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Finite Element Analysis for Improved Crutches Design

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***Abstract* -**
Crutches are a globally known aid for the walking impaired and have needed improvement. Users who require permanent walking assistance or those who are temporarily injured have voiced complaints about the discomfort endured after consistent use. Not only is satisfaction inadequate with existing designs but the ability to use crutches on different terrains has also been an issue. Crutches are a tool that requires modification in order to better suit the needs of all users. The areas of improvement are sectioned into comfortability for users, versatility in design, and widespread applicability on various terrains.

This project intends to modify the common axillary crutch to a more versatile design. When analyzing the existing model, noticeable issues included discomfort and large amounts of stress in the wrists and armpits of users. In addition to aiding the user in motion, the objective of the proposed crutch is to address those issues and fold to serve as a leg rest. This allows the user to elevate their legs at different heights when sitting. Different models of crutches are designed using SolidWorks with general design constraints. A final model is then designed, tested and manufactured. Both the prototype and existing axillary crutch are tested under cyclic loading conditions and a friction coefficient measurement apparatus. The theoretical and measured results are gathered and used to evaluate success for the new design. The strength of the adapters is tested by using the Instron machine, a pressure is applied to the top of the adapter until failure or 2000 lbs. The pressure sensor is designed to slide under the foam padding on the handle of the crutch to allow an accurate measurement of the pressure applied to it. The Arduino pressure system can accurately measure pressure readings.

***Keywords*:** crutch, design, FEA, friction coefficient, pressure sensor

1. Introduction

A critical issue noticed when researching crutches were the health problems that any type of user can develop over time, such as brachial plexus compressive neuropathy. This rather rare condition, more commonly known as crutch palsy, occurs when the radial nerve is compressed from improper use of axillary crutches. The radial nerve extends down the arm and joins much of the forearm, wrist, and fingers together. A specific case study conducted by researchers at Boston University's School of Medicine witnessed a man using axillary crutches for just three weeks before experiencing numbness in his fingers and wrists [1]. He was immediately advised to stop using the axillary crutches and began partaking in both physical and occupational therapy to initiate the healing process. Because the modified design is improving upon the axillary-style crutch, this condition was considered to lessen the chance of this diagnosis from happening.

Leading designs include axillary crutches which are the most common design. A large portion of the weight is distributed underneath the armpits and in the wrists. The elbow crutch, which is also referred to as the forearm crutch shifts the weight distribution to the upper forearms. Another crutch uses the triceps as a form of stabilization and distribution of force. The elbow crutches' and triceps crutches' primary focus reduces the amount of force resulting in the hands. Research has shown when someone uses a crutch in motion, they support 1.1 to 3.4 times their own body weight with their hands [2]. 1

Even though some crutch designs reduce the amount of stress applied to the body and the possibility of nerve damage, there are other problems not addressed. Two problems users have been irritation and energy expenditure. Studies have shown that crutches require two times the amount of energy to walk with [2]. Irritation is common around the armpits due to consistent contact with the armpit pad. This rubbing has caused acne to form [2].

The new crutches utilize a spring at the leg of the crutch. This has shown a reduction in the ground reaction force by 1326% which in turn reduces the force acting upon the rest of the body [3]. The spring not only decreases the force applied to the body but also uses the stored energy to increase stride length and reduce the energy needed to walk with crutches [3]. This would overall improve comfort and allow for longer use without breaks.

2. Design and FEA Analysis

The design has several key attributes that distance itself from its predecessor. The most notable design variation is the two sets of hinges in the design. One set lies between the armpit pad and the handle and the other where the two tubes of aluminum conform toward the single leg as shown in Figure 1. The hinges allow for the crutch to be collapsible for easy storage and for the crutch to turn into a footrest. A secondary feature in the design is the spring inside the leg of the crutch. The spring aims to dampen the force the user puts on the crutches which in return they would feel in their armpits and wrists. The armpit pad was made out of memory foam to make it more comfortable on the user. This decreased the associated pain in the armpit substantially. Not displayed in the SolidWorks model is a pressure sensor that is installed in the handle of the crutch. The pressure sensor allows for the user or medical professional to view the patient's dependency on the crutches.

