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User-Driven Prosthetic Robotic Arm for Patients with Lower Arm Amputation

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Abstract: It is a very painful experience for a person would be the loss of a limb thus creating a user-driven prosthetic robotic arm targeted to patients with lower arm amputation is necessary to better understand the technology that is required. For this project it is necessary to design a robotic arm with all the fingers moving synchronously with signal from EMG sensor and is able to test whether the robotic arm is capable to clench and hold basic objects while the scope and limitations are the system can utilize the electromyographic signals from the muscle signal, capable of moving the servo motor and the robotic arm will be a right-handed design. The creation of a Prosthetic Robotic Arm through its electrical and mechanical architecture is addressed in this project. This project uses an Arduino microcontroller to design a prosthetic that uses electromyographic sensor to detect signals from the residual limb and powers motors for movement. From the 3D simulation we can see that the design is capable of holding onto a bottle and a ball, it also shows the stress and strain analysis of the design. An electrical system simulation was made to show the signal value that may be produced. A prototype was later made based on the electrical and 3D design. From the result, the prototype wasn't able to fully copy the simulations made due to the design flaw. Future researchers can improve the prosthetic arm design and implement better material choices to make it work more efficiently.

Keywords: Prosthetic, Robotic, Electromyographic, Arduino, Amputee, Signals, Limb, Arm,

1. Introduction

The human hand is capable of performing complicated and subtle gestures that allow a person to communicate and interact with the world. The opposable thumb has allowed humanity to reach high dexterity speeds, enabling human creation to proceed quickly over other species [1]. It is important to synthesize an immense amount of information about the environment, including fine touch, sensation, discomfort, temperature, and proprioception, to execute complicated hand gestures. The loss of a hand

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is catastrophic and the physical difficulties after hand loss are crushing, unlike losing a limb. With 67 per cent of upper limb amputees being male, men are slightly more likely to lose their hands than women. With 60 percent between the ages of 16 and 54, upper limb amputations most often occur during healthy working years. Within the amputee group, the practical criteria are strong and the demands for a prosthetic limb are high. [2].

Due to the inefficiency of technologies a couple hundred years back, an amputee with a missing hand may only manage to get a hook prosthesis with limited function and significant can cause social degradation. A hand amputee today, though, should expect a substitute that replicates a whole host of standard hand functionality. There have been significant developments in bionic hand technology, and this field is now considered a triumph of innovation in medical engineering.

In both form and performance, the modern prosthetic hand has been designed to closely approximate the natural limb. Given the specific undeniable fact that the bionic hand has recently been hailed as a achievement for engineering innovation, it remains an inferior substitute for the essential thing however there are therefore many challenges to its acknowledgement by the upper limb amputee group. This limits the prosthetic hand from reaching the final word target of any prothesis, its users agree 100 %.

1.1 Problem Statement

Amputee is a term often used for a person who has lost a limb due to various of reasons. Many amputees have turned to the prosthetic arm to adapt to common society. However, most prosthetics have restricted functions due to inefficient design. Therefore, it is important to provide a robotic arm with a sophisticated physical design that can match the human arm with the dexterity it can provide. Usually, a robotic arm costs a fortune due to the performance of the device, so this device should be in an affordable cost range to provide amputees with more allowable options [3]. Some of the problems that other researchers have faced are, getting accurate signals from their EMG sensors as well as the number of EMG sensors needed for each finger to move independently.

1.2 Objectives

The objective of the project is to design a robotic arm with all the fingers moving synchronously with signal from EMG sensor. The prosthetic robotic arm must be tested whether the robotic arm is capable to clench and hold basic objects.

1.3 Scope of Study

Firstly, the scope and limitations that need to be considered for completing this project are, the system can utilize the electromyographic signals from the muscle signal while it is capable of moving the servo motor. The robotic arm will be a right-handed design.

2. Literature Review

2.1 Human skeletal hand structure

The hand contains several specialized structures that include precise motor biomechanics and fine tactile senses in synchrony [4]. The structural bone of the hand can be separate into three group which is carpals, metacarpals, and phalanxes. The anatomical term for the wrist that connects the forearm radius and ulna with the hand's metacarpal bones is the carpus or carpals [5] The hand has 27 bones, eight of which are carpal bones, five metacarpals and 14 phalanges, as illustrated in Figure 1.

Figure 1: The bones of the hand

2.2 The Bebionic 3

The Bebionic 3 is perhaps the world's biggest industrial myoelectric arm. The Bebionic 3 uses a predefined grip device, like those of its kind. 14 different muscle activity grip patterns that a person can pick by using around their upper forearm. The consumer doesn't essentially have control over individual finger movements, but they can pick an edge pattern and use muscle activity to trigger the movements of that particular grip [8]. The thumb accounts for arguably 40 percent of human hand use. In both prosthetic hands, the thumb configuration is important and is more complicated than the other digits.

Figure 2: The Bebionic 3

2.3 Openbionic's Hero Arm

A prosthetic arm dubbed Hero Arm has been made by Openbionics, it is the world's first medically approved bionic arm with multi-grip functions. It originated in Bristol, United Kingdom and the Hero Arm is a lightweight and inexpensive myoelectric prosthesis. Their primary aim is for adults and children aged eight and over who are below elbow amputee. The Hero Arm is a muscle controlled bionic limb, with lifelike precision [11]. They designed the arm to be custom-made, ideally crafted for the user, with a removable breathable socket for better ventilation. High-performance engines, sophisticated technologies and long-lasting batteries fuel the bionic arm. As shown in Figure 3.

Figure 3: Openbionic's Hero Arm

3. Methodology

3.1 Methods

This project process is to design an EMG controlled prosthetic limb and it can be divided into a couple of phases. The main stage relies on the principle of mechanical and electrical architecture for the prosthetic limb. It is possible to split the later stages into two sections; mechanical production is the first section. Therefore, computer-assisted software such as Solidwork software is used to draw the prosthetic limb that is suggested and planned. Another segment is the development of the prosthetic limb's internal and external electrical design. The final stage finishes with checking, analysis, and a small role adjustment.

