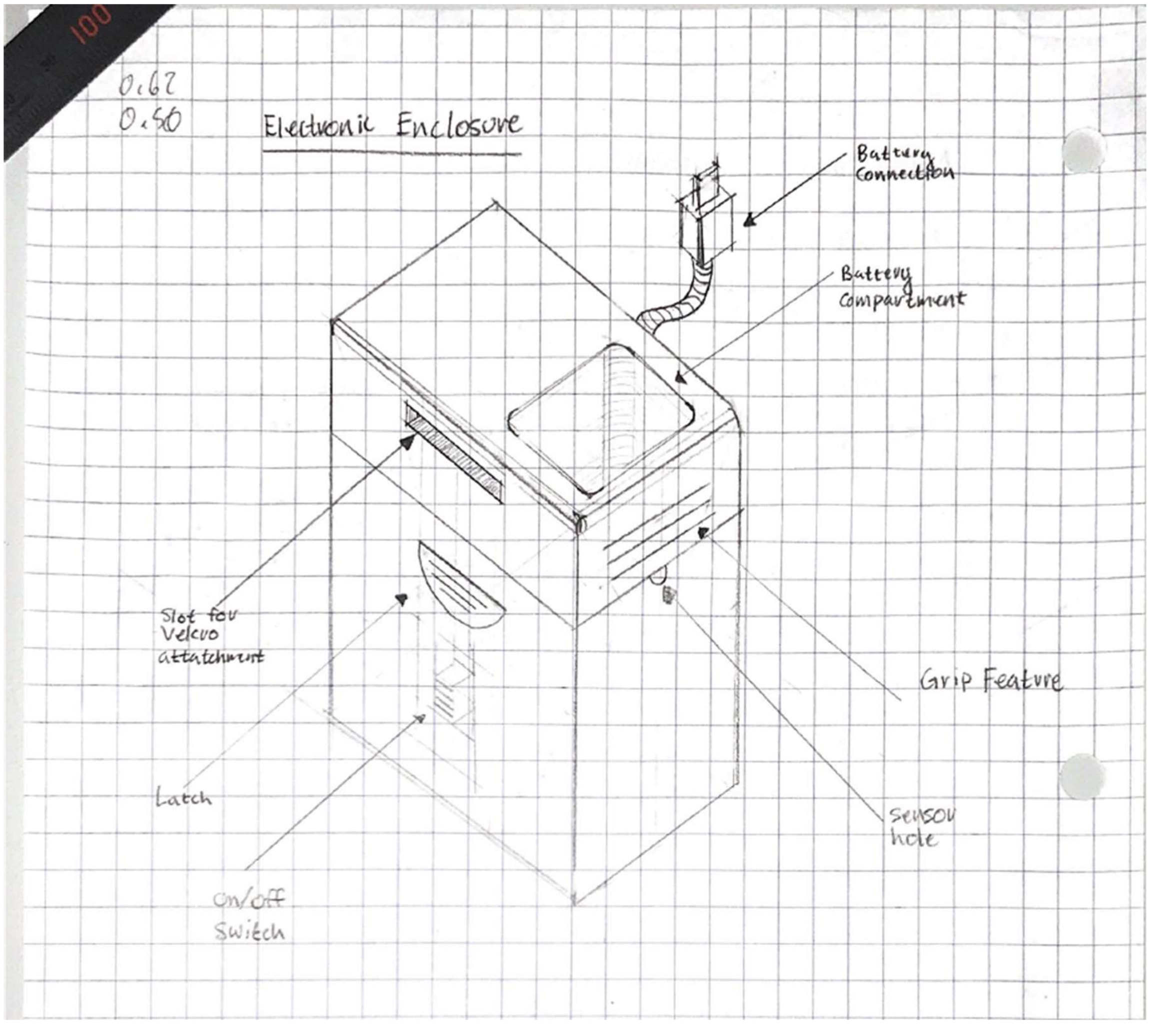


Figure 29: Isometric view of the electronic unit

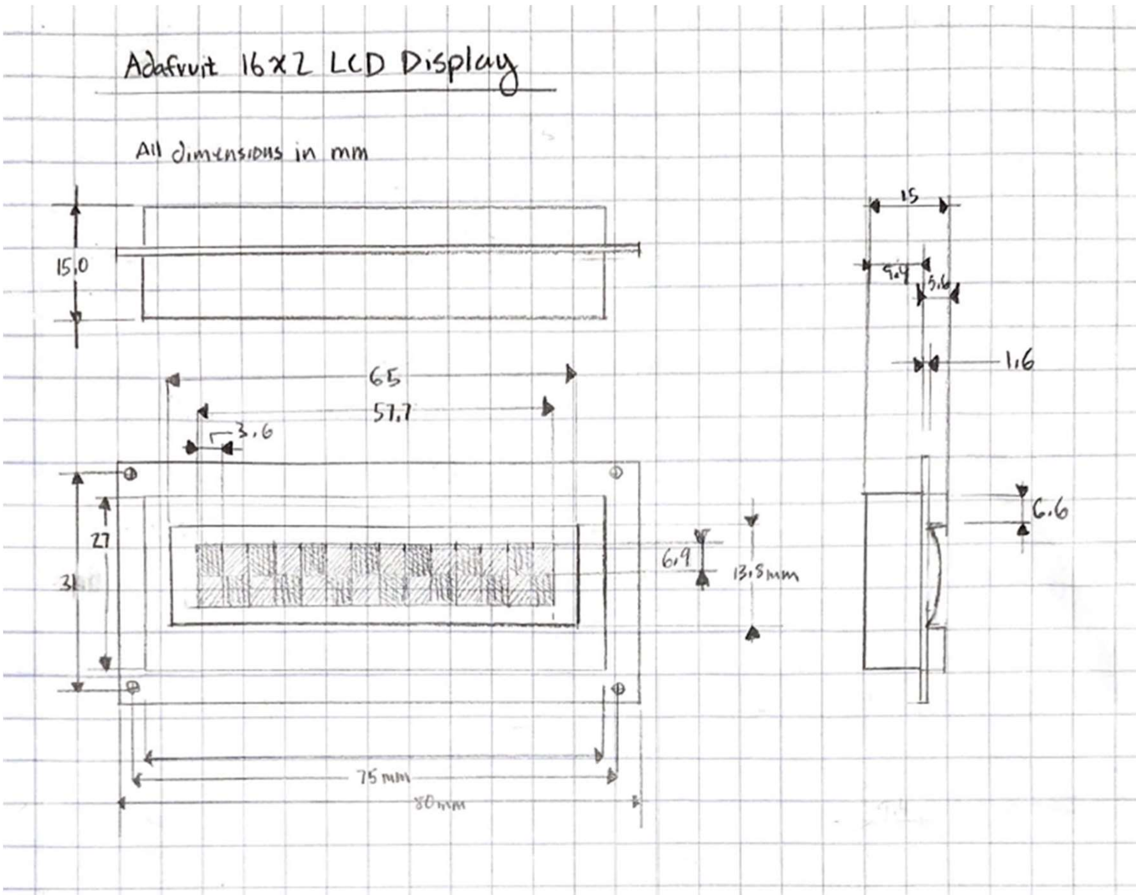


Figure 30: Dimensioned orthographic view of the electronic unit

## Appendix H: Performance Testing Report

### Purpose

Of the various mockup designs, the load cell handle design appeared to be the most promising based on our mockup testing during class and the feedback from our client during user testing. The objective of this performance testing is to further explore possible ways to attached the design onto the handle of a walker and determine possible weaknesses of the designs, mainly focusing on the stability of the structure.

### Methodology

Our testing mainly composed of two parts. In the first part, we tested different ways of attachment. We installed each of the three attachment methods as described below and tested if those options are feasible. In the second part, we tested the stability of the attachment method that we deemed feasible in the first part of our testing. The details about each part of our testing are shown below.

1. Different ways for attachment.

First, we experimented with different ways to attach our design to the handle of a walker. We mainly experimented three possible ways for attachment:

II. A double-sided clamp, as shown in Figure 31
III. Manufacturing a PVC pipe that has the same curvature as the handle of the walker and fitting the PVC pipe onto the handle, as shown in Figure 31
IV. A combination of a pin, zip tie, and hot glue, as shown in Figure 32

Figure 31: Ways for attachment (left:double-sided clamp, right:curvature fitting PVC pipe)

Figure 32: Pin & zip tie & hot glue attachment

Mechanism of the three attachments are described below:

I) The double-sided clamp: Two pieces of wood were attached to each side of the walker handle and sandwiched the handle in the middle. Two screws were used to tighten the two pieces of wood onto each other so that they do not wobble. The clamp could prevent our design from rotating sideways and forward/backward. After installing the clamp, we could push it down with force so that the screw touched the handle of the walker, and this would prevent our design from moving downward. Then we would further tighten the screws and use the friction between wood and the walker handle to prevent our design from moving upward.

II) The curvature fitting PVC pipe: We would manufacture a piece of PVC pipe that could be fitted to the curvature of the front part of the walker handle, as shown in Figure 32. Then we would squeeze the handle of the walker into the PVC pipe. Due to the unique curvature of the front part of the handle, the PVC pipe would not be fixed onto the handle and would not move at all.

III) The pin-zip tie-hot glue attachment: We first made a piece of PVC pipe with the same curvature as the middle part of the walker handle and fitted it unto the handle of the walker. The PVC pipe was fastened unto the handle by two zip ties. Then we drilled a small hole through the PVC pipe and handle of the walker and used a small aluminum rod that has the same diameter as the hole as a pin. We inserted the pin through the holes and drilled another hole of the same diameter on the bottom of our mockup. We then applied hot glue onto the PVC pipe, inserted the pin into our mockup through the hole on the bottom of the latter, and let the hot glue secure the mockup unto the PVC pipe. The rod of this attachment design could prevent our mockup from moving sideways and back and forth. The hot glue further secured the mockup against movement in any directions.

Testing plan:

We first built the mockup according to the descriptions above. Then we installed each attachment to see if those options are feasible. After that, we commented on the process of installing and also the aesthetics of the attachment method to determine if they are good enough to be passed onto the next stage of testing.

2. Testing the stability of the attachment method

Due to the limitations of the double-sided clamp approach and the curvature fitting PVC pipe approach, we abandoned those two methods and only focused on the pin-zip tie-hot glue attachment method.

First of all, we tested the ability of the method to prevent our design from rotating in sideways and back and forth direction. This was done by applying a sideway force on our mockup and testing if the attachment method could hold that force.

Secondly, we interacted with the mockup and tested how the mockup would perform if we lift up the handle of our design. We then pressed down onto the handle and observed where failures are most likely to happen in our design.

**Results**

Table 2 shows the result of our testing on the attachment methods:

Table 2: Feasibility of each attachment

| **Attachment Method** | **Feasible? (Yes/No)** |
|---|---|
| Double-sided clamp | No |

| | |
|---|---|
| Curvature fitting PVC pipe | No |
| The pin-zip tie-hot glue attachment | Yes |

Table 3 shows the result of our testing on the durability of the force handle with our attachment method:

Table 3: Durability of the attachment

| **Force (N)** | **Still functional (Yes/No)** |
|---|---|
| 10 | Yes |
| 20 | Yes |
| 30 | Yes |
| 40 | Yes |
| 50 | Yes (the 3D printing material failed) |

**Analysis**

1. Different ways for attachment.

I) the double-sided clamp attachment

Ease of attaching: The double-sided clamp attachment was very difficult to attach and it took us 10 minutes to finish the attachment. This is because we had to make sure that both of the screws are screwed in at the same rate. If we only fastened one of them, the other end of the wood would separate out and thus became difficult to be fastened.