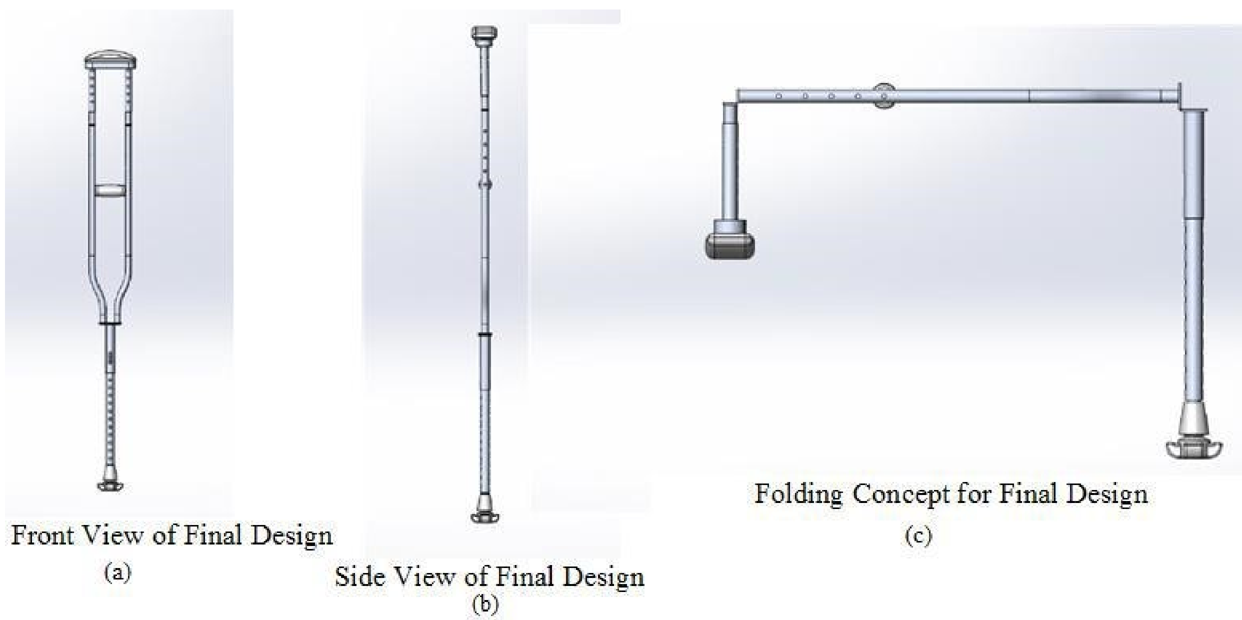

Fig. 1: shows the different views of the Crutch, (a) Front view, (b) side view, (c) folding concept

FEA simulations were done for the final design of the crutch as shown in figure 2 and 3. When trying to complete the FEA on this final design many problems occurred which decreased the chances of the results being accurate. The major difficulty was trying to get the FEA to not fail. This task was made difficult due to the various curvatures throughout the system, the multitude of individual parts, and the connections between them. This difficulty also increases the length of time the simulation took to complete. The average run time for these simulations on the final design were around six hours. To decrease the chances of the simulation failing the joints were simplified and a curvature-based mesh was used to increase the chances of success. Through these methods the FEA simulation was able to run at all the specified forces.

In the designs containing springs, an equivalent spring force was estimated. To calculate this spring force, the proper spring had to be specified. With a desired spring constant of 4.5 *kN/m*, or 25.7 *lb/in*, a spring from Lee Spring Manufacturer was found and reversedesigned with. Below are the calculations and equations used to determine the theoretical spring force that the spring will produce (which should equal the "Load at Solid Length" value provided.) the overall displacement desired would be from its free length to its solid length, which was calculated as 2.197 *in*. The final spring force resulted as 56.46 *lbf* which is in an acceptable range from the provided load at solid length of 55.15 *lb*. Three standard materials were selected to use throughout simulation. By standardizing the materials, the difference in results would mostly be influenced by the design of the crutch only. SolidWorks did not possess some properties necessary for simulation nor the materials themselves, so properties such as Poisson's ratio, elastic modulus, tensile strength, and yield strength were determined through searching published data. [4] [5] [6] In *Table 1.*, the materials and properties are recorded.