3.2 Working Flow

This section presents about the workflow of creating the Prosthetic Robotic Arm. At the start of the process, both the 3D modelling process and electrical design process will begin almost simultaneously. In the 3D modelling process the prosthetic robotic arm is divided into 3 main parts, the forearm, the palm and the finger. The forearm is designed with compartments to fit electrical components such as servo motors, batteries, and the Arduino board. 3 different pieces will be designed and when assembled will create a finger.5 sets of the finger design is required to make the prosthetic robotic arm look similar to a normal human hand. The parts mentioned will be discussed in a more detailed manor below.

On the other hand, for the electrical design process, an electrical schematic is made. An electromyographic sensor is used as the main input to the whole system. An Arduino board will be used as the microcontroller to control the system, from receiving the input from the electromyographic sensor sending it to the actuators. 4 servo motors are used as the actuators for the fingers and are connected directly to the Arduino board. Batteries will be used to power up the whole system, the batteries must supply sufficient power to start the system and power the servo motors.

After both of the 3D modelling and electrical design has been approved, the prototype fabrication process begins. A simple prototype is made from readily available materials for the body structure and the design is based on the 3D model that was made. The electrical components are placed inside of the forearm and attached to the finger. Lastly, the testing phase could begin. Tests such as holding on to objects can be made when the prototype is completed. Figure 4 illustrates the matter.

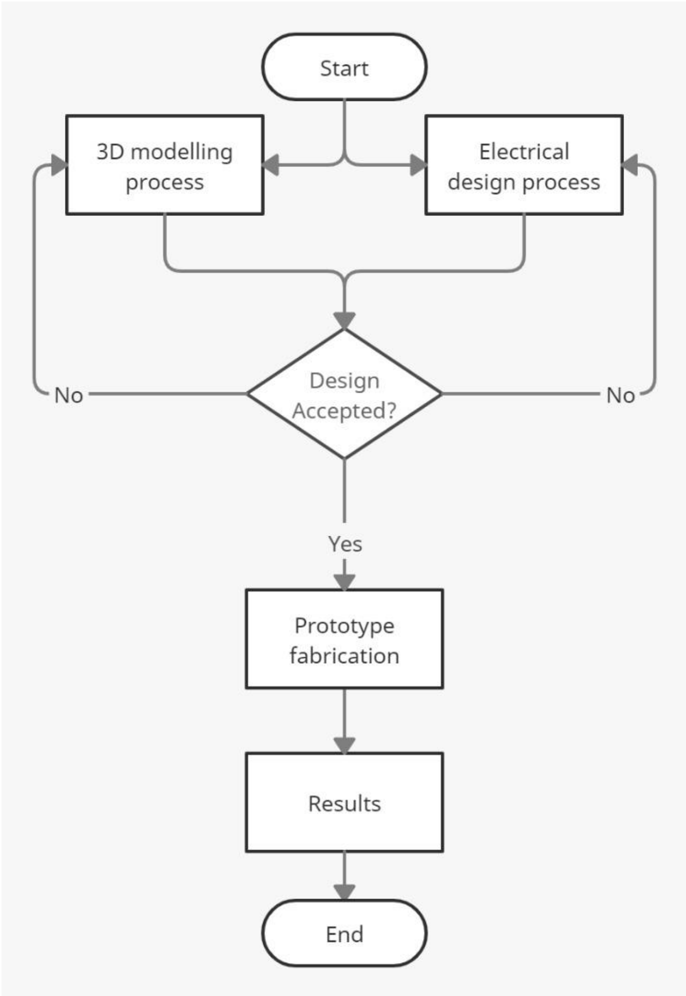

Figure 4: Working Flow

3.3 System Design

Figure 5 shows the operational flow of the Prosthetic Robotic Arm. The operations starts when power is supplied to the system. Then, the sensor will collect data from the muscle signal. The servo motors will also start operating when Arduino board gives the signal. When the Prosthetic Robotic Arm is attached to an amputee below elbow stub, the sensors start to collect the data of muscle signal. If sensors are not working, switch on the Arduino microcontroller for troubleshooting the connection of the sensor. After troubleshooting the connection of sensors, switch on the Arduino microcontroller to run again the progress. When the sensor has detected the muscle signal which works as an input, it will be sent microcontroller to distinguish the action to take by the motor driver. The motor driver than will move the prosthetic arm depending on the signal data.

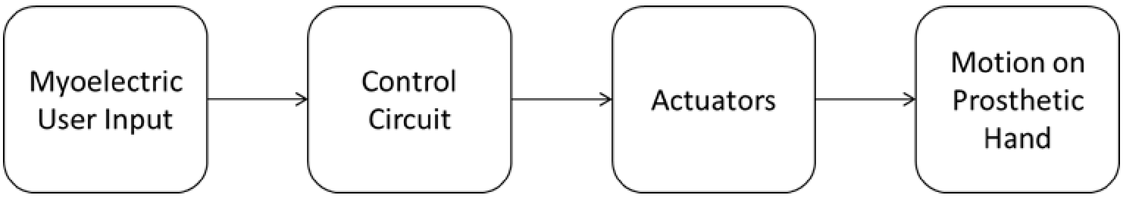

Figure 5: Operational Flow

3.4 3D Drawing

Figures 6 shows a possible design that will be used in making the project. The design of the arm is made to achieve the dexterity of a normal arm. This prosthetic arm is targeted for below elbow amputees; thus, the stub of an amputee must be at the forearm. In the forearm area below the wrist, most of the components will be placed there. After assessing various methods of action for prosthetic arms and artificial tendon design, artificial tendons are a feasible way to work bionic hands. Tendons may be any line of high strength that does not extend when stressed. These lines are attached to the fingertips and are tightened by the forearm motors. The fingertips open and shut by pulling on the tendons. To make it compact and attachable to an amputee, the electrical motors driving these tendons must be fully housed within the unit. Ideally, we would prefer to put these motors as close to the fingertips as possible, but we cannot house the motors used inside the palm segment due to their comparatively large scale. Instead, the motors were situated within the forearm. Figure 7 shows the drawing with dimensions of the forearm on the left and the hand on the right as a drawing view format.

