# ENGINEERING DESIGN AND INNOVATION

# DESN1000

# DESIGN REPORT

## Project Bionic Hand

TEAM 7

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## Executive Summary

The purpose of this project is to construct a mechanical hand prosthesis that allows our client, who is a bilateral amputee, to pick up and carry a bag of groceries weighing a minimum of 1kg. In particular, the client's priority is a design that is simple to operate and can reliably perform the required task, which are qualities that are absent from many modern prostheses. In this report, we will explain the operating principles of our final design, showcase its performance during testing, and reflect on the design and our project planning.

Our solution successfully addresses these requirements through its innovative activation system that simply requires a button press. The press initiates the electronic subsystem, which is programmed to spin a motor. Strings threaded through each finger of the gripper attach to the motor, so the motor's rotation causes the gripper to open and close. However, our device suffers from the limitation of being attached using Velcro straps, which fails to address the client's preference that it should be independently attached and detached.

However, our design underperformed during testing, as it was only able to carry 4kg instead of the anticipated 10kg of weight. This was likely the result of the torque produced by the motor being distributed across each finger, as well as inefficiencies in energy transfer such as due to friction. From our design's performance, we have identified that although the activation system was highly successful, the attachment mechanism and electrical circuitry should be improved in later designs. In addition, several recommendations are included for future project plans, including placing a greater focus on the person assigned to each task, and the need for more effective duration estimation tools.

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## 1. Introduction

Globally, it is estimated that 65 million people live with the loss of a limb, with a further 1.5 million people undergoing amputations annually. 40% of these amputations are upper limb amputations (Lao et al. 2020). Losing a hand is a disability that leads to a significant loss of independence, causing many amputees to utilise prostheses. However, they report that current prostheses provide limited benefit and are not suitable for daily tasks (Resnik et al. 2017), despite becoming increasingly complex to operate (Kerver et al. 2023). Notably, this results in amputees choosing to not use not to use their prostheses for prehensile tasks (Spiers et al. 2021). Our client is a bilateral amputee seeking a new mechanical hand prosthesis to pick up and carry a bag of groceries. The minimum requirements include holding a bag weighing 1 kilogram within 5 seconds and walking with it for 20 metres. The solution must be fixed to the client's transradial amputation and controlled without the opposite elbow, forearm, or hand. They strongly value a prosthesis that is simple to operate which can preferably be independently attached and reattached. It must be designed and built within 10 weeks with a $150 budget. Hence, our team has explored how to design a prosthesis that fulfils these requirements whilst accounting for the constraints of the task. In addition, we have considered what qualities are necessary for a prosthesis to be ‘simple to operate’ and used these to guide our design. The purpose of this report is to exhibit our finalised design for a suitable hand prosthesis, as well as further reflect on both the design’s performance and the outcome of our project plan. The format of this report is as follows. First, we will introduce our design and explain how the subsystems and components of our design function and interact. Then, we will outline and explain the performance of our design during testing. After that, we will reflect upon the successful aspects and inadequacies of our design, whilst providing recommendations for future iterations. Lastly, we will reflect on how our project plan contributed to our team’s performance, taking note of suggestions that are useful for future projects.

## 2. Design Operating Principles

In this section, we will introduce our proposed design for the prosthesis and explain how it will execute its function. Firstly, we will provide an outline of our design in the System Overview, including a description of the overall concept and an introduction to its operating mechanisms. Also, we will clarify how this solution fulfils the project brief. Then, in Subsystem Design and Interaction, we will expand on how we have divided the device into mechanical, electrical, and passive subsystems. Lastly, we will provide a detailed description of each component present in our design in Component Design.

### 2.1 System Overview

Our solution consists of a hand prosthesis with two controllable fingers that act as a gripper, allowing the client to pick up, carry, and release a bag of groceries. Each finger features a string that is tied onto a shaft coupler secured to a motor. Upon the press of a button, the motor will spin, changing the tension in the string and thus causing the gripper to switch between its stages of being open or closed. This system is mounted upon a plank of wood with Velcro straps which can be used to secure the prosthesis to the client's residual limb. These key aspects of our design are evident in Figure 1.