These values were used to generate custom materials in SolidWorks for the simulations. The armpit pad will be formed out of polyurethane foam, the frame is made from 6061-T6 Aluminum (SS), and the feet will be made with butyl rubber.

Table 1. Material Properties

Material	Elastic Modulus (psi)	Poisson's Ratio	Mass Density (lb/in^3)	Tensile Strength (psi)	Yield Strength (psi)
Butyl Rubber	217.55	0.45	3.2875e-2	1087.78	362.6
6061-T6 (SS)	1.007e7	0.33	9.75437e-2	44961.69	39885.37
Polyurethane Foam (Flexible)	3872.5	0.3	2.31215e-3	114.58	-

The butyl rubber originally had a larger Poisson's ratio of 0.72, however for an undetermined reason SolidWorks would not allow the simulation to run if Poisson's ratio was above 0.49. To correct this, Poisson's ratio was changed to 0.45 for all designs to remain consistent. While researching properties for polyurethane foam, an acceptable value for yield strength could not be concluded.

The group selected loads for the crutch based off estimated weights of users. The loads were kept constant throughout the simulations. A factor of safety of 1.5 was incorporated to determine the maximum amount of weight that the crutches will aim to support. Table 2. displays the weight of the user and the resulting force on the crutch for that weight. The loads were drawn in the "-y" direction which causes the magnitude to equal the load. In these simulations it is assumed there is no force acting upon the design in the horizontal direction. The values gathered for these loads will help generate a trend line which can be applied for loads not specifically simulated. To gather a widespread range of data, the loads placed on the crutch are 75, 100, 125, 150 lb. A 150 lb load on one crutch indicates that the user weighs about 300 lbs and their weight would be distributed evenly between the two crutches. The maximum load of 300 lbs was multiplied by the factor of safety of 1.5 to get 450 lbs, which is why the final load is 225 lbs. The results simulated from this load will guide the design of the crutch. Two types of simulations were performed. The first had the load applied directly to the armpit pad, depicting a situation where the user is standing at rest. The second type of simulation applied the load directly to the handles on the crutch, resembling a scenario where the user is at a midpoint in their gait with crutches, in which both feet are not in contact with the ground.

Table 2. Loading Conditions

Weight of User (lbm)	Load per Crutch (lbf)	Magnitude (lbf)
150	-75	75
200	-100	100
250	-125	125
300	-150	150
450	-225	225

The meshing is examined more closely when the results are produced to determine which values are most successful as well as accurate. Tables 3 shows the list the maximum von Mises stress and maximum strain in each design under different predefined loads. Included in the charts are the displacement of the model under each load as well as the spring force if the design included a spring. The von Mises value is used to predict when a given material will yield. If the maximum von Mises stress exceeds the yield strength for a specified material then that part of the model will most likely fail.

Table 3. Armpit Pad Analysis

Load (lbs)	Max. von Mises (psi)	Displacement (in)	Max. Strain (in/in)	Spring Force [if applicable] (lbf)
75	2.28E+05	1.67E-03	3.85E-02	56.46
100	2.30E+05	2.93E-04	5.13E-02	56.46
125	2.32E+05	3.66E-04	6.41E-02	56.46
150	2.34E+05	4.38E-04	7.70E-02	56.46
225	2.39E+05	6.53E-04	1.15E-01	56.46