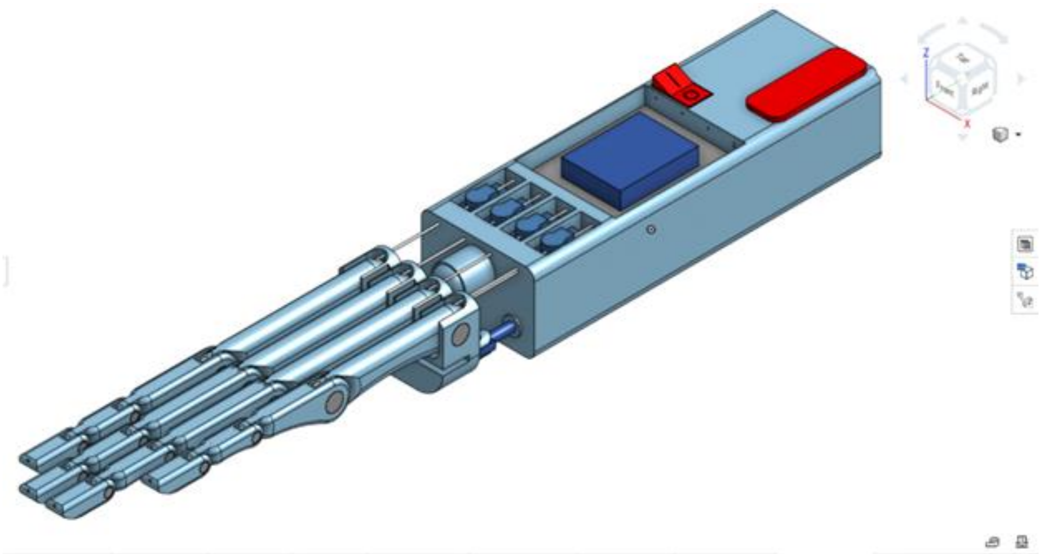

Figure 6: 3D design of the Prosthetic limb

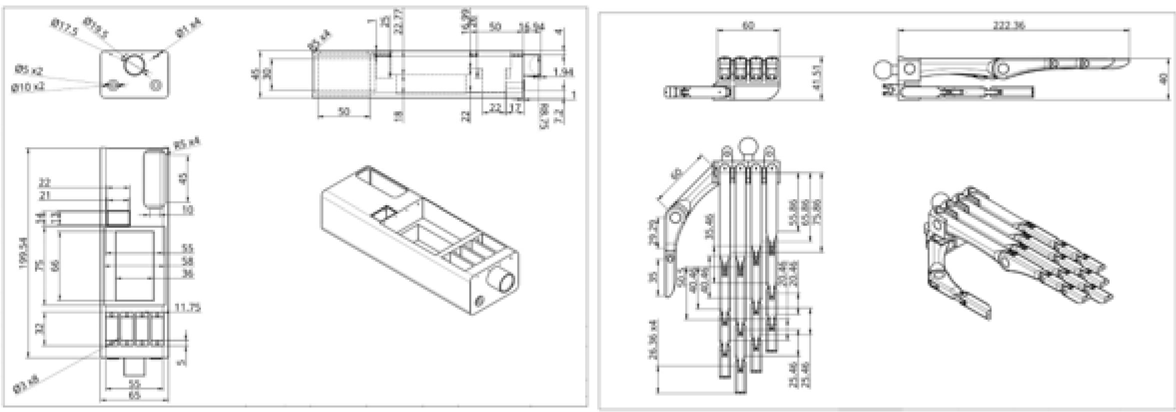

Figure 7: Isometric Drawing of the forearm (left) and hand (right) with dimensions

3.5 Circuit Design

Figure 8 shows the early circuit schematic, a 9.0 V battery is used to power up the whole system by connecting both of the positive and negative pins to Vin and Ground pins on the Arduino Uno board. Next, the electromyographic sensor will act as the input, the EMG sensor has 3 pins which are positive, negative and signal which is connected to pin 3.3 V, Ground and A0. The EMG sensor will detect signals produced by the muscles, the signal will be converted and sent to the Arduino Uno board. From there, it will activate the 4 servo motors to move according to the instruction set on the microcontroller. The servo motors have 3 pins, positive is connected to 5.0 V while the negative pin is connected to Ground pin. The third pin which is the signal pin will be connected to pin 3, 9, 10, and 11 respectively. In the mechanical design portion, the operation of the servo motors to drive the fingers will be further clarified.

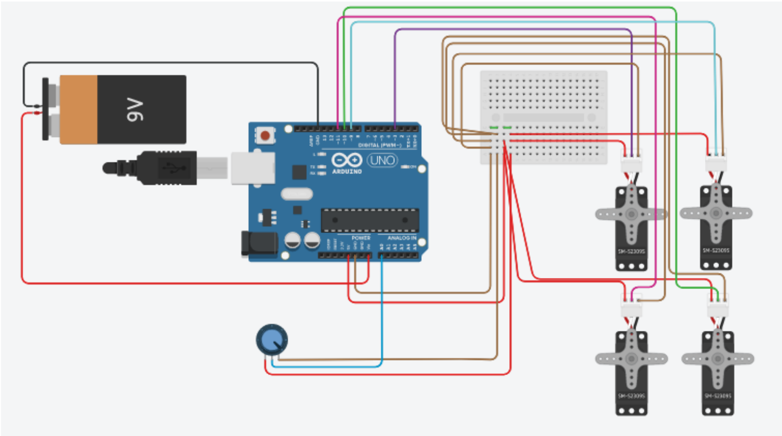

Figure 8: Circuit Schematic

3.6 Drive System

The tendons coil around the horns of the servo motors, forming a closed circle. It pulls on the tendon and closes the finger while the servo motor rotates one direction. The motor would spin in the opposite direction to open the finger. For the index finger indicates the artificial tendon drive. For clarification, all other tendons have been omitted. Specific servo motors are attached to the thumb, index and middle fingers. The ring and small fingers have both been attached to the same servo so the inner space of the arm is limited, ensuring they open and close in unison. Figure 9 shows the drive system of the fingers.