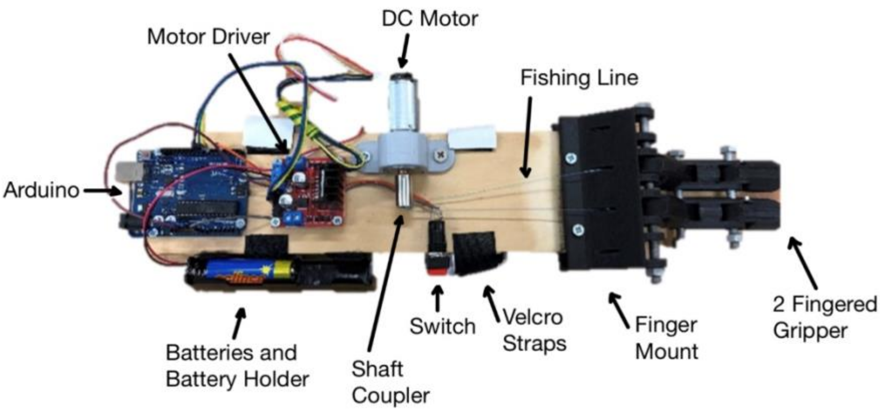


*Figure 1: Overview of the prosthesis*

The activation of the prosthesis occurs when the user presses an accessible momentary switch positioned on the side of the prosthesis, which can be easily reached using parts of the leg. Such a design was chosen as it does not require the use of the opposite hand, elbow, or forearm, thus adhering to the project's constraints. Furthermore, as the prosthesis is controlled using only one switch, it ensures the design meets the key objective of being simple to operate.

Initially, the resting state of the hand is open whilst unactuated, where each of the two fingers are loosely aligned parallel to the palm. During this stage, the user can position the gripper to prepare to pick up the bag. We have decided to only include 2 fingers in our design, centralising the force applied from the motor to the gripper since the torque would be applied over a greater area if more fingers were added. This would reduce the strength of the gripper. Furthermore, more fingers would make it difficult to manoeuvre the gripper underneath the straps of the bag, increasing the time taken to pick up the bag, which opposes the client's desire for a prosthesis that efficiently performs the required task.

Each finger features 3 joints, allowing them to curl and switch to the closed stage, during which the bag can be securely carried. The difference between the stages can be seen in Figure 2. This change occurs upon the activation of the prosthesis. However, there is a three second interval before the hand closes, giving the user an opportunity to correctly position the gripper. Similarly, pressing the button while the hand is closed will cause the gripper to reopen, so the bag can be released. A longer five second delay is included so the user can place the bag at the desired position such as a nearby table.

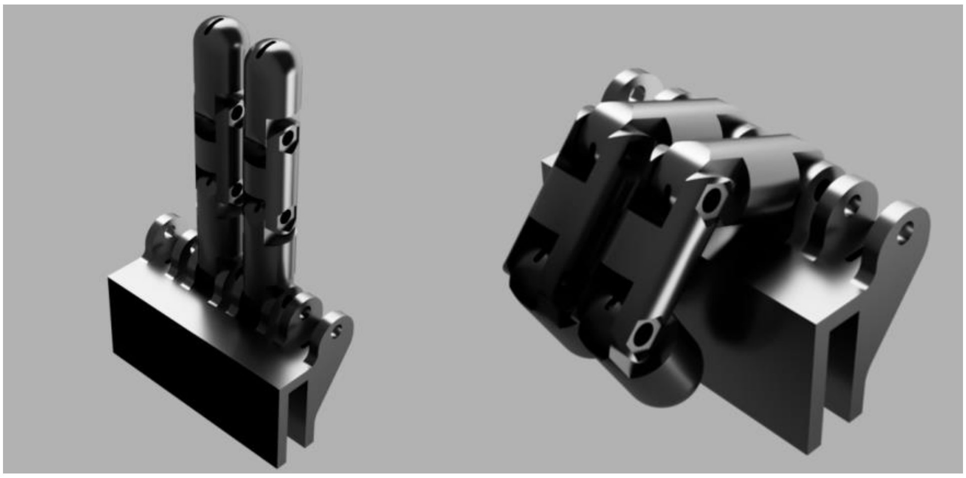

*Figure 2: Comparison between open (left) and closed (right) stages of the gripper.*

This mechanism is controlled by string that is threaded through each individual finger. The two strings are tied and knotted onto a shaft coupler that turns with the motor shaft. When the motor spins, it tightens the string, which leads to the fingers closing. It also continues to spin whilst the bag is being carried to ensure that tension is maintained so the bag is not dropped. Likewise, the tension is released when the motor spins in the opposite direction, reopening the gripper.

The prosthesis is attached to the user's residual limb using Velcro straps. Although it does not fulfil the client's preference for an arm that can be independently attached and detached, we believe it is more important to meet the design's primary objectives of performing its function and being simple to operate. Velcro can be easily adjusted, which accounts for a variety of arm sizes, and allows a balance between stability and comfort to be found. In particular, it is important to ensure that the prosthesis is secure so that it will not fall off when the user is carrying a heavy bag. Since the straps are fastened around the user's forearm, they will also be able to use their elbow to freely manoeuvre the prosthesis, maximising its functionality.

In summary, our design focuses on meeting its primary objective of performing the required task of carrying a bag of groceries. This is achieved through our inclusion of multi-jointed fingers and a secure attachment system. The inclusion of its single-press activation and control system further allows such a task to be completed with ease, fulfilling the secondary objective of being simple to operate, which is valued the most by the client.