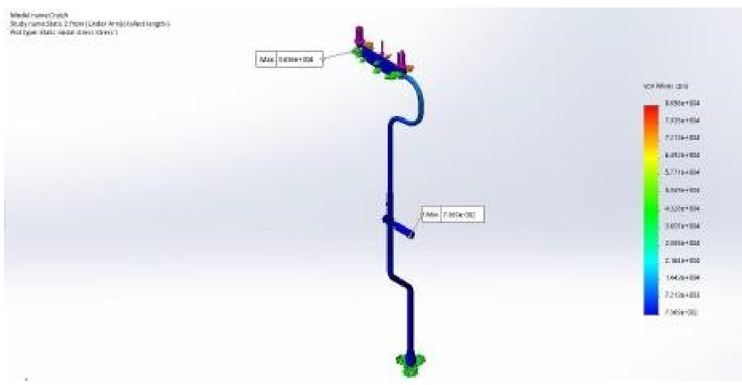

Fig. 2: Von Mises Plot, 225 lbs Applied to Armpit Pad

While making the SolidWorks models and running simulations, numerous problems occurred that slowed efforts to obtain accurate results. A major issue was the lack of usable SolidWorks materials and their properties. SolidWorks has a diverse database, yet it did not include two of the three materials that were desired for the designs. Another set of problems occurred during the execution of the simulations. Meshing the designs proved difficult as well as locating appropriate points of contact sets.

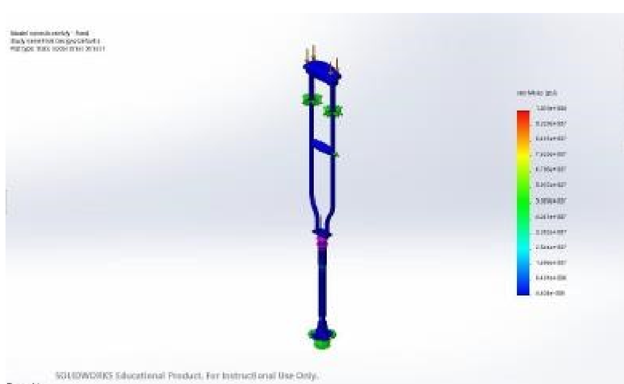

Fig. 3. FEA for the Final Design

3. Manufacturing and Testing

Different sized aluminium tubes with varying inner and outer diameters, along with a 2 in. x 2 in. x 4 in rubber block, single- and double-sided push pins, six hinges, and two springs were used. The following tools and pieces of equipment were used to manufacture the needed parts:

- Pipe Cutter: A pipe cutter was used to cut all of the aluminium stock to the right size.

Bandsaw: A band saw was used to cut and shape the rubber into a foot.

- Lathe: A lathe was used to turn down some of the aluminium stock so that it will fit inside another tube. Mill: A mill was used to drill holes into the piping for the snaps and screws.
- Pipe Bender: A pipe bender was used to bend some of tubes into the desired shape.
- Drill Press: A drill press was used to open up holes in the adapters and rubber block.
- 3D Printer: A 3D printer was used to print adapters for the hinges on the crutches.

The rubber used for the feet was originally shipped as a 2 in. x 2 in. x 4 in. block which needed to be cut to match the design. The bandsaw cut the block into two 2 in. x 2 in. x 2 in. cubes and the following process was repeated for both. The drill press created a small hole measuring 0.75 in. deep into the rubber block. A slightly larger drill bit was then drilled, and the hole diameter was incrementally increased up to a 0.5625 in. sized hole for the aluminium tubing to be press fit into the rubber block. Because a press fit is not a strong enough connection between the aluminium tube and the rubber foot, Loctite glue is used when the design is complete for a more secure fit. The general goal for the foot is to remove as much excess material as possible to reduce the weight but not too much so that the structural integrity is compromised upon use. The bandsaw was again used to create a 45° angle on all four sides of the foot. One size of aluminium tubing was purchased in two sets of 7 ft. The other three sizes were purchased in lengths of 3 ft. each. A pipe cutter was used to cut estimates of each tube. It was important to order lengths slightly longer than necessary because the cuts provided on the stock pieces were rough and uneven. Because of this, all tubes were placed in the lathe to create a flat, clean edge that could be dimensioned from when measuring hole locations and the overall length of each tube. The tubes were then moved to the mill where holes for the push pins could be drilled. This was a very important step because any slight variation in the distance between the holes and the ends of the tubes could disrupt the entire design. A 0.25 in. drill bit was used to drill all of the holes for the different height variations. Walking is a term in manufacturing used to describe the drill moving slightly after use and can result in the holes not lining up.