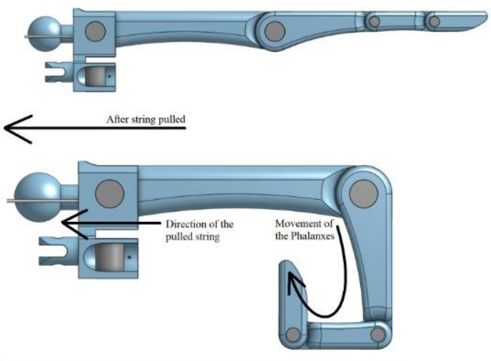

Figure 9: Drive System

4. Results and Discussion

4.1 Grasping Operation Simulation

With the success of the design in performing open-palm and closed-knuckle action, the next process is for the design to simulate a grasping operation on two objects with different geometrical shape which is cylindrical and spherical object. For cylindrical object is a water bottle with 230 mm of length and diameter of 58 mm. For spherical object is a ball with diameter of 100 mm. In Figure 10 illustrated before and after the operation of grasping the bottle. The flexibility of hand model design allows it to grasp the bottle. In Figure 11 illustrated before and after the operation of grasping the ball. The flexibility of hand model design allows it to grasp the ball.

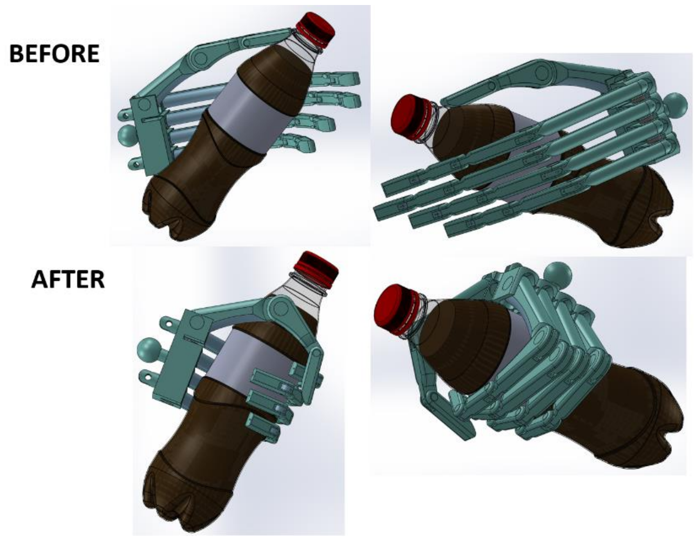

Figure 10: Hand model before and after grasping cylindrical object

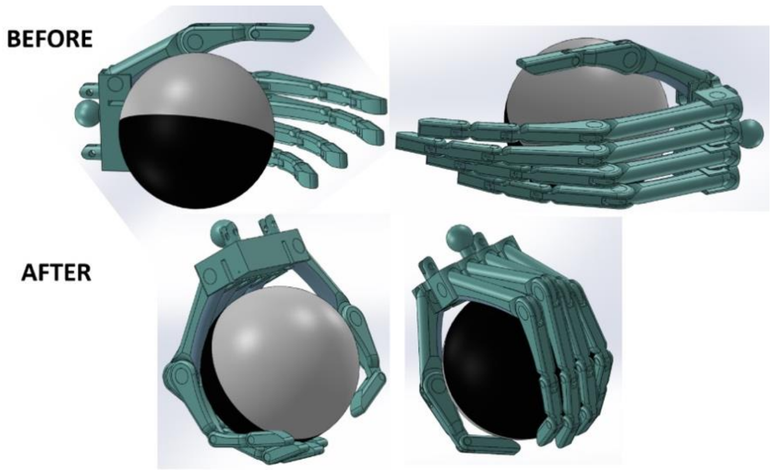

Figure 11: Hand model before and after grasping spherical object

4.2 Stress and Displacement Analysis

Table 1: Data on stress and strain analysis

Force applied, N	Equivalent Stress, N/m^2	Displacement, mm
10	6.29E+07	1.091E+01
20	1.72E+08	2.093E+01
30	3.14E+08	2.973E+01
40	4.75E+08	3.733E+01
50	6.44E+08	4.400E+01
60	7.96E+08	5.123E+01
70	9.63E+08	5.772E+01
80	1.13E+09	6.235E+01
90	1.28E+09	6.799E+01
100	1.41E+09	7.337E+01

Throughout this project, only two simulation that can be conducted which is stress and strain analysis of a static model. The reason for this shortage is because of the limited access of the simulation software. Table 1 shows the data calculated by SolidWorks throughout the simulation. Only the hand model was chosen to experience the simulation as an effort to proof the practicality of the design. The hand model was set at a fix position (green arrow) and the force applied on the surface of each fingers (purple arrow). Because of the material set for this model, which is as polyethylene terephthalate glycol-modified or PETg, the yield of strength of the materials is equal to 5.040E+07 N/m^2. The force applied is gradually increase by 10 starting from 10 N until 100 N. This prosthetic forearm model was design to use for common activity in everyday life. It is highly unlikely for this prosthetic forearm to be exposed to high force frequently. Hence, the range of the force applied.

Figures 12 illustrated the difference in visual of the hand model when force applied at 10 N and 100 N. The red arrow represents the yield strength of the material. At 10 N, the red arrow point at the yellow-coloured bar and the hand model is in blue coloured. This can be concluded that the hand model able to handle a 10 N of force without breaking. When the force applied at 100 N the red arrow point at the blue-coloured bar and the entire hand model is in blue. Hence, at 100 N the hand model may break because the pressure applied is exceed its yield strength.