Aesthetics: The double-sided clamp was very bulky and extremely inconvenient to use. Since it took up a lot of space, it might affect the way patients use the walker. Moreover, the volume of the clamp would also mean the clamp could be heavy. This would further cause the patients to not be able to lift up the walker.

Due to the difficulty of attaching the clamp and the inconvenient of its bulky size, we decided to discard this attachment method.

II) the curvature fitting PVC pipe

Ease of attachment: The idea of the pipe was to use the unique curvature and the stiffness of the PVC material to stick the pipe in place and prevent it from moving. However, the strength of the design turned out to be its biggest weakness. The stiffness of the PVC pipe caused it to be impossible to bend and thus we were not able to install it onto the walker simply by pressing it onto the handle by hand, as shown in Figure 31. The difficulty of installing that PVC pipe led us to the decision of abandoning this design.

III) the pin-zip tie-hot glue attachment

Ease of attachment: This attachment method was designed to permanently attach our handle onto the walker, and thus the ease of attachment was not as important as it is in the removable cases. Still, this attachment method was very complicated to attach. It involved using many different materials and following a long procedure.

Aesthetics: This attachment was very small compared to the double-clamp design. Also, it did not involve any heavy structure. Though the handle might not be removable anymore with this type of attachment, we still decided to keep on our testing with this attachment due to above-mentioned reasons.

2. Testing the stability of the attachment method

We first interacted with our mockup by lifting up and pressing down on the handle. The main issues we discovered was that there needs to be a mechanism to stop over-rotation of the handle and that the hinge on the end of the handle was very vulnerable upon stress.

When lifting up on the handle of our design, the handle rotated accordingly, as shown in Figure 33. This is troublesome because when the handle is vertical, it is impossible to lift up the walker for the patients. Thus, we will need to add a mechanism to prevent this over-rotation in our final prototype.

Figure 33: Over-rotation of the handle

When pressing down onto the handle, we gradually increased the force applied and the hinge on the end of the handle snapped (see Figure 34). Thus the hinge would be a potential point of failure and we need to have a stronger connection in our final prototype.

Figure 34: The hinge is a potential point of failure

The second part of the test was quantitative, we applied sideway forces on our mockup which was attached to the PVC pipe and observed if the attachment broke. The results are shown in Table 3. The limiting factor in this experiment was the durability of the material we used for mockup. When building the mockup, we used 3D printing material which was composed of different layers and was not very strong itself. Thus the material itself broke before the attachment does. In the final prototype, we will be using metal materials which are way stronger than the 3D printing material.

The problem with this design was that the materials we used could not be copied in the final prototype simply because they were not strong enough. But the good news is that the concept of this connection could potentially be useful. In the final prototype, we could substitute the vulnerable 3D printing material with metal, use stronger JB weld instead of hot glue, and use a hose clamp to replace the zip ties.

**Conclusions**

From the data obtained from the testing, the following can be concluded:

- The double-sided clamp attachment was difficult to install and its bulky size was problematic since it might create extra weight and the clumsy size might affect the way patients use a walker. The PVC curvature fitting pipe was impossible to install. Thus, both of the two designs were abandoned.
- Though the pin-zip tie-hot glue design was very difficult to install and it disallowed our design to be removable, it remains to be our best choice as for now.
- When lifting up on the handle, we do not want the handle to over-rotate and become vertical. Thus, we need to devise a mechanism to prevent such over-rotation. One of the current solutions to the problem is to remove the rotation feature and use the bending of the metal to measure the force.
- Another safety concern of the design was that the hinge was a potential point of failure.
- Our durability testing proved that the pin-zip tie-hot glue approach could withstand a reasonable amount of sideway forces. This concept could be used in the final prototype albeit the fact that the materials used in mockup and performance testing need to be substituted by stronger materials.

**Limitations**

- Since these are just mockups, they do not accurately represent the designs as they would be when they are final prototypes.
- Due to the vulnerability of the 3D printing material, we were not able to test the upper limit of the amount of sideway force that can be applied to the pin-zip tie-hot glue attachment without breaking the attachment itself.
- Due to the vulnerability of the 3D printing material, we were not able to measure how much downward force could be applied on the handle of our design without breaking it. However, we simulated the force analysis using Solidworks and the

result showed that aluminum handles could withstand of the same size more than 100 lbs force (that is, a total of 200 lbs for both handles combined).

## APPENDIX I: DESIGN REVIEW SUMMARY

At 3:30 pm on Thursday, May 16th, 2019, our team presented our Design Review to the other teams in our class, Prof. Wood, and Prof. Mejia. We introduced our force handle design and discussed the strengths and weaknesses of the design. We especially focused on the mechanism to connect our design to the handle of the walker, and the over-rotation problem we discovered during performance testing.

We also asked each of the members in our class to fill in a questionnaire in response to our design review presentation. The questionnaire asked each person to vote on whether we should remove the rotation feature of the handle in our design or we should add a mechanism to prevent over-rotation. The questionnaire also asked the reviewers for their suggestions on material choice, their ideas on how to attach our design onto the walker and their concerns or recommendations on our design.

The figures for the force handle design are shown in Figure 35, 36, and 37. The design is a force measuring system consisted of a load cell and a handle that could rotate around a fixed hinge (Figure 35). The mockup was connected to the handle of the walker through a pin-zip tie-hot glue mechanism, which prevented it from wobbling when force was exerted onto the handle (Figure 36). To use our design, users would put force onto the handle, which would cause the handle to exert a downward force onto the load cell (Figure 37). The load cell would then provide a reading of the force exerted on the handle of our design. The mockup was built using 3D printed materials while we intended to build the prototype using metal materials. Prior to the design review, we were also considering removing the rotating feature of the handle and the hinge and use the bending of the metal bar to measure the force.

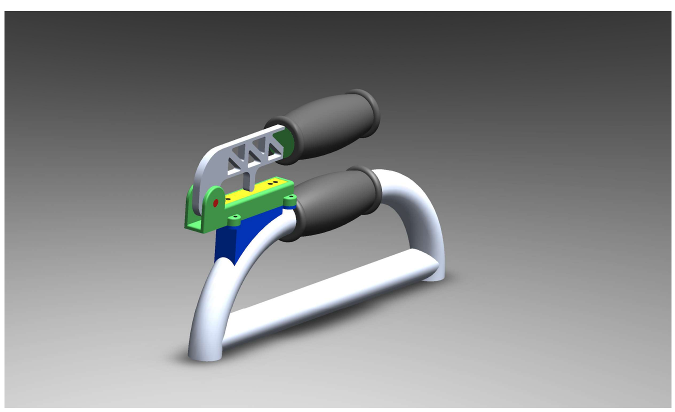


Figure 35: The concept of our mockup

Figure 36: Connecting our design to the handle of the walker

Figure 37: Using our design

Overall, the review session was helpful in that the class was vocal in their concerns, criticisms, and suggestions. However, there are a few reviews who did not answer our questions on the questionnaire or provided very poor quality answers. The reviewers especially expressed their concerns about our current method of connecting the design to the walker. A few of the reviewers proposed alternative designs. Our team collected the questionnaire results and our notes taken during the Q&A session and classified the concerns and suggestions from our reviewers into different categories. We focused on resolving the major concerns—those raised by multiple reviewers—and the related safety concerns. The results of the feedback are summarized in the following tables.

Table 4 displays the results from the second question on the questionnaire that the teams filled out, showing the number of students who would suggest us to remove the rotating feature of the handle and who would suggest us to keep the feature but restrict rotation. Table 5 summarizes the feedback from our reviews both during the in-class Q&A session and from the responses to the other questions on the questionnaire. Table 6 displays our team's decided implementations for the major suggestions and criticisms we garnered from the design review session.

Table 4: Questionnaire results on the over-rotation problem

| Way to address the problem | Number of reviewers who preferred each way | Reason |
|---|---|---|
| Keep the rotation feature but restrict it | 8 out of 12 | -The over-rotation was clumsy<br>-Restricting rotation might also prevent the hinge from breaking |
| Remove the rotation feature | 2 out of 12 | |
| No response | 2 out of 12 | |

Table 5: Detailed feedback about the load cell handle design

| Reviewers Like | Reviewers dislike | Features to be added | Features to be removed | Additional Comments |
|---|---|---|---|---|
| | **<u>Connection</u>**<br>Reviewers generally disliked our current way of attachment<br><br>**<u>Position of the Handle</u>**<br>Some of the reviewers suggested that we should place our handle directly on top of the original handle instead of the | A new method of connection that would secure our design onto the walker handle without adding too much weight | The current connecting mechanisms | **<u>Connection</u>**<br>Some of the reviewers suggested that we could use clamps combined with bolts to attach the design<br><br>One reviewer suggested that we should drill holes through the handle of the walker and permanently attach our design to the handle using a screw |

| | | | | |
|---|---|---|---|---|
| | slightly forward position in the mockup<br><br>**Accuracy**<br>The measurement might vary according to where the force is applied on the handle<br><br>**Stability**<br>The force was applied on the front of the handle of the walker, which might create instability due to the unbalanced force | | | **Materials**<br>One of the reviewers suggested that we should use heavier metal such as steel<br><br>**Safety**<br>We need to make sure that sideway forces would not break the handle or cause it to rotate |

Table 6: Implementation for design review advice

| **Suggestion/Criticism** | **Implementation** |
|---|---|
| Connecting our design to the handle of the walker | Talk to a prototype specialist to find out if there are better ways to connect the design with the handle of the walker while still making our design removable |
| Over rotation problem | Remove the over-rotation feature. We would instead use the bending of metal to replace rotation |
| Accuracy of the measurement | We would put a sign or a cushion on the end of the handle to indicate where the patients should put their hands at |
| Position of the handle | Make the handle of our design longer so that the handle of our design was directly on top of the original handle on the walker. |

In conclusion, the main takeaways from the design review were that the method of connecting our design to the handle of the walker needs to be modified. The reviewers provided some alternative methods of attaching our design, and we would also talk to shop specialist about other possible ways for attachment. As for the over-rotation problem, though in the questionnaire 8 out of 12 reviewers suggested that we should keep the rotation feature and come up with a way to restrict the rotation, we still decided to abandon the rotation feature and use the bending of the metal to measure the force. This is because we could not come up with a reliable way to stop the over rotation. Some of the reviewers suggested us to modify the hinge. However, according to torque analysis, the force near the hinge would be huge and none of the suggestions from our reviewers was reliable enough. If the stopping mechanism snapped when the patients were trying to lift up the walker, the patients might be severely injured. We will need to discuss with prototype specialist on Friday, May 17th to discuss possible connecting mechanisms and other issues regarding our design. Our team will also have a meeting on Sunday, May 19th to discuss the feedback from shop specialist and our reviewers and then finalized the design.