A Center drill was used to prevent this. After the holes for the different heights were completed, a 0.328 in. drill was used to drill the holes to line up with the adapters. Once all of the holes were drilled into each aluminium tube, they were then placed back into the lathe to more precisely dimension the length of the tube to match the blueprint's specifications. Some tubes slide into others, so it is important to have a clean fit between them. Because the inner diameter of one set of tubes was equivalent to the outer diameter of another set at 0.75 in., the 0.75 in. outer diameter tubes needed to be turned down to provide an uninterrupted fit as shown in figure 4.

Fig. 4: Prototype

3.1. Testing

A method for determining the friction coefficient of the rubber foot was deemed necessary when planning the prototype. The use of the rubber block selected needed to be supported with the evidence that it is both practical and durable. One of the hinges ordered was screwed into two planks of wood. Several different material surfaces were tested including wood, tile, linoleum, three different types of carpet, and an asphalt substitute. These were the agreed surfaces that the crutches would most likely be used on. Three nails were placed in a line across the middle of the top plank so they could rest in place while the rubber foot was placed on top of it. The top plank was lifted until the rubber foot either began to slide or tipped from its own weight. At that point of movement, the angle of the plank when lifted was taken from a Smart Tool Digital Angle Finder attached to the apparatus, which was recorded. Five tests for each material were taken place, and the average of the angles was used to calculate the coefficient of frictions. The coefficient of friction was calculated using the equation $F=\arctan(\theta)$, where θ is the angle measured from the Smart Tool Digital Angle Finder. These tests were run for the current foot design and the new foot design.

Table 4. Coefficient of Friction of New Foot Design

Test Run	Material	Total Max Angle (deg)	Mass of Foot (g)	Tipped or Slipped	Coefficient of Friction
1-5 Average	Wood	28.16	83.3	Tipped	0.53699
6-10 Average	Tile	26.94	83.3	Tipped	0.50979
11-15 Average	Linoleum	28.36	83.3	Tipped	0.54151
16-20 Average	Short Carpet	26.72	83.3	Tipped	0.50495
21-25 Average	Medium Carpet	23.08	83.3	Tipped	0.42739
26-30 Average	Long Carpet	13.36	83.3	Tipped	0.23816
31-35 Average	Asphalt	26.72	83.3	Tipped	0.50495

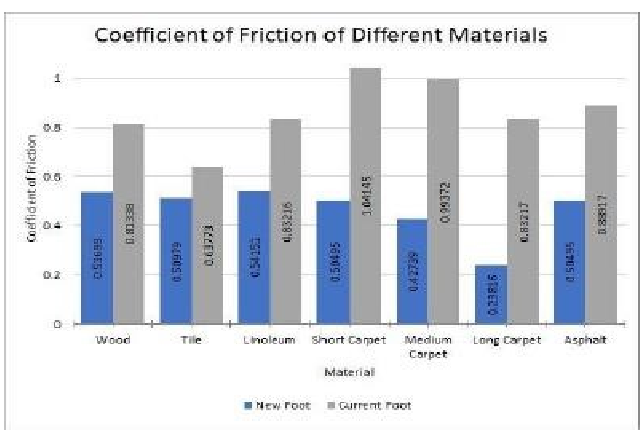

Fig. 5: Comparison of Coefficient of Friction between Two Feet

From the result above, it is clear that the current market crutch foot has a higher coefficient of friction than the prototype. This is because the current market crutch foot has more of its weight at the bottom of the foot, lowering its center of gravity. The new design has a higher center of gravity making easier to tip.