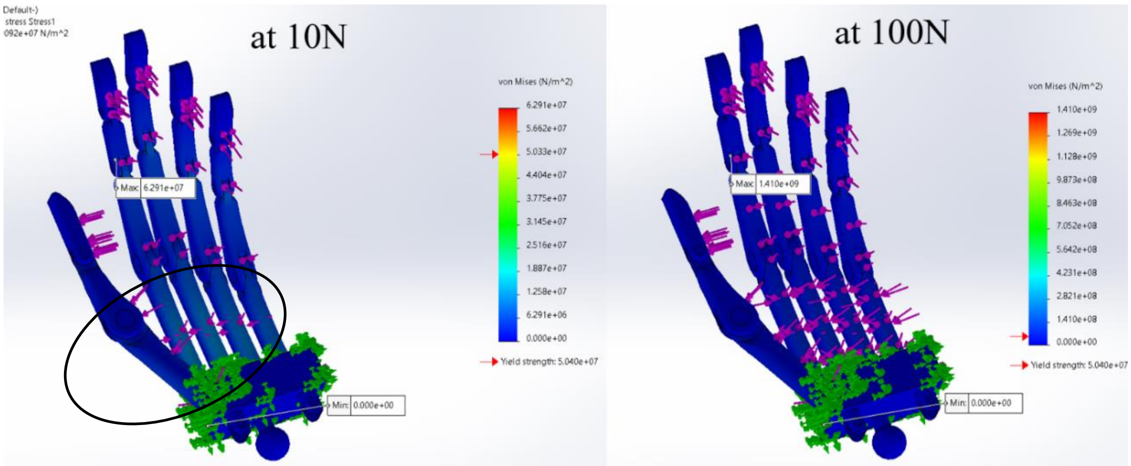

Figure 12: Comparison of hand model stress when at 10 N and 100 N of force

Figures 13 shows the changes happen in the hand model during the simulation. When the force applied is at 10 N the displacement can be seen happen vividly in the circled part. Comparing when the force applied at 100 N, the displacement can be seen more clearly in the circle part. This proved that when applying high force on the hand model can and will cause great changes in its shape.

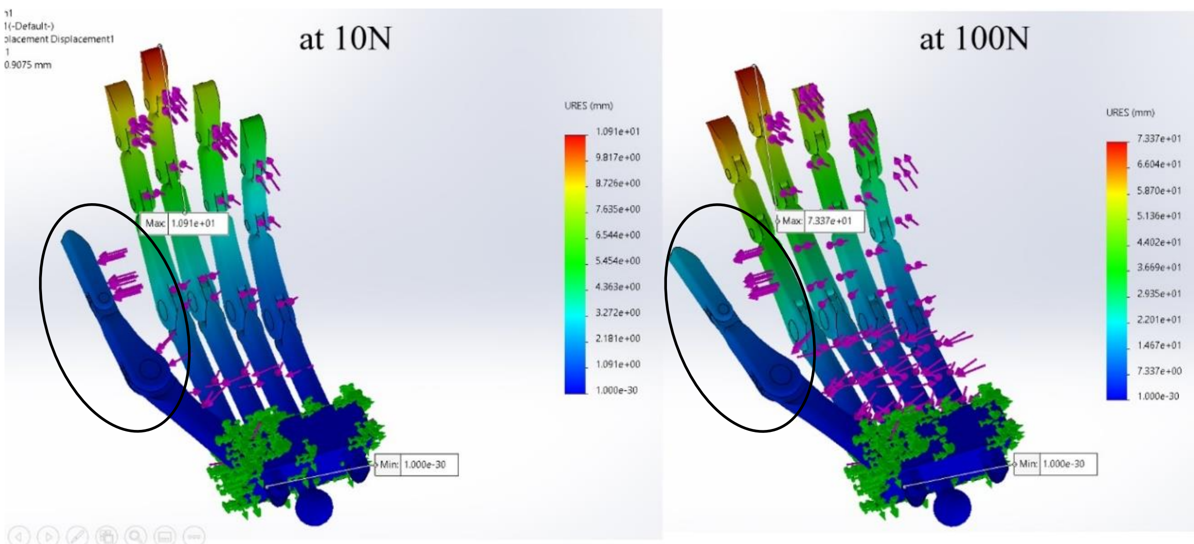

Figure 13: Comparison of hand model displacement when at 10 N and 100 N of force

4.3 Electrical System Simulation

This subtopic discusses the simulation for the prosthetic robotic arm circuit. The tools that are used for the prosthetic robotic arm simulation are Tinkercad software. Figure 14 shows the circuit diagram that was used for the simulation. A potentiometer was used to replace the EMG sensor because both produce values from 0 to 1000. The potentiometer legs are connected to 3.3 V, Ground and A0 respectively on the Arduino uno board. A 9.0 V battery is used to power up the whole system and is connected to pin 5.5 V and Ground. A second power source of 4 pieces of 1.5 V batteries is connected to the servo motor's power pin. 4 servo motors act as the output actuators and their positive leg is connected to the positive pin of the battery while its negative leg is connected to ground. All 4 servo motors signals are connected to port 3, 9, 10 and 11 respectively. This port was chosen because it could release variable signal outputs.