## Appendix J: Background Research Summary

At the start of the project, our client, Ms. Erin Walaszek, a physical therapist at Shirley Ryan AbilityLab (SRAL), provided a description of the problem asking us to design a device that can monitor the force applied by the user onto a walker. People recovering from open-chest surgery often require sternal precautions to facilitate recovery and protect their healing sternum. The sternal precautions, among other things, limit the user from using their arms to apply forces greater than 10 lbs. One of the jobs of physical therapists is to teach patients to walk with walkers safely and make sure that the force exerted by the patients onto the walker is within the limit of the sternal precautions. The background research we conducted clarified circumstances surrounding the description given to us and gave us ideas as to what materials might be used in the construction of the final prototype. Specifically, we researched four different categories: sternal precautions and recovery from open chest surgery; different types of walkers; existing competitive solutions to our problem; and commercially available force sensors.

### Sternal precautions and recovery from open chest surgery

During open chest surgery, the sternum, also known as the breastbone, must be cut in half in order to access the internal organs of the patient. After surgery, wires are tied through holes drilled in the sternum, as seen in Figure 38, so that it can remain aligned and heal properly. Even though the wires are meant to hold the sternum in place, excessive force can still cause the sternum to become misaligned.

For this reason, patients are advised to take sternal precautions for "about six to eight weeks" after an open-chest surgery. According to Healthline (2018), these precautions "typically include" instructing the user to not push or pull on objects, lift "more than 5 to 8 pounds," or "reach both arms overhead," "out to the side," or "behind [their] back," among other, more specific restrictions.

Recently, less restrictive sternal precautions have been researched, and this "Keep Your Move in the Tube" approach is shown visually in Figure 39. This new approach "applies standard kinesiological principles" so that patients can still "perform load-bearing movements in a way that avoids excessive stress to the sternum" (Adams et. al., 2016). In Figure 39, the images that are highlighted in green show the correct way to perform actions under sternal precautions, whereas those in red show the incorrect way.

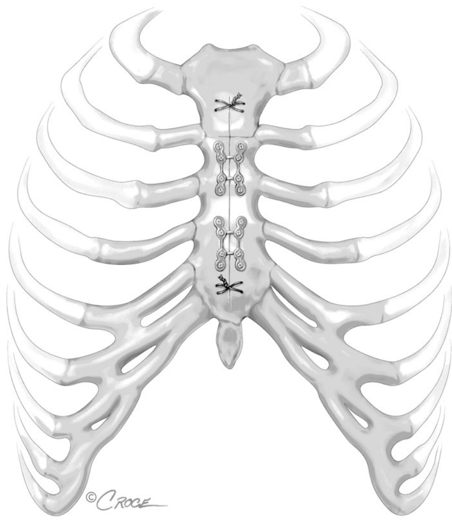


Figure 38: Wires threaded through the sternum after open chest surgery to hold it in place

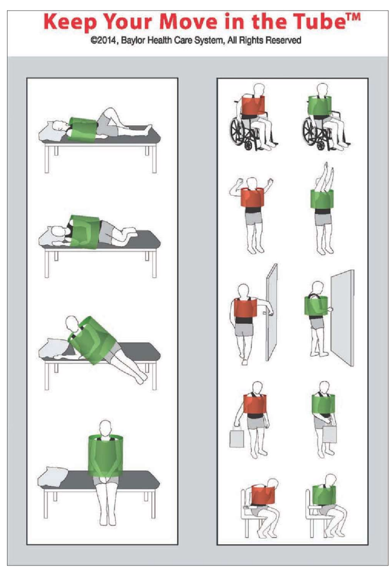



Figure 39: A visual representation of a new type of sternal precaution that looks to reduce the restrictions on patients

**Types of walkers and competitive products**

*Standard Walker*

Figure 40: Standard walkers
Sources: https://justwalkers.com/dual-release-adult-walker.html, https://www.healthproductsforyou.com/p-guardian-easy-care-folding-walker-with-5-inch-fixed-wheels.html

Figure 40 shows two standard walkers, one of which has two wheels in the front and one that has no wheels. The intended way the walker should be used is by holding the grips on the side and lifting the walker each time one takes a step.

*Platform Walker*

Figure 41: Platform walker
Source: https://www.4mdmedical.com/catalog/product/view/id/287410/

The features that distinguish the platform walker from standard walkers are the padded areas where users can strap in their forearms and the handles which they can grip with their hands, yielding more stability. The legs on the bottom of the walker can be removed and replaced with wheels (4MD Medical, 2018).

*The Eva Walker*

Figure 42: Eva Walker
Source: https://www.alimed.com/eva-support-walkers.html

Eva Walker was an alternative type of walker. This walker has 2 locking wheels in the back, and 2 non-locking wheels in the front, and similarly has an area for users to rest their forearms and handles to grip with their hands. This walker is much more expensive than other models, with a cost exceeding $1000 (AliMed, 2019).

*Three-Legged Walker*

Figure 43: A four-legged, two-wheeled walker and a three-legged, three-wheeled walker
Sources: https://www.homedepot.com/p/Drive-2-Button-Folding-Universal-Walker-with-5-in-Wheels-10253-1/204079814, https://www.karmanhealthcare.com/product/r-3600/

Three-legged walkers are a more modern type of walker and seem to be an improvement over the more traditional four-legged design. Mahoney, Euhardy, and Carnes (1992) conducted a study using “15 male and female frail elderly veterans (mean age, 82 years)” to determine whether a two-wheeled and four-legged walker or a three-legged and -wheeled walker was better. The subjects were asked to walk across “a 15-foot walkway and 60-foot obstacle course” three times (Mahoney et al. 1992). They walked across once without a walker, once with a four-legged, two-wheeled walker, and once with the three-legged walker, and the researchers took data and additionally asked the subjects which walker they personally preferred. The results were that on average, “stride length was 1.4 inches (3.6 cm) greater with the 3-wheeled walker than with the two-wheeled walker,” and on average, when the three-wheeled walker was used, the time taken to cross the 60-foot course was 16.0 seconds faster than when the two-wheeled walker was used, and the test subjects “subjectively preferred” the three-wheeled walker (Mahoney et al. 1992). The data taken in this study suggests that three-wheeled walkers provide a great advantage over two-wheeled ones.

*Four-Wheeled Walker*

Figure 44: Four-wheeled walker
Source: https://www.amazon.com/Drive-Medical-Rollator-Removable-Support/dp/B00NFJX0PU?th=1

Another alternative to the two and three-wheeled designs is the four-legged and four-wheeled walker design, shown in Figure 44. This design features handbrakes, as well as the ability to act as a seat. Finkel, Fernie, and Cleghorn (1997), however, deemed this type of walker “potentially dangerous” in reference to their ability to act as a seat, since the walkers were found to be prone to tipping over when the seat function was used.

**Competitive Products**

*Stationary force plate or scale*

Currently, at the Shirley Ryan AbilityLab, the force exerted by a patient onto a walker can be measured by placing a scale under the walker and observing the difference in the reading when the patient is putting force on the walker versus when they are not. This solution is limited, however, by the fact that the scale is stationary, meaning that the patient's force on the walker can only be measured while they are standing still, and cannot be measured while the patient is walking.

Figure 45: Walker with the PAMM2 attached
Source:
https://66.media.tumblr.com/0084bcc5ce16da0007dc131092dba28e/tumblr_inline_pf4m1owRwF1qc240l_500.png

*Personal Aid for Mobility and Health Monitoring, version 2 (PAMM2)*

This walker attachment, created by MIT student Steven Jens Jorgensen, incorporates force sensors in the handles of the walker, an "electronics box" on the front bar of the walker, and encoders on the wheels of the walker (Jorgensen, 2014). This product records a variety of data, such as the acceleration of the walker and the force exerted by a user in order to monitor patients with Parkinson's Disease. This product shows that force sensors can be integrated into the handlebars of a walker, but does not have its own display. It records data on an SD card that can be transferred to a computer, meaning that real-time data cannot be shown, which was a requirement of the client.

Figure 46: Smart walker with FlexiForce sensors
Source: https://www.tekscan.com/applications/smart-walker-using-flexiforce-sensors

*Smart Walker using FlexiForce sensors*
Flexiforce sensors are “ultra-thin,” flexible force sensors that researchers attached to the handles of a walker (Tekscan, 2014). In this context, the sensors were used to control the speed of motors attached to the wheels of the walker, but this suggests that the Flexiforce sensors could be viable for use in this project, as they were able to be attached to the handles of the walker and not intrude on the user’s ability to use the walker.

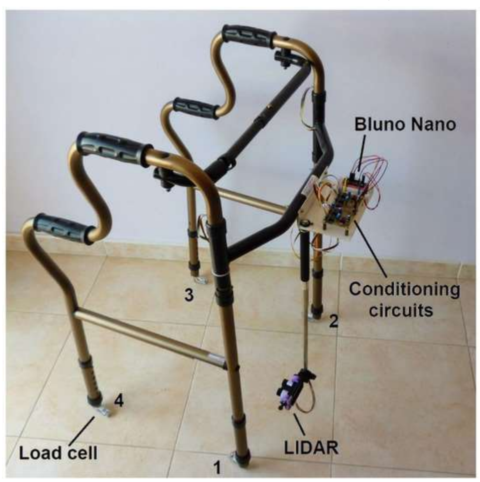



Figure 47: Walker with load cells
Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5855870/

*Walkers with load cells*
Another existing solution is to have load cells attached to the ends of the walker legs, pictured in Figure 47. The load cells measure the force exerted by the walker onto the floor, and when the weight of the walker by itself is known, the force exerted by the patient can be determined. The model in Figure 47 was created for a study that measured “force unbalance” on either side of a walker while in use, but it demonstrates that load

cells can be implemented into the design of a walker attachment that measures force in an unobtrusive way.

**Commercially available force sensors**

There are many different types of force sensors with various prices and measuring mechanisms. They can be generally classified into mechanical sensors and electrical sensors.


Figure 48: Spring scale
Source: https://www.amazon.com/Ohaus-8008-Pull-Spring-Scales/dp/B00CLX9IWA.

*Spring Scale*
One of the mechanical ways to measure the force is by using a spring. The spring becomes extended when a force is exerted on the hook, and as seen in Figure 48, there is a way to see how many pounds of force are being exerted. The issue with using this type of scale is that it can only measure a force that pulls on the hook and can move it downward and that the spring will stretch out over time due to repeated use, leading to inaccurate measurements.

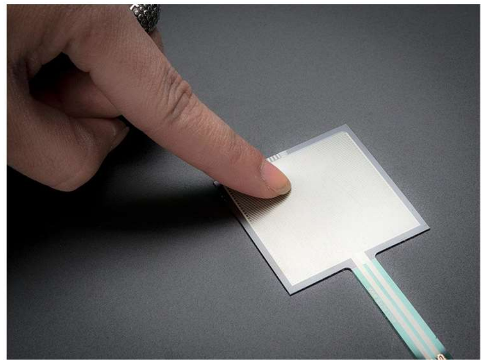
 

Figure 49: Resistive force sensors
Sources: https://www.alibaba.com/product-detail/thin-film-pressure-sensitive-resistor-force_60583453546.html, https://www.adafruit.com/product/1075?gclid=EAIaIQobChMI-9e-hb604QIViobACh07jgM-EAYYAyABEgK3KvD_BwE

*Resistive force sensors*
A resistive force sensor consists of a highly resistive flexible material placed between two metal grids. When load is applied, the metal grids become closer together, which lowers the effective resistance in the circuit. This resistance can be converted to a force value with a calibration curve.