Cyclic loading was another method of testing that was attempted. The goal of cyclic loading is to test performance over time with varying pressure, determining the lifespan of the crutch. The results will support the design if it can withstand the simulated weight for an extended period of time. There are two forms of testing for cyclic loading. A physical test which requires certain machines with specific attachments to run, and simulated cyclic loading using SolidWorks. Because Wentworth does not have the required attachments or space to perform a cyclic loading test on the prototype, SolidWorks Simulation was the only option. Several problems were encountered when trying to run the simulation. The simulation would either run for a few minutes and fail or run for over six hours and have made no progress. Due to these issues, the team decided to forego the cyclic loading testing due to the difficulty of getting the system to run efficiently.

The strength of the adapters needed to be tested. The Instron machine which was used to determine the strength. A three point compression test was performed where a pressure was applied to the top of the adapter until failure or 2000 lbs. Was met. Three different designs for the adapters were put through this test. Adapter A was the first iteration of the adapter design, B1 was the second iteration and connected the bent tubes to the upper armpit adjustment tubes, and B2 connected the two bent tubes to the tube housing the spring. Below is a picture of the setup of the adapter in the Instron machine and the results obtained.

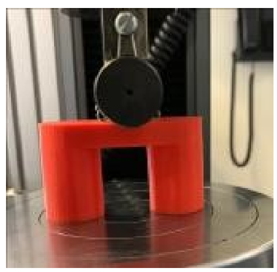

Fig. 6: Setup of the Adapter in the Instron Machine

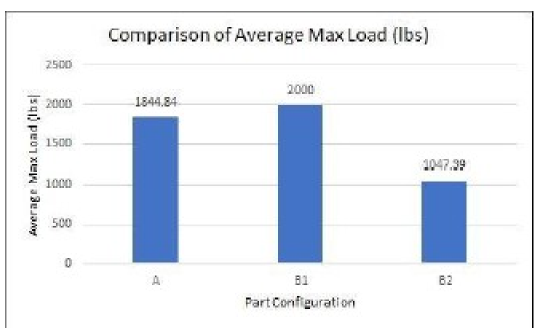

Fig. 7: Comparison of Max Loads of Different Part Configurations

The pressure sensor assembly for the crutch consists of seven components: an Arduino Uno, an SD card shield, a pressure se`nsor, an SD card, two 2 kΩ resistors, one 10 kΩ resistor, and one 9 V battery as shown in figure 9. The Arduino uno is used as the computer to sense the output of voltage while the SD card adapter for the Arduino allows an SD card to be inserted. At the other end of the system, the pressure sensor responds to the pressure applied as a varying output voltage. By using an SD card with the shield, the data can be stored and the user or medical professional can review the dependency on the crutches. Within the circuitry set-up for the pressure sensor, the resistors were used to reduce voltage and the 9V battery to produce power. The pressure sensor is designed to slide under the foam padding on the handle of the crutch to allow an accurate measurement of the pressure applied to it. The coding for this system was conducted in the Arduino software which is based off a mixture of C and C++. Below is the code for the pressure sensor system as shown in figure 8.

```
int fsrPin = 0;
int fsrReading;
int fsrVoltage;
int Time = 1000;
long Timee = 1000;
long fsrForce;
long fsrPsi;
#include <SPI.h>
#include <SD.h>
#include "RTClib.h"
#include <Wire.h>
RTC_PCF8523 rtc;
File myFile;

void setup(void) {
  Serial.begin(9600);
   Wire.begin();
   if (! rtc.begin()){
    Serial.println("Couldn't Find RTC");
    while (1);
   }
  // put your setup code here, to run once:

Serial.print("Initializing SD Card...");
if (! rtc.initialized()){
  Serial.println("RTC is Not Running");
rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
}

if (!SD.begin(10)) {
  Serial.println("initialization failed!");
  return;
}
Serial.println("initialization done.");
myFile = SD.open("test.txt", FILE_WRITE);
myFile.print("Date");
myFile.print("\t");
myFile.print("\t");
myFile.print("Time");
myFile.print("\t");
myFile.print("Force in PSI");
myFile.println("");

myFile.close();
}

void loop(void) {
  fsrReading = analogRead(fsrPin);
  Serial.print("Analog reading = ");
  Serial.println(fsrReading);

  fsrVoltage = map(fsrReading, 0,1023, 0, 5000);
  Serial.print("Voltage reading in mV= ");
  Serial.println(fsrVoltage);

  if (fsrVoltage ==0) {
    Serial.println("No pressure");
  }

  fsrForce = fsrVoltage / 80;
  Serial.print("Force in PSI: ");
  Serial.println(fsrForce);

  DateTime now = rtc.now();
  Serial.print(now.year(), DEC);
  Serial.print('/');
  Serial.print(now.month(), DEC);
  Serial.print('/');
  Serial.print(now.day(), DEC);
  Serial.print("...");
  Serial.print(now.hour(),DEC);
  Serial.print(':');
  Serial.print(now.minute(),DEC);
  Serial.print(':');
  Serial.print(now.second(), DEC);
  Serial.println();

 myFile = SD.open("test.txt", FILE_WRITE);
  Serial.println("Writing to test.txt...");
  if (myFile) {
    myFile.print(now.year(), DEC);
    myFile.print("/");
    myFile.print(now.month(), DEC);
    myFile.print("/");
    myFile.print(now.day(), DEC);
    myFile.print("\t");
    myFile.print(now.hour(), DEC);
    myFile.print(':');
    myFile.print(now.minute(),DEC);
    myFile.print(':');
    myFile.print(now.second(),DEC);
    myFile.print("\t");
    myFile.print(fsrForce);
    myFile.println("");
  }
 else {
   Serial.println("error opening test.txt");
 }
 Timee=Timee+1000;
 Serial.println(Timee);
 myFile.close();
 delay(Time);
}
```