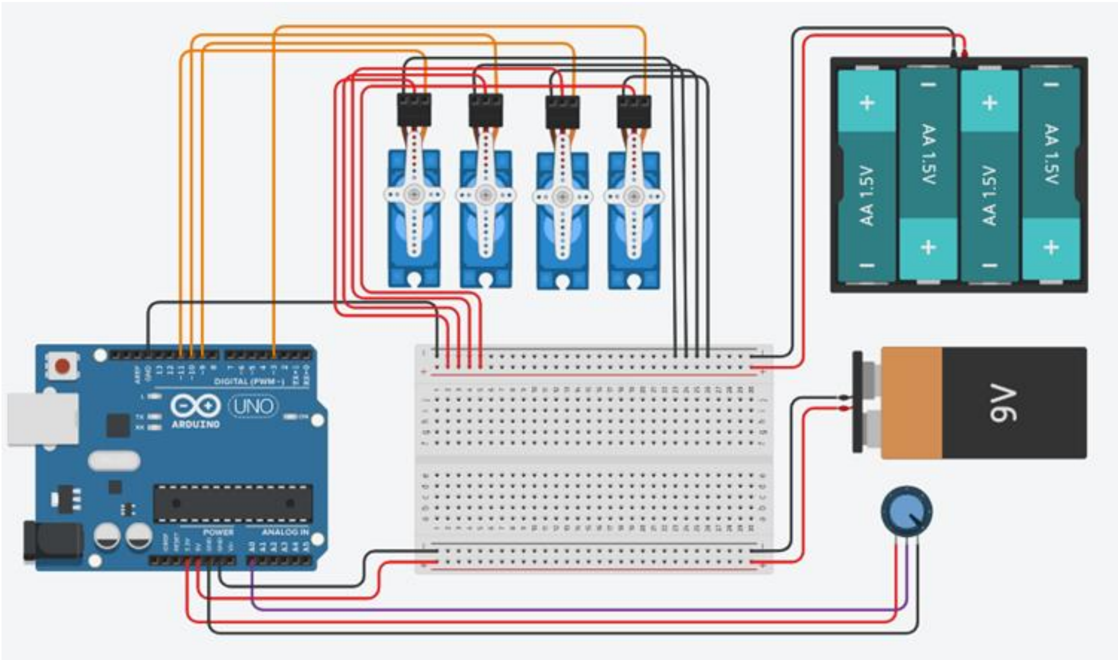

Figure 14: Circuit Design

Table 2: Analogue Signal Value in Serial Monitor

2	247	165	104	308	145	247	430	410
63	63	206	104	267	124	369	471	430
185	63	165	43	267	43	226	410	389
247	84	63	22	287	2	124	369	389
369	2	247	22	247	43	84	369	389
430	2	328	2	145	185	63	389	308
511	43	410	2	63	348	63	287	226
450	84	430	43	43	389	63	206	165
369	124	348	84	43	389	84	145	63

410	124	267	63	145	267	63	63	22
308	63	348	22	247	206	2	22	63
247	22	206	145	287	165	2	43	2
185	104	84	287	308	124	2	22	22
145	145	63	328	226	43	43	2	63
63	247	63	369	145	2	43	43	84
43	308	185	410	84	22	2	84	206
206	450	348	389	22	63	2	22	308
287	491	410	369	145	43	63	22	410
328	410	430	450	267	145	63	43	471
348	267	348	532	389	226	22	63	389
450	206	247	430	410	369	308	267	430
369	84	145	389	247	450	369	308	308
410	84	104	389	185	308	410	369	185

Table 2 shows the variable signal produced in the serial monitor. Data that was captured in the table below are analogue value and is set in decimals. The potentiometers lowest value is at 2 while Its highest value is at 550. When the potentiometer is raised above 200 as set at threshold it will indicate to the servo motor to rotate and if the signal value does not reach 200 the servo will not rotate.

Figure 15 shows the waveform from the serial monitor in Tinkercad. As shown in the waveform and stated from the previous table, the signal will fluctuate from signal value of 0 up to 550. The threshold that was set is at 200, it is provable that every time the peak reaches above the 300 line, the servo motor will react by rotating to position 170 ° and the hand will start to close in a fist shape. When the line drops below the 300 line, the servo motor will return to its initial position at 10 ° and the hand will open up into a more relaxed form.

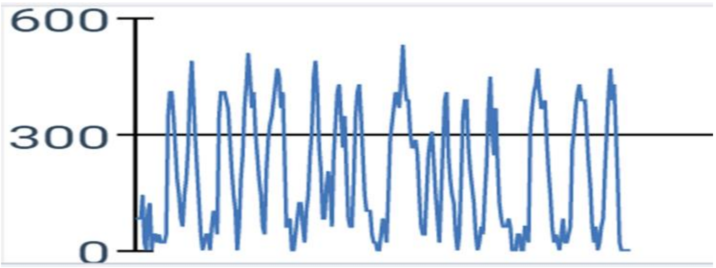

Figure 15: Signal Waveform

4.4 Prosthetic Robotic Arm Prototype

In Figure 16, the Myoware EMG sensor was tested via using Myoware LED shield to check the accuracy of the sensor by flexing the muscles. EMG sensor or an electromyographic sensor is a sensor that is attached to the outside of the muscle and can detect muscle signals. The LED shield is an extension of the EMG sensor, it takes the signal and transferred it into the led and lights up according to the signal value. When the sensor is at idle, the led will only light up 1 bar or not at all. The led bars will light up more when the signal value is higher. The LED shield contains a small battery where it could power up the EMG sensor independently and without any other external power source.

Figure 16: EMG Sensor Testing

Figure 17 shows the testing on the movement of the fingers. The purpose of using 4 servo motors is because, 1 servo motor was connected to the thumb, another servo motor was connected to the index finger, 1 more servo motor to the middle finger. The last servo motor was connected to the ring finger and little finger because it is unnecessary for both of the fingers to move independently. A 9 V battery is used to power up the servo motors because 4 pieces of AA batteries does not provide enough current. The 4 pieces of AA batteries is used to power up the whole system including the Arduino Uno and the EMG sensor.