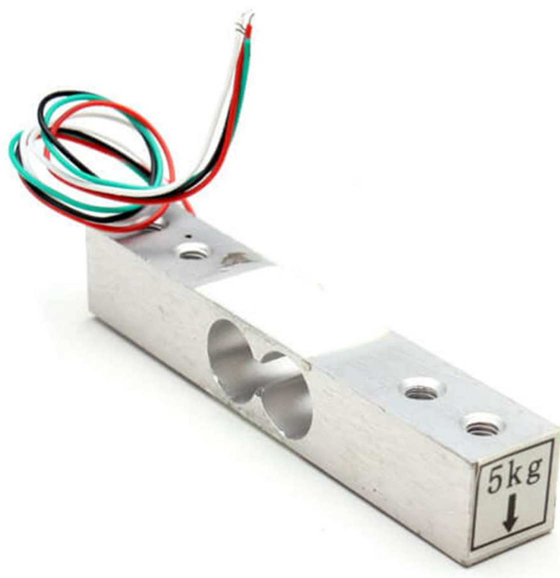



Figure 50: Load cell
Source: https://www.jsumo.com/load-cell-bar-0-5kg.

*Load Cells*
Load cells produce proportional output to the amount of load being applied. They typically measure the deflection of an object with several strain gauges. They are typically much more expensive than resistive force sensors.

**Conclusion**
Our background research gave many insights into potential designs for a final prototype, mostly in the area of how the force will be measured. Load cells and resistive force sensors both seem like viable options, and both have been used to measure the force on a walker in similar products. A remaining question, though, is how a real-time display can be incorporated into the design.

References

Sternal Precautions (2018). Retrieved from https://www.healthline.com/health/sternal-precautions.
J. M. Dias Pereira et al. "Combining distance and force measurements to monitor the usage of walker assistive devices" (2017). Retrieved from https://ieeexplore.ieee.org/document/7969673.
Range of different force sensors including torque sensors: Honeywell International Incorporated. Force Sensors. Retrieved from https://sensing.honeywell.com/sensors/force-sensors.
Adams, J; Lotshaw, A; Exum, E; Campbell, M; Spranger, C; Beveridge, J; Baker, S; McCray, S; Bilbrey, T; Shock, T; Lawrence, A; Hamman, B; Schussler, J. An alternative approach to prescribing sternal precautions after median sternotomy, "Keep Your Move in the Tube" (2016). Retrieved from https://www.semanticscholar.org/paper/An-alternative-approach-to-prescribing-sternal-Your-Adams-Lotshaw/0c0461ca53abf019d8263546c873751f01a155b8.
Mahoney, J; Euhardy, R; Carnes, M (1992). A comparison of a 2-wheeled walker and a 3-wheeled walker in a geriatric population. *Journal of the American Geriatrics Society*, 40(3), 208-212. Retrieved from https://onlinelibrary-wiley-com.turing.library.northwestern.edu/doi/full/10.1111/j.1532-5415.1992.tb02069.x.
Finkel, J; Fernie, G; Cleghorn, W (1997). A guideline for the design of a four-wheeled walker. *Assistive Technology*, 9(2). 116-129. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/10400435.1997.10132303.
Jorgensen, S.J. PAMM2 (Personal Aid for Mobility and Health Monitoring, version 2) (2014). Retrieved from http://handsonlearning.tumblr.com/.
Viegas, V.; Pereira, J.M.D.; Postolache, O.; Girão, P.S. "Monitoring Walker Assistive Devices: A Novel Approach Based on Load Cells and Optical Distance Measurements. Retrieved from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5855870/.

## Appendix K: Conversations with Prototyping Specialists

We met with prototyping specialists to discuss how to attach our design to a walker as well as materials that would be needed in our design. See Table 7 for more detailed information about the decisions made during our meetings as well as next steps.

Table 7: Discussions with prototyping specialists

| Date | Team Members Present | Prototyping Specialist's Name | Topic | Decision(s) Made | Next Steps |
|---|---|---|---|---|---|
| 5/17/2019 | Rossoneri | Scott Simpson | Recommendations for connecting design to the walker | Use a set of two screws to secure the design onto the handle of the walker | Purchase necessary materials and build our updated design |
| 5/21/2019 | Shane | Bob | Material selection for load cell bed | 3D printing is likely easiest. Speak with Beltran about higher quality print. | Email Beltran about pricing and materials. |
| 5/21/2019 | Shane | Beltran | 3D printing assembly with ABS. | Talk to RP lab TA during office hours, send STL of print files, meet for price quote. Print on Fortus printer | Meet with TA |

Note on 3D printing:

In order to begin the process of printing the load cell bed, our team first consulted with Professor Beltran, the director of the RP lab to discuss materials and an appropriate printer. Based on our discussion, we concluded that it would be best to print in ABS on the Fortus Stratasys printer. The final cad model was converted to an STL file type and emailed to the RP lab. And a quote was returned in the email. The lab TA then began the print in white ABS at 100% infill for maximum strength. When the print order was submitted an initial job processing time estimate was given. We expected the print to be completed in 5 days. This print, however, took 8 days which lead to delays in the prototype construction phase. This delay was due to the queue of 3D printing. Since similar delays are common in engineering projects, users should be aware of this issue when rebuilding our design.

## Appendix L: User Testing Report

### Purpose

The purpose of user testing was to show proof-of-concept mockups to Erin Walaszek, as she is both a client and a user, seeing as she is a physical therapist at the Shirley Ryan AbilityLab. Since our mockups were not completely functional and untested for weight limits, it would be completely unsafe to have the patients test them. As a result, we instead showed our client designs and explained them to gather her input on each one.

### Mockup Information

1. Force Sensing Handle

This mockup was full size, 3D printed, mockup of the force sensing handle (see Figure 51). The components were constructed of 3D printed Polylactic Acid (PLA) and m2x12 black oxide machine fasteners.

Figure 51: Force sensing handle

2. Load Cell Legs

The mockup is constructed of a walker leg, a length of wire, two zip-ties, and a piece of foam core (see Figure 52). Two pieces of foam core were cut to roughly the size of a type of load cell we have been researching to potentially be used in our final design. A hole was then cut in the middle of one piece so that it could be slid onto the leg, emulating how the leg would look in our theoretical final design, where the leg would be cut into two pieces and the load cell would be inserted between them. The wire was affixed to the foam core and then zip-tied to the leg to emulate the wired connection of the load cell and a way in which we might hold the wire down to avoid it getting tangled. The other piece of foam core was used to demonstrate an alternative yet similar mockup, one in which the load cell would be attached to the bottom of the leg through a modified end cap. These two mockups are referred to as the integrated leg design and the end cap design, respectively.

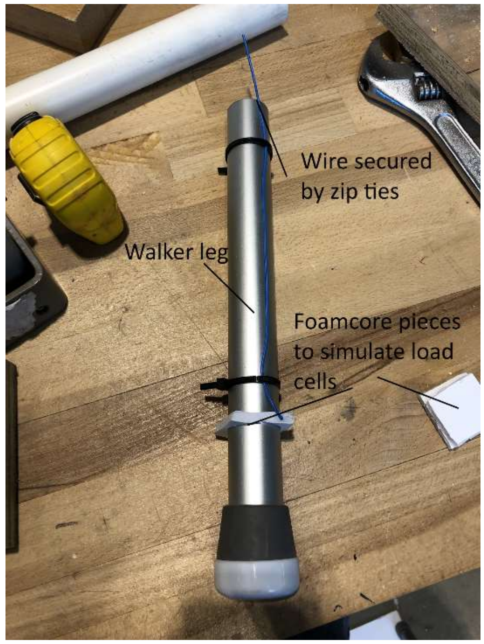


Figure 52: Load cell legs

3. Springy Handle

A wooden rod handle attached at both sides to a spring and polyvinyl chloride (PVC) tube contraption that compresses to a certain height when a certain force is applied. Being mechanical, this mockup does not require an external energy source, such as a battery, and is thus more environmentally and economically friendly. The mockup and interaction with it are shown in Figure 53 and 54.

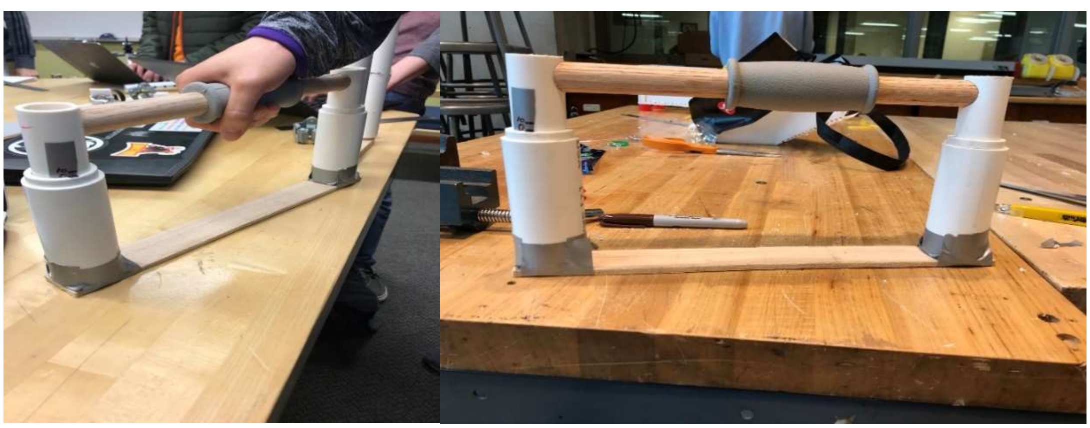


Figure 53: Spring handle

Figure 54: Applying high force upon the spring handle mockup

4. Bathroom Scale

The bathroom scale design consists of the force measuring device from a bathroom scale sandwiched in two pieces of glass or hard plastic. The legs of the walker would be sliced in half and the sandwiched scale would be inserted. In the mockup, we did not plan to test the measuring function of the design and instead, we focused on testing the feasibility of the structure of the design. The mockup was built by cutting a large piece of foam core into a U shaped plate with four holes on it. The holes were then aligned with the leg of the walkers and then the mockup scale was installed on the walker by inserting the legs through the holes. The users can walk with our design in the same way that they would do with a standard walker (see Figure 55).

Figure 55: The bathroom scale

**Methodology**

On May 6, 2019, team members Shane Dolan and Davis Miller went to the Shirley Ryan AbilityLab to meet with Ms. Walaszek from 2:00 PM to 4:00 PM. All four mockups were then attached to a provided walker. One by one, each mockup was explained, and feedback from Ms. Walaszek was recorded.