Fig. 8: Pressure Sensor Code

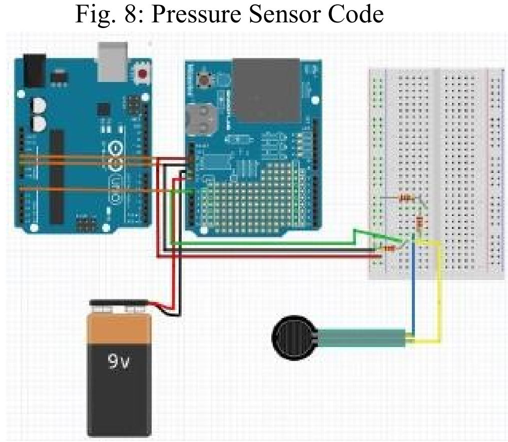

Fig. 9: Pressure Sensor Wire Diagram

4. Conclusion

The primary objective was to design a crutch that is more useful and desirable than the current market axillary crutch. After constructing the prototype and testing both types of crutches, the results gathered supported the design as a proof-ofconcept. There are some alterations that can be made to further improve the design.

The rubber block was a basic waterproof, non-skid material. The definitive purpose was originally not accounting for consistent ground contact. After several tests on the friction coefficient apparatus and shaping it to the desired dimensions, the feet began to abrade. It is projected that if this rubber were to be implemented into a final product, the lifespan would not align with the project goals. A more flexible, less dense rubber would more suitably fit the design.

The adapters and hinges were originally separate pieces. When the prototype was being built, it was apparent the tolerances between the tubes, hinges, and adapters were too large and the crutch wobbled excessively. To combat this issue, the adapters were redesigned in SolidWorks to incorporate the hinge feature. Four separate pieces were reduced to two, however the material used was not strong enough. The PLA parts fractured under a large, applied load. On top of that, the hinges were not able to lock all the way, making the hinges move if enough force was applied. Those two main problems made it difficult to use the crutches once assembled. Ideally, if the prototype were to move toward a final product, the hingeadapters would be manufactured out of aluminium to be stronger.

There were concepts in our design that were deemed successful. Adding the memory foam to the underarm did make it noticeably more comfortable for the user. Examining the bottom of the crutch, the spring system that was put in place did reduce the impact the user experiences. The hinge concept did allow for them to fold up for easy storage and was successful in working as a footrest. The Arduino pressure system was also working and was able to accurately measure pressure readings. The prototype had enough favourable attributes that together prove this proof-of-concept to be a success.

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