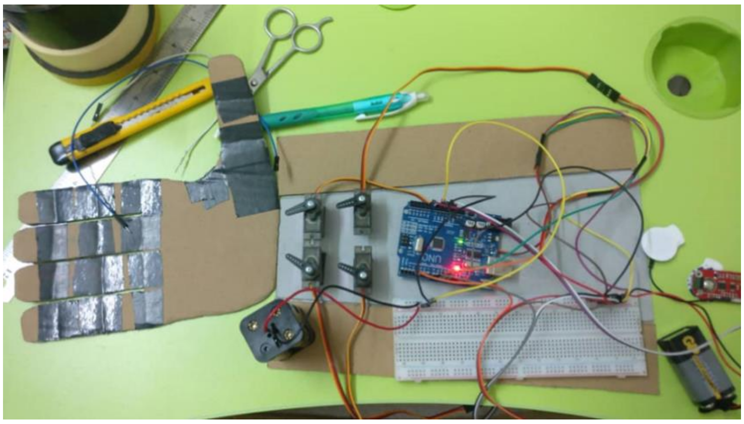

Figure 17: Fingers Movement Testing

Figure 18 shows that the prosthetic robotic arm divided into 3 parts, the fingers, the palm and the forearm. Each finger consists of 3 parts bonded together to form a finger. At the tip of the fingers a fishing line is tied to a servo motor. The thumb is connected to the servo motor on the top left while the index finger is connected to the top right servo motor. The middle finger is connected to the bottom right servo motor while the ring finger and the little finger is connected to the bottom left servo motor. At the centre of the palm, a cylindrical pathway is placed to guide the fishing line from the tip of the finger to the servo motor.

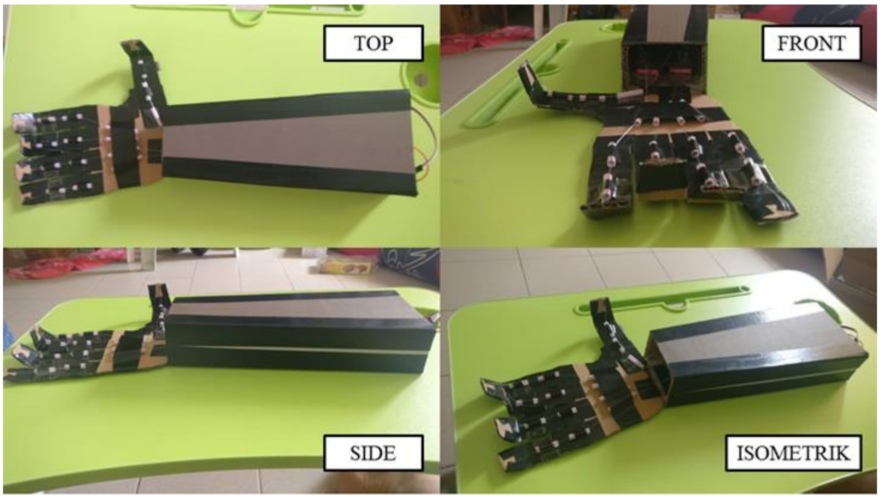

Figure 18: Completed Prosthetic Robotic Arm

Figure 19 shows the main part which is the forearm because most of the components are placed here. 4 servo motors that act as the actuators are placed at the front of the forearm near the wrist. The Arduino Uno is placed at the middle because it is easier to connect all the components. A 9.0 V battery is placed next to the Arduino while the 4 AA batteries is placed on top of the Arduino. A breadboard that connects the servo motors and batteries to the Arduino is place far right of other components. The EMG sensor is connected directly to the Arduino and is placed outside of the prosthetic robotic arm because it is easier to stick it to a muscle for testing and experimenting. EMG sensor begins to collect the data when the power supply is switched on and the data returned to the Arduino.

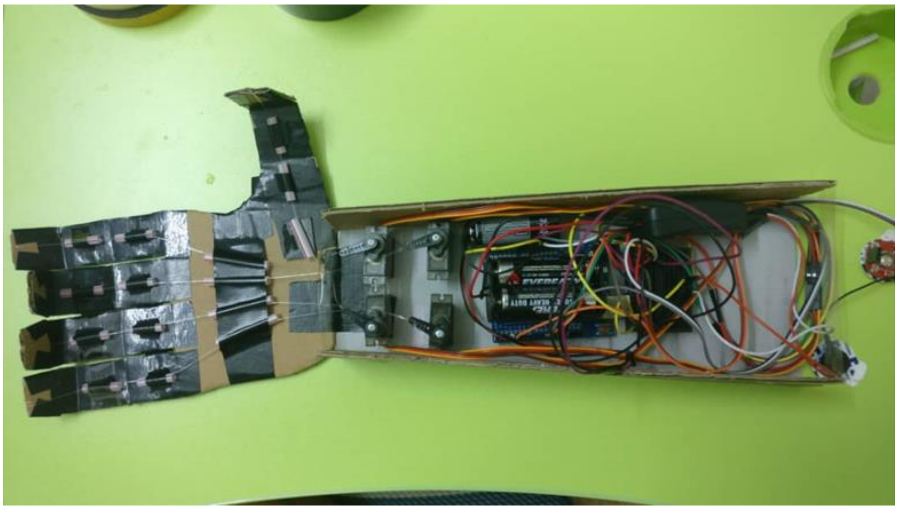

Figure 19: The Components on the Prosthetic Robotic Arm

Figure 20 shows the signal value when viewing it through the serial monitor at Arduino IDE. Figure 21 also shows the waveform of the signal value through serial plotter in Arduino IDE. By viewing through both of these tools, it is possible to record the data that was detected by the EMG sensor.