**Results**

The table below records the comments the client had for each of our mockups:

Table 8: Feedback from the client regarding each mockup

| Mockup | Liked | Disliked | Other comments |
|---|---|---|---|
| Force Sensing Handle | | Our client was worried that this mockup would not be able to withstand the full body of a patient if they were to fall. She noted that in the case of slip or fall, the patient would be applying a force much larger than 10 pounds to the walker. | Our client recommend that we redesign our handle with a max anticipated load case of 125 lbs per handle (total load across both handles = 125*2 = 250 lbs, or the max load rating of the walker) |
| Load Cell Legs | | Our client was worried about the structural integrity of the walker leg design. | The client advised we avoid changing the actual walker as much as possible because modifying it is quite risky. We also presented a slight spin-off of this design (placing load cells in caps in the ends of the feet), but the client noted that not all walkers use end caps and that this design was likely not feasible for walkers with wheels. |
| Springy Handle | | Our client didn't like how challenging it was to read the force gauge on our mechanical design. We explained that the only way to achieve a higher degree of precision would be to reduce the effective spring constant of our system. In turn, this would result in a larger deflection of the handles each | |

| | | | |
|---|---|---|---|
| | | time force was applied. This would make the walking experience very unstable. | |
| Bathroom Scale | | The largest issue that she found with this prototype was that it would not be able to measure force actively while the user was walking. She was also put off by the mobility restriction placed on the patient by the large device. | Due to the nature of this mockup and our method of attaching it, we presented it to the client as a device that would be permanently attached. She was comfortable with a permanent solution. |

**Analysis**

For the force sensing handle, our client raised concerns about the maximum force the handle is able to withstand. To address the issue, we will need to use stronger materials with load cells that can handle more force.

For the load cell legs, the client was worried about the structural integrity of the design. Generally, our client does not want us to modify the walkers too much.

The problem about the springy handle, there were safety concerns that the springiness will lead to poor stability for the users to use and the client did not like to read from a spring scale.

The issue with the bathroom scale design was that our client did not think the method could provide reliable readings. Also, the size of the device made the walker very clumsy to handle, which will cause inconveniences for the patients.

**Conclusion**

In conclusion, our client found flaws with each of our mockups, and she did not particularly like any of our mockups. Moreover, the user testing process was more 'user-feedback' and less testing as our mockups didn't lend themselves to physical testing. From user testing, we learned that there were many changes that would need to be made in the coming weeks in order to meet the demands of our client with a design that appropriately satisfied our project definition and mission statement.

**Limitations**

- The mockups we used are first generation mockups. The materials were generally cheap and not reliable enough for the final prototype. This might give our user false impressions about the structural integrity of our designs.
- We were not able to meet any patient and get feedback from them. Thus, we do not know how the experience would look like for patients to use our mockups.

## Appendix M: Failure Mode and Effect Analysis

In failure modes and effects analysis, we investigated possible risks and failures related to our design. We evaluated the severity and frequency of each failure and decided on actions to address each problem. The result is shown in Table 9 below.

Table 9: Failure modes and effect analysis

| Item: | Failure mode | Failure cause | Failure impact on component | Failure effect on system | Failure detection method | Severity* | Frequency* | Failure Score** | Action |
|---|---|---|---|---|---|---|---|---|---|
| Handle | Break | Stress | Prototype can no longer be used | Prototype is rendered unusable | Visual | 5 | 1 | 5 | Ensure that the handles can withstand the entire body weight of users |
| Load cell bed | Break | Stress from misuse | Prototype can no longer be used | Prototype is rendered unusable | Visual | 5 | 2 | 10 | Ensure that the part is durable enough to withstand the stress it will experience during use. |
| Load cell | Malfunction | Damage | Measurements cannot be taken | Prototype can still be used, but cannot take measurements | No measurements will be displayed (visual) | 5 | 1 | 5 | None |
| Arduino | Malfunction | Damage | Measurements cannot be read and converted | Prototype can still be used, but cannot take measurements | No measurements will be displayed (visual) | 5 | 1 | 5 | House the Arduino inside of a plastic case that will hold it snugly and not apply stress. |
| Display | Malfunction | Damage | Measurements cannot be read | Prototype can still be used, but cannot take measurements | No measurements will be displayed (visual) | 5 | 1 | 5 | House the display inside a plastic case that will protect its internals. |
| Battery | Malfunction, runs out of power | Damage | Power cannot be provided to the electronic components | Prototype can still be used, but cannot take measurements | No measurements will be displayed (visual) | 5 | 2 | 10 | Test battery life so that the client will know how often they must charge the battery. |
| Plastic electronic housings | Break | Stress | Electronic elements become exposed | Electronic elements become exposed. They cannot be wiped down, meaning the design cannot be cleaned and is now unusable. | Visual | 5 | 2 | 10 | Performance test various casing designs to make sure the design will be durable in case it is dropped. |

* Rated on a scale 1-5, with 5 being most severe/frequent and 1 being the least severe/frequent.

Severity Values (user/device)
1 = mild annoyance/visual but not functional defect
2 = really irritated/damaged part, still functional
3 = minor injury/part requires replacement
4 = serious injury/ device requires replacement

Frequency Values
1 = 1 in 10,000 uses
2 = 1 in 1,000 uses
3 = 1 in 100 uses
4 = 1 in 10 uses

** Severity Score multiplied by Frequency Score.

Conclusion: Though all of the parts of our design are extremely important to the operation of the prototype, to the point where if any one part fails, the entire design will fail, we think that the infrequency of these failures means that the design is good and does not require revisions to address issues discovered through this analysis.

## Appendix N: Instruction for Construction

### Introduction

Our prototype, the +ReinFORCEment, is an attachment for a walker that measures the force being put onto the walker by its user through the use of load cells. The information gathered by the load cells is then displayed on an LED display so that a physical therapist can monitor the force being put on the walker by a patient during a physical therapy session.

### Materials and tools

Table 10 lists the materials needed to construct the +ReinFORCEment

Table 10: Materials needed to construct our design

| Material | Specifications | Quantity |
|---|---|---|
| Aluminum sheet | 12” *12” * 0.25” | 1 |
| Bolt | M5 x 30mm w 20 mm shoulder | 8 |
| Washer | M5 | 16 |
| Hex nuts | M5 | 8 |
| Arduino nano | 328P | 1 |
| Load cell | Maximum weight 50kg | 2 |
| Breadboard | 30 * 12 pin | 1 |
| Wire | 2 ft | 1 |
| LCD display | 16x2 i2c | 1 |
| Load Cell Voltage Amplifier | HX711 Load Cell Voltage Amplifier | 1 |
| SD Card Module | TF SPI SD Card Module | 1 |
| Silicone Zip ties | | 4 |
| Heat Shrink Tubing | 2 ft | 1 |
| SD Card | 8GB Micro SD Card | 1 |
| Portable Battery Charger | 1” * 1” * 5” | 1 |
| Acrylic Sheet | 2 ft * 2 ft | 1 |

| | | |
|---|---|---|
| Battery | 2200 mAh | 1 |

The following tools are required to construct the prototype:

- ➢ Soldering iron
- ➢ Drill
- ➢ Sandpaper
- ➢ Exacto knife
- ➢ Wirestripper
- ➢ Wirecutter
- ➢ Water jet
- ➢ Mill
- ➢ Drill press
- ➢ Allen wrench
- ➢ Screwdriver
- ➢ File
- ➢ Laptop
- ➢ USB Cable
- ➢ Caliper
- ➢ 3d Printer
- ➢ Laser Cutter

**Instructions for Construction**

Part 1: Internal Electronics:

1. Solder the amplifier of the load cell (the green computer chip) onto a breadboard (see Figure 56 & 57), along with the Arduino nano board and the display, and plug the Arduino into a computer using the USB mini to USB cable. (see Appendix O: Circuit Design and Display Layout)

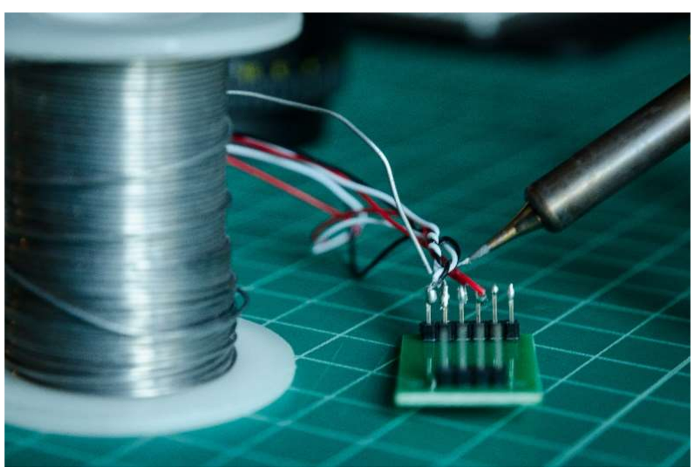


Figure 56: Soldering the electronics

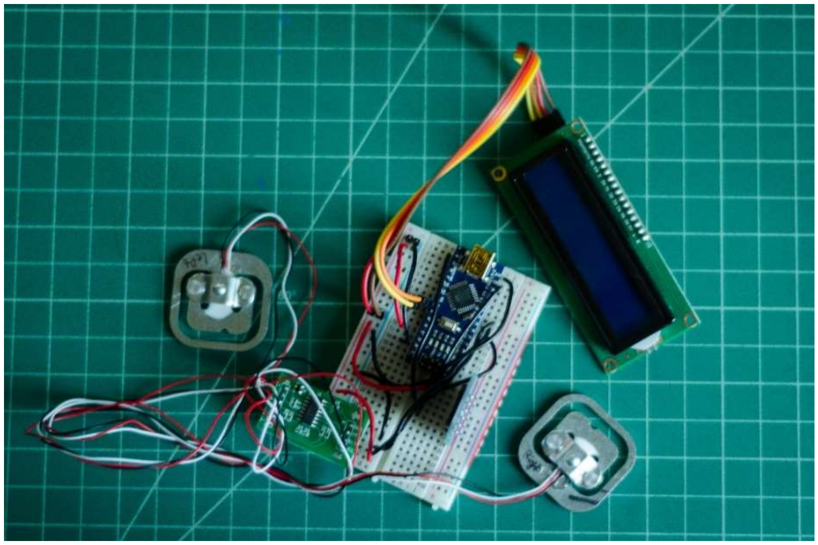


Figure 57: The completed circuit

2. Code the Arduino nano with the code that will make the display give the combined force reading, in pounds, registered by the two load cells (see Appendix P: Arduino Nano Code).

Part 2: Handles:

1. Using the AutoCAD model provided (see Appendix Q: AutoCAD Model for Aluminum Handles), use a waterjet to cut two pieces of aluminum into the shape of the handles (see Figure 58 & 59). Using a file, remove any scraps and sharp edges and slip the rubber grips over the handles.

Figure 58: Waterjetting the handle

Figure 59: The handle

Part 3: Plastic Components:

1. Using the Solidworks models titled “X” and “Y” (see Appendix R: Solidworks Model for the Load Cell Bed), use a Fortus 3D printer and ABS filaments to print two load cell beds and one electronics housing (see Figure 60).
2. After removing the prints from the machine, use a file or sandpaper to even out the rough edges and remove support struts.