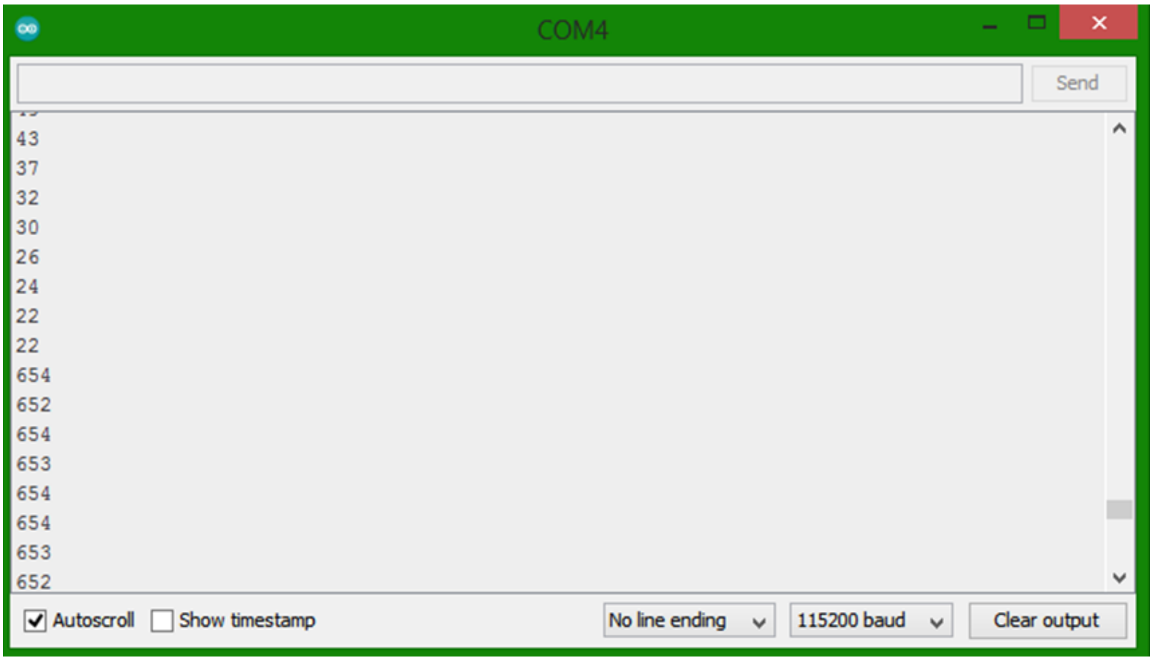

Figure 20: Signal Value from Serial Monitoring in Arduino IDE

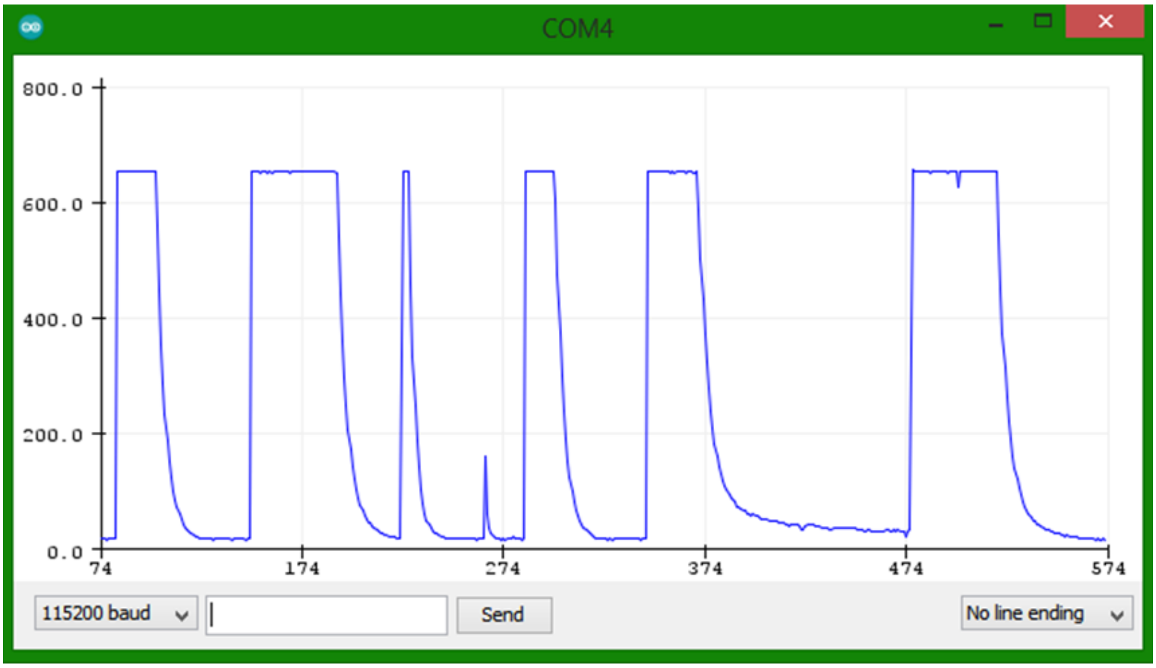

Figure 21: Waveform from Serial Plotter in Arduino IDE

4.6 Gripping Testing

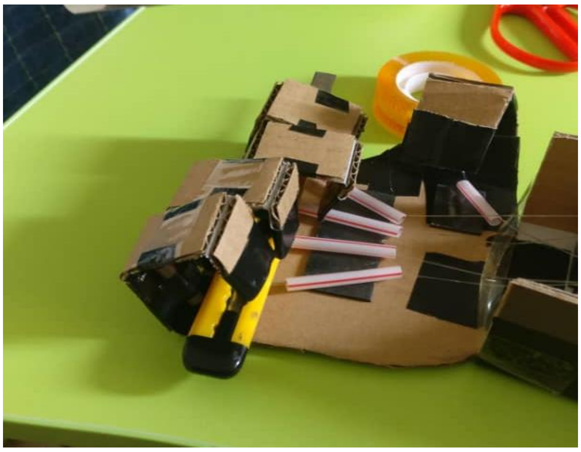

Figure 22: Gripping Test

Following the completion of the prosthetic robotic arm, the prosthetic arm will start to try and hold objects. Some tapes were used to increase its gripping capabilities. In Figure 22, due to the construction of the fingers it can only hold onto objects with a width and thickness of 2cm x 2cm. The prosthetic arm was tested to hold on a box cutter and it was able to hold on to it until the arm releases it. While the prosthetic arm is still holding the box cutter, the arm is lifted to see whether the box cutter will fall down but the prosthetic arm was able to keep hold of it.

5. Conclusion

In conclusion the prosthetic robotic arm was able to achieve the objective that was set to it. The EMG sensor that was used is able to efficiently detect muscle signals every time a muscle flex. The signal will then be transferred to the servo motor to pull on the finger and the prosthetic robotic arm will clench its fist. When the muscle stops flexing, the EMG sensor stops detecting signal and this will indicate to the servo that the signal value has drop and will return to its original position thus releasing the fingers.

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