Figure 60: The 3D printed load cell bed

Part 4: Prototype Assembly:

1. Place the load cells into the load cell beds, and place the breadboard and display into the appropriate places in the plastic casing.
2. Screw the handle into the load cell bed.
3. Drill a 30 mm into the walker using the drill press, and screw the handles into the walker. See Figure 61 for reference on where to drill the hole.

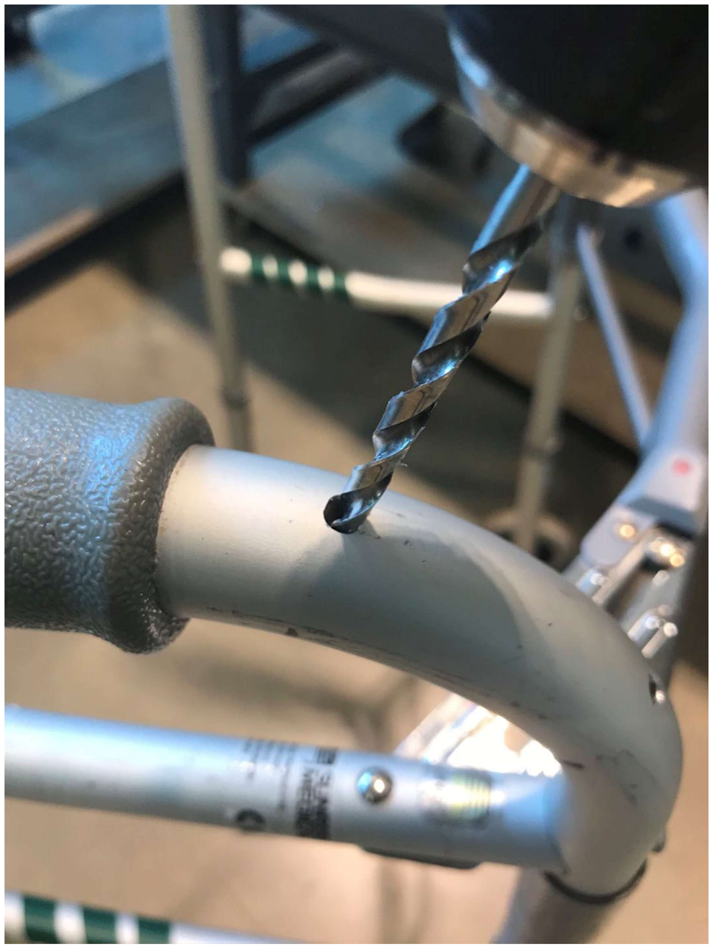


Figure 61: Drilling holes on the walker handle

4. Turn the device on using the switch on the electronics casing.

## Appendix O: Circuit Design and Display Layout

### I. Goal

Display calibrated force reading that compensates for the length of the lever arm. Display should also display left and right values.

### II. Components

1. ATmega 328p Rapid Prototyping Board
2. 16 x 2 i2c Multi-segment Display
3. Adafruit Clone HX711 Load Cell Amplifier
4. (2x) 50 kg Load Cell
5. Optional: HiLetgo TF Micro SD SPI Card Reader Module

### III. Design

Data read by the load each load cell will be processed and amplified by the HX711 board and be send to the Arduino. The Arduino will start a log of force data on the SD card. The Arduino will print out the force being applied on the LCD screen.

### III. Wiring Diagram

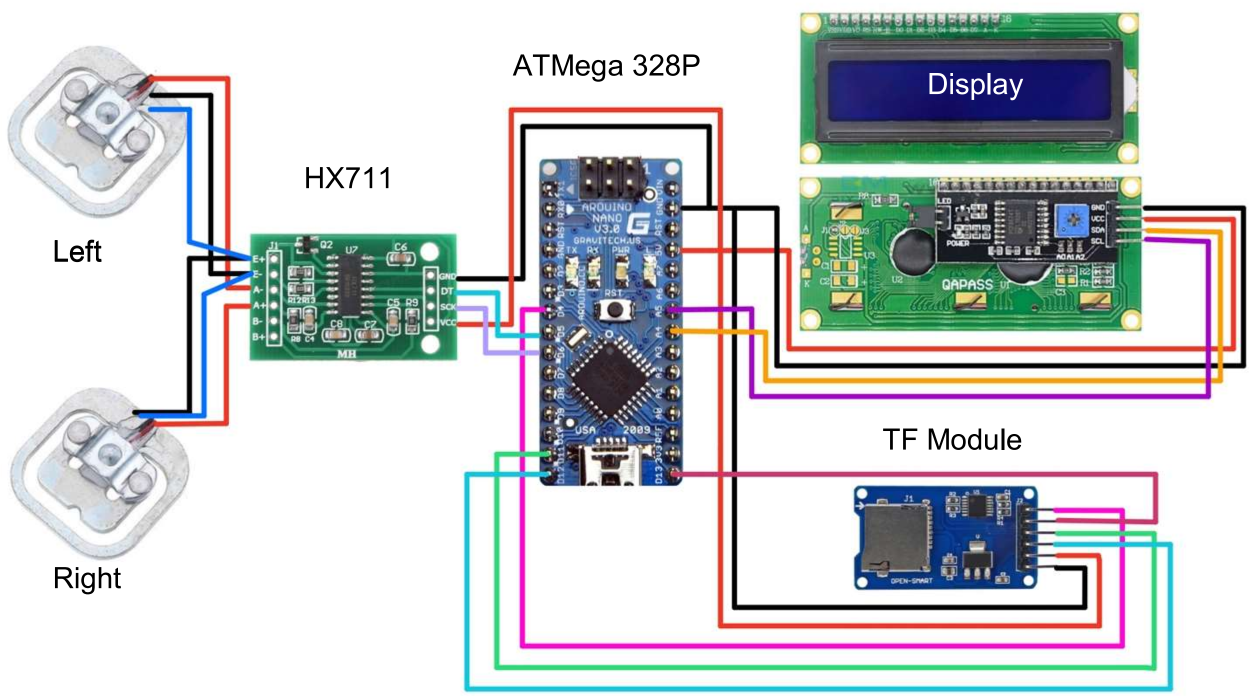



Figure 62: Circuit diagram

**IV. Method**

As a mechanical engineer with no previous experience using programmable integrated circuits, my ability to complete a project like this should mimic the ability of the client. Components are soldered or connected using simple wire jumpers. The battery is connected to the circuit with a standard micro-usb cable.

**V. Screen Layout**

To determine what information should be displayed on the screen, I looked at our project definition. At a minimum, the client needed the total force applied by both arms to the walker. Our screen is large enough to provide that data as well as the individual forces applied by right and left arms. To figure out a good layout, I made a an excel table that was the same size as our display and placed characters in the cells to simulate the screen. Here are a few options that we came up with:

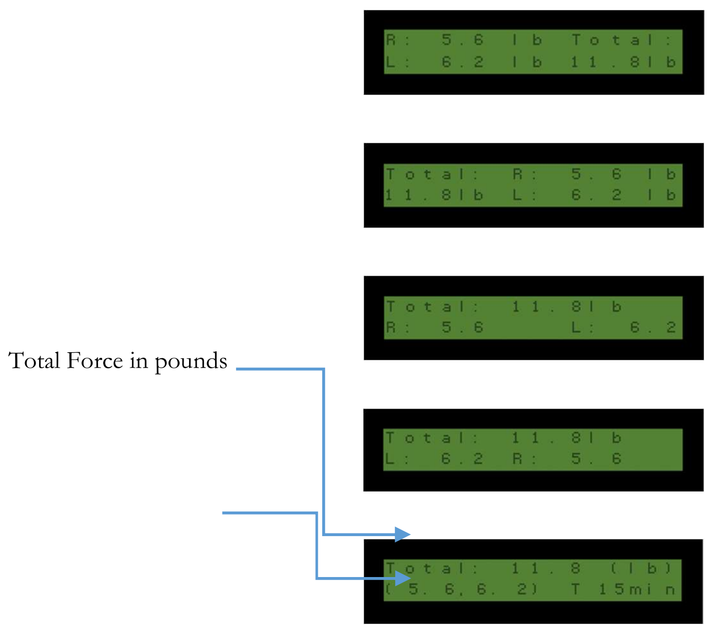



Figure 63: Screen layout options

I decided to go with the last display layout because it provided critical information in a simple, organized layout. On the top row, the total force is displayed to one decimal with the force unit in parenthesis. On the second row, the left and rights forces are displayed on the right as (left_force, right_force) with an implied unit from the previous row. On the right, the runtime of the circuit is displayed in minutes.

After some testing, I realize that it would not be possible to display both right and left forces with a single HX711 amplifier. The final lcd layout that we decided to use is as follows:

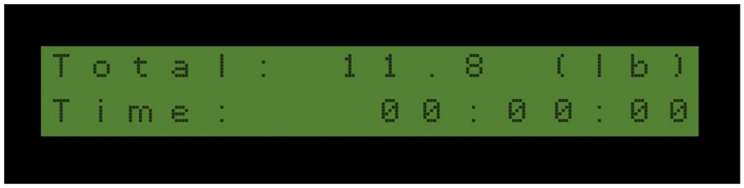



Figure 64: Final LCD screen layout

### VI. Tick-Rate and Data Logging

Due to fluctuations in sensor production and random variance in sensor outputs, it is important to set a tick rate that gives the user the best of two worlds. If the display update frequency updates is too fast, the display will become unusable as the characters presented on it will change faster than they can be read. On the other hand, if the display updates too infrequently, it's possible that important force maximums and minimums will be missed. While the tick rate for the display should be optimized for human viewing, the data stored on the SD card does not necessarily need to match that which is logged to the sd card. For the sake of maximum data fidelity, we will log data points to the SD card much more frequently than we log them to the LCD.

Data will be logged to comma delimited text file so that it can be easily be imported into an excel spreadsheet or MATLAB and analyzed. In our current setup a data point is recorded every 500 ms (every 0.5 seconds). This provides our physical therapists with 120 data points per minute.

As mentioned previously, data is logged in a comma delimited format. The format that we have chosen is:

relative_time,total_force

Each line of the data log uses 13 bytes. A 4 gigabyte micro SD card is capable of storing 4 x $10^9$ bytes of data.

$$4\ GB\ SD\ Card \times \frac{4 \times 10^9\ Bytes}{4\ GB\ SD\ Card} \times \frac{1\ Data\ Point}{13\ Bytes} \times \frac{500\ ms}{1\ Data\ Point} \times \frac{1\ s}{1000\ ms} \times \frac{1\ min}{3600\ s} = 42{,}723\ min$$

Our SD can store up to 42,735 minutes (~30 days) of continuous force data. If the client needs to store more data, they have the option to use a larger SD card.

## VI. Instructions for Importing and Analyzing Data

### Excel

To import data into excel, use “Data → From Text →” then select the data file on the SD card and create the appropriate columns using the comma delimiters. The data is now easily useable. Data is reported in 0.5 second increments.

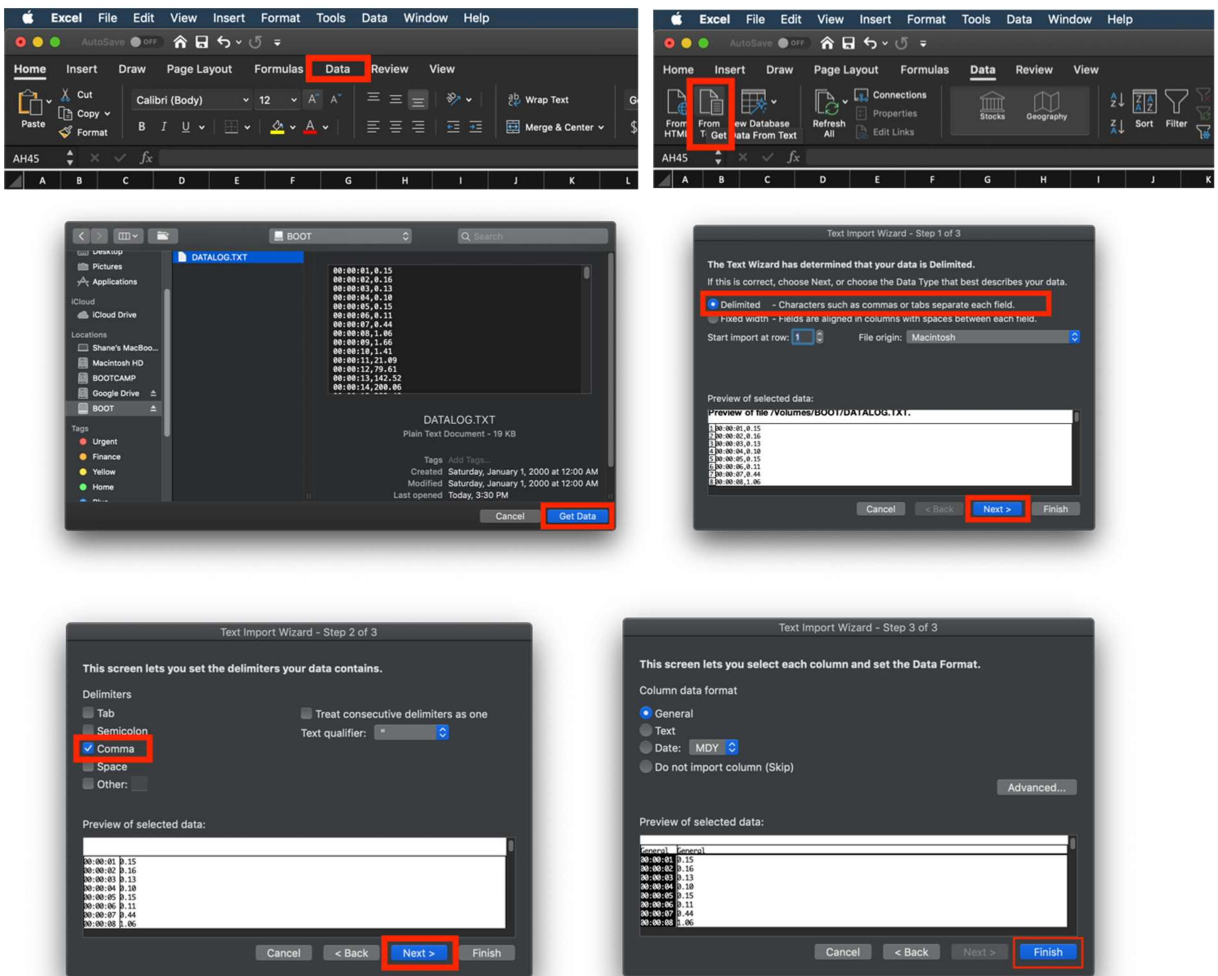



Figure 65: Importing data to excel

### MATLAB

For larger walker sessions, the use of a more powerful processing application is recommended as excel uses a lot of computational resources. MATLAB is recommended for data files over 1000 lines long. Importing data into MATLAB is just as easy as importing data into excel. To begin, open MATLAB and click “import data” under the home tab. After this, select the text file on the SD card. Select the comma delimiter to sort the file into rows and columns. After the data is imported, the script will run and plot the force data in a convenient graph. The following are the steps to import data:

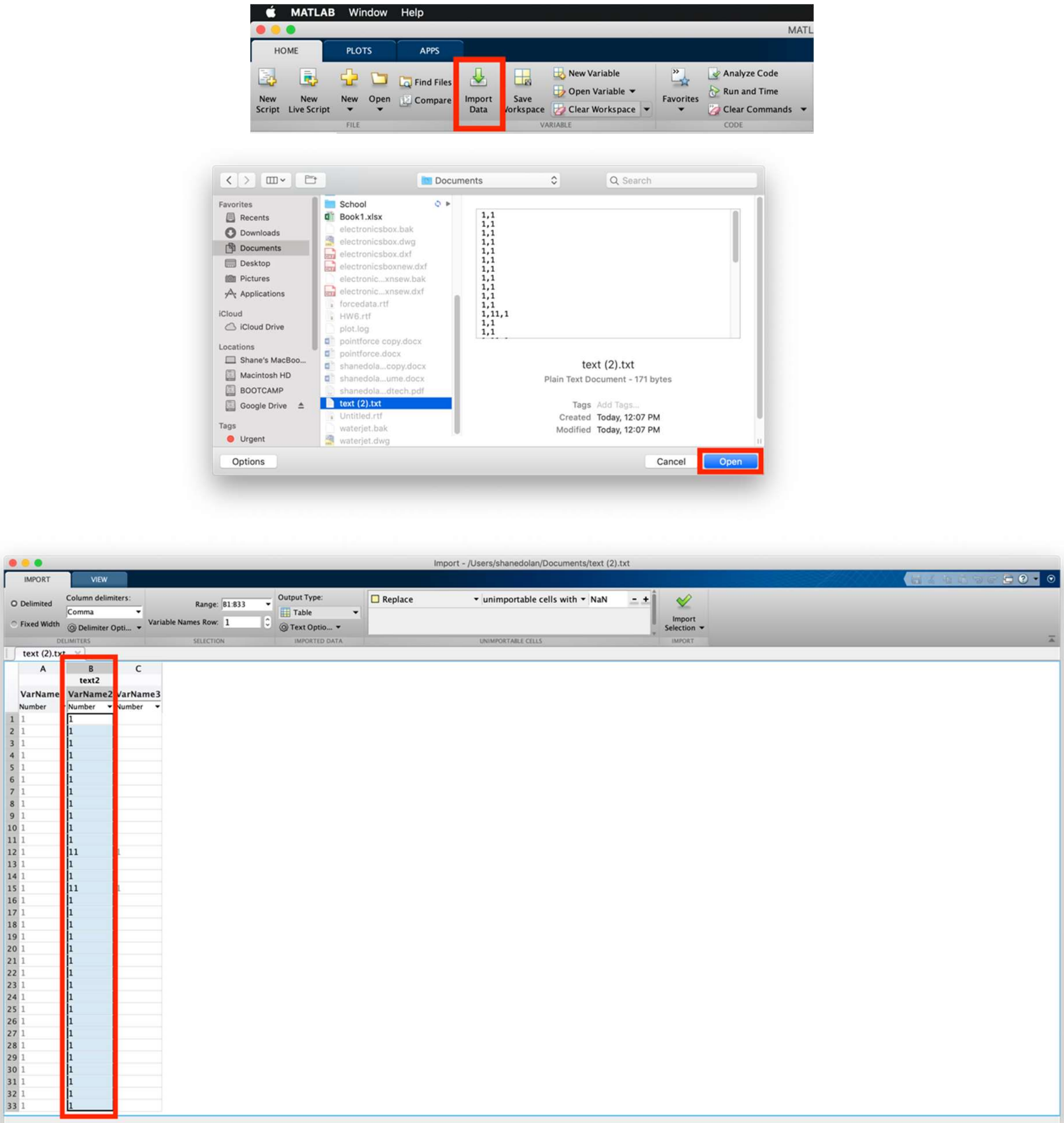



Figure 66: Importing data to MATLAB

### VI. MATLAB Code

```
figure(1);

clf(1);

new = table2array(DATALOG);

plot([1:size(DATALOG,1)],new,'-r','linewidth',4);
xlabel('Time (100s of ms');
ylabel('Force (lb)');
title('+reinFORCEment Force Data');
legend('Total Force Applied');
```

## Appendix P: Arduino Nano Code

Below is the code used to program the Arduino nano:

```
#include <HX711.h>              //Load HX711 Load Cell Library
#include <Wire.h>               //Load Wire Library
#include <LiquidCrystal_I2C.h>       //Load LCD Library
#include <SD.h>                 //Load SD card library
#include <SPI.h>             //Load SPI Library

// Set the LCD address to 0x27 for a 16 chars and 2 line display
LiquidCrystal_I2C lcd(0x27, 16, 2);

// VARIABLES:
float total_force;              // This will later be defined as the sum of the left and right
forces

// HX711 SETUP
const int LOADCELL_DOUT_PIN = 5;  // Arduino pin 6 connect to HX711 DOUT
const int LOADCELL_SCK_PIN = 6;   //  Arduino pin 5 connect to HX711 CLK
HX711 scale;

// DATA LOGGING
const int chipSelect = 4;         // Initialize the SD card reader using the chip select pin 4

// CLOCK SETUP
unsigned long previousTime = 0;
byte seconds ;
byte minutes ;
byte hours ;

void setup()
{
 // INITIALIZE THE SERIAL MONITOR FOR DEBUGGING
 Serial.begin(38400);
 while (!Serial) {
        ; // wait for serial port to connect. Needed for native USB port only
 }
 Serial.println("---> SERIAL MONITOR INITIATED");

 // INITIALIZE THE LCD
 lcd.begin();
 lcd.clear();
 Serial.println("---> LCD INITIATED");
```

```
  // DISPLAY BOOT SCREEN
  Serial.println("Booting Display");
  lcd.backlight();
  lcd.setCursor(4, 1);
  lcd.print("DTC 13.4");
  lcd.setCursor(1, 0);
  lcd.print("+reinFORCEment");
  delay(2000);
  lcd.clear();

  // INITIALIZE THE HX711 AMPLIPHIER
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  Serial.println("---> HX711 AMPLIPHIER INITIATED");

  // LOAD CELL CALIBRATION
  //Before Calibration
  Serial.println("---> BEGINNING LOAD CELL CALIBRATION");
  lcd.setCursor(0, 0);
  lcd.print("! CALIBRATION  !");
  lcd.setCursor(0, 1);
  lcd.print("  DO NOT TOUCH  ");
  delay(3000);
  Serial.println(scale.get_units(5), 1);          // print the average of 5 readings from the
ADC minus tare weight (not set) divided
  Serial.println("---> APPLYING CALIBRATION FACTOR");
  scale.set_scale(2000.f);                // this value is obtained by calibrating the scale with
known weights; see the README for details
  scale.tare();                           // reset the scale to 0
  //Calibration Complete
  Serial.println("---> CALIBRATION COMPLETE");
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("   Calibration  ");
  lcd.setCursor(0, 1);
  lcd.print("     Complete    ");
  delay(2000);
  lcd.clear();


  // INITIALIZE SD CARD READER

Serial.print("Initializing SD card...");

  // see if the card is present and can be initialized:
  if (!SD.begin(chipSelect)) {
```

```
        Serial.println("Card failed, or not present");
        // don't do anything more:
        while (1);
  }
  Serial.println("card initialized.");

  // INITIALIZE LCD INTERFACE
  Serial.println("---> LCD INTERFACE INITIATED");
  lcd.setCursor(0, 0);
  lcd.print("Total:");
  lcd.setCursor(12, 0);
  lcd.print("(lb)");
  lcd.setCursor(0, 1);
  //Time Row Formatting
  lcd.setCursor(0, 1);
  lcd.print("Time: ");
}


void loop()
{
  //  MAKE DATA STRING
  String dataString = "";
  total_force = -1*scale.get_units(5),5;
  if (total_force<=0) {
        total_force= 0.0;
  }
  dataString += total_force;


  // WRITE TO SD CARD
  File dataFile = SD.open("datalog.txt", FILE_WRITE);

if (millis() >= (previousTime))
  {
        previousTime = previousTime + 500;  // use 100000 for uS
        seconds = seconds +1;
        if (seconds == 60)
        {
        seconds = 0;
        minutes = minutes +1;
        }
        if (minutes == 60)
        {
        minutes = 0;
        hours = hours +1;
```

```
}
if (hours == 13)
{
hours = 1;
}
lcd.setCursor(8,1);
if (hours <= 9){
Serial.print ("0");
Serial.print (hours, DEC);
lcd.print("0");
lcd.print(hours, DEC);
dataFile.print("0");
dataFile.print(hours, DEC);
}
else {
Serial.print (hours, DEC);
lcd.print(hours, DEC);
dataFile.print(hours, DEC);
}
Serial.print (":");
lcd.print(":");
dataFile.print(":");

if (minutes <= 9){
Serial.print ("0");
Serial.print (minutes, DEC);
lcd.print ("0");
lcd.print(minutes, DEC);
dataFile.print("0");
dataFile.print(minutes, DEC);
}
else {
Serial.print (minutes, DEC);
lcd.print(minutes, DEC);
dataFile.print(minutes, DEC);
}
Serial.print (":");
lcd.print(":");
dataFile.print(":");

if (seconds <= 9) {
Serial.print ("0");
Serial.print(seconds, DEC);
lcd.print ("0");
lcd.print(seconds, DEC);
dataFile.print("0");
```

```
        dataFile.print(seconds, DEC);
        }
        else {
        Serial.print(seconds, DEC);
        lcd.print(seconds, DEC);
        dataFile.print(seconds, DEC);
        }
}

 if (dataFile) {
        dataFile.print(",");
        dataFile.println(dataString);
        dataFile.close();
        Serial.print(",");
        Serial.println(dataString);
 }else {
        Serial.print(",");
        Serial.println(dataString);
        Serial.println("error opening datalog.txt");
 }



 lcd.setCursor(6,0);
 lcd.print("      ");
 lcd.setCursor(7,0);
 dataString.remove(5,10);
 lcd.print(dataString);
 delay(500);
}
```

## Appendix Q: AutoCAD Model for Aluminum Handles

Figure 67 shows the AutoCAD Model for the aluminum handles and Figure 68 shows the dimension of each component.

Figure 67: AutoCAD model for the handle

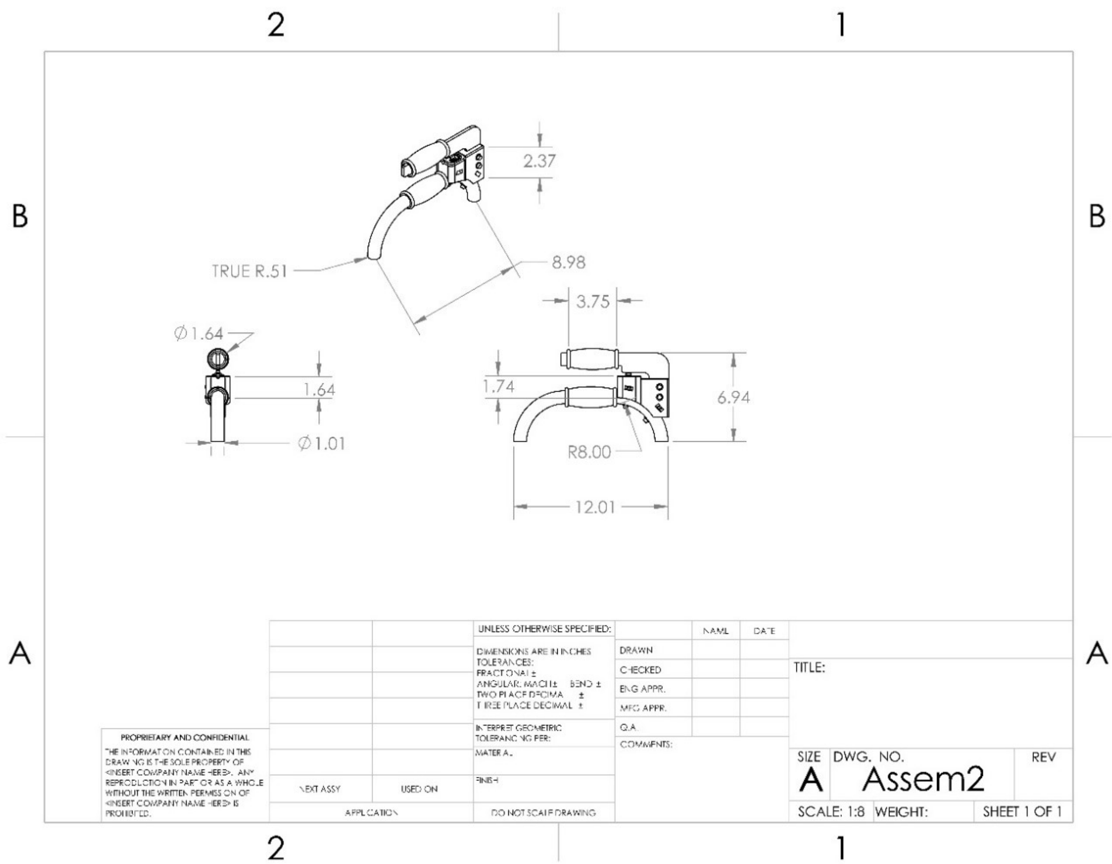



Figure 68: Dimensioned AutoCAD model for the handle

## **Appendix R: Solidworks Model for the Load Cell Bed**

Figure 69 shows the AutoCAD Model for the aluminum handles and Figure 70 shows the dimension of each component.

Figure 69: Solidworks model for the load cell bed

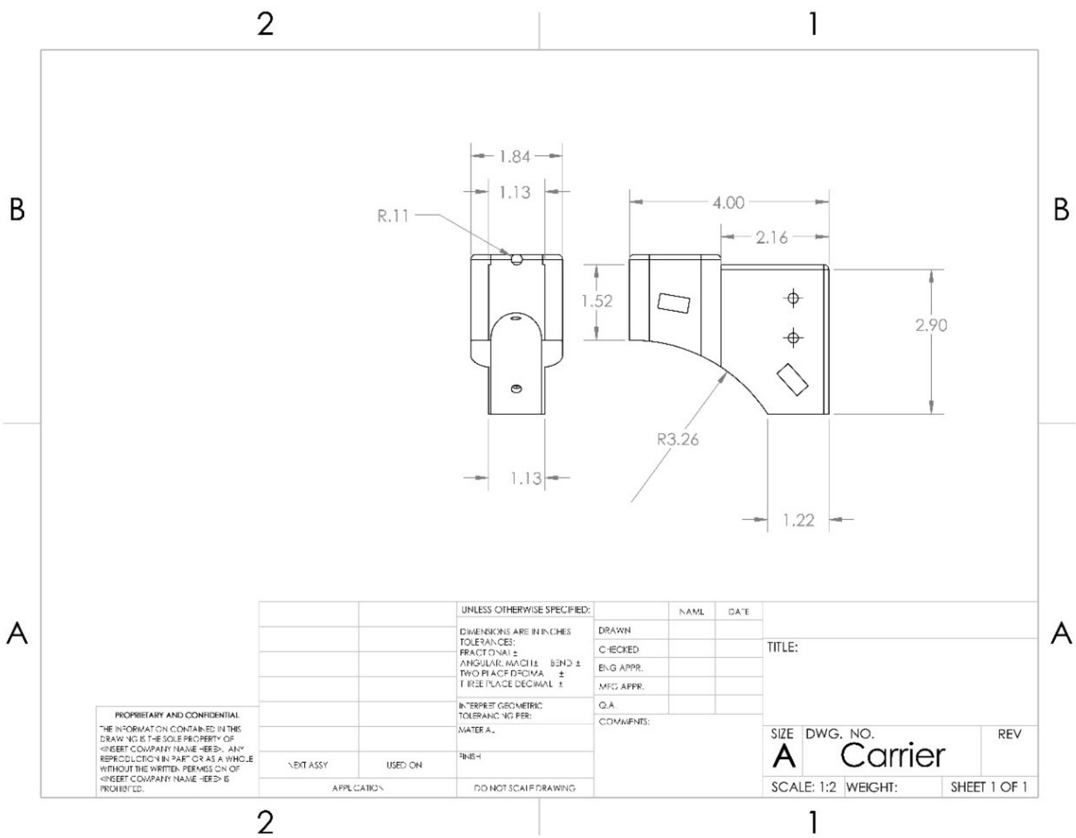



Figure 70: Dimensioned Solidworks model for the load cell bed

## Appendix S: Bill of Materials

Table 11 lists all the materials that we would like to order for our final prototype

Table 11: Bill of materials

| Item | Description | Source | Part # | Qty | Unit cost | Total Cost |
|---|---|---|---|---|---|---|
| CHENBO Digital Load Cell | A set of four load cell that weighs up to 200 kg of force. | Amazon | HX-2071 | 1 | $9.50 | $9.50 |
| Arduino Nano | A small, complete, and breadboard-friendly board. | Amazon | | 1 | $13.99 | $13.99 |
| LCD 16x2 White on Blue Display | 24 mm x 96 mm LCD Display. | Amazon | | 1 | $9.99 | $9.99 |
| MicroSD Card Adapter | Micro SD card reader module for reading and writing through the file system and the SPI interface driver. | Amazon | | 1 | $6.99 | $6.99 |
| | | | | | Total | $ 40.47 |

Table 12 lists all the materials that we used from the shop.

Table 12: Shop materials used

| Material | Specifications | Quantity |
|---|---|---|
| Aluminum sheet | 12” *12” * 0.25” | 1 |
| Bolt | M5 x 30mm w 20 mm shoulder | 8 |
| Washer | M5 | 16 |
| Hex nuts | M5 | 8 |
| Breadboard | 30 * 12 pin | 1 |
| Wire | 2 ft | 1 |
| Silicone Zip ties | | 4 |

| | | |
|---|---|---|
| Heat Shrink Tubing | 2 ft | 1 |
| SD Card | 8GB Micro SD Card | 1 |
| Portable Battery Charger | 1” * 1” * 5” | 1 |
| Acrylic Sheet | 2 ft * 2 ft | 1 |
| Battery | 2200 mAh | 1 |