## 2.2 Subsystem Design and Interaction

The system can be divided into 3 subsystems: mechanical, electronic, and passive. The mechanical subsystem outlines the role of components in opening and closing the hand. The electrical subsystem shows how such a mechanical process can be controlled with a power supply and other electrical hardware. The passive subsystem holds all the components together and allows the prosthesis to be worn.

### 2.2.1 Mechanical Subsystem

This subsystem utilises a powered DC motor to control the tension in a string, allowing our gripper to simulate the movement of the hand. String is tied onto a shaft coupler which is fastened onto the motor shaft. As the motor spins, it unravels or tightens the string, which changes its tension. This can be controlled by alternating the direction of motor rotation. For both fingers of the hand to move simultaneously, the DC motor controls two separate strings, each directing one finger. As the material of the string is the same in all connections, tension is also maintained from the DC motor to the fingers.

Each finger has 3 joints and 3 subsections. The string runs within the finger past all 3 joints and attaches to the last subsection of each finger. By applying tension to the strings, the fingers will collapse by folding inwards towards the inside of the palm. The bag will fit in between the clasp of the finger subsections when the hand has been closed. The first finger joint connects to the top of the palm and will not be affected by string tension.

### 2.2.2 Electronic Subsystem

The electronic subsystem consists of an Arduino microcontroller, H-bridge motor module, DC motor, batteries, battery holder and a switch. The Arduino board will control the DC motor's rotation speed and the number of rotations to adjust the tension in the string. Adding the H-bridge to the circuit means that the motor will be able to spin in both directions (forward and reverse). This allows the strings to be both tightened and loosened so the gripper can open and close.

When the switch is pressed, there will be a three second interval, before the motor starts to turn. This gives the client an opportunity to pick up the bag before the gripper automatically closes. Similarly, pressing the button again will cause the motor to stop turning after a five second delay, reopening the gripper. The code that has been uploaded to the Arduino to execute this function can be seen in Appendix 1. The batteries secured inside the battery holder are necessary to provide power to the circuit. The connections between the components of the electronic subsystem are shown in Figure 3.

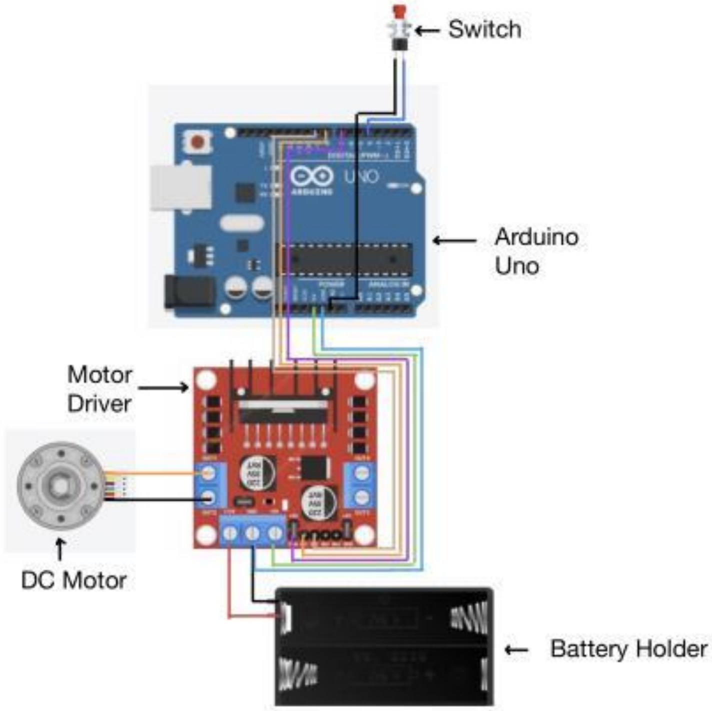


*Figure 3: Circuitry connecting electronic components.*

### 2.2.3 Passive Subsystem

The attachment subsystem comprises of Velcro straps, screws, a mount, saddle, and a plank of wood. The plank acts as the body of the prosthesis, the mount connects the fingers to the wooden body, and the saddle is used to attach the motor. Similarly, the screws allow the other components to be secured to the body. Velcro straps have been adhered to the side of the prosthesis. These can be adjusted by the user to modify the diameter to be larger or smaller depending on the size of their arm. Hence, a smaller diameter will cause the prosthesis to be attached more tightly while a larger diameter will cause the prosthesis to be attached more loosely.

### 2.2.4 Subsystem interaction

The interactions between subsystems are shown in Figure 4. Our mechanical and electronic subsystems operate together to achieve the required gripping mechanism. The DC motor converts electrical energy into kinetic energy and thus is a component of both subsystems. The direction of motor rotation is controlled by the direction of current within our electrical circuit. Therefore, to change the direction of rotation, the direction of current must be reversed. For example, if the hand were opened by the DC motor spinning clockwise with positive current, the hand could only be closed if the motor spun anticlockwise with negative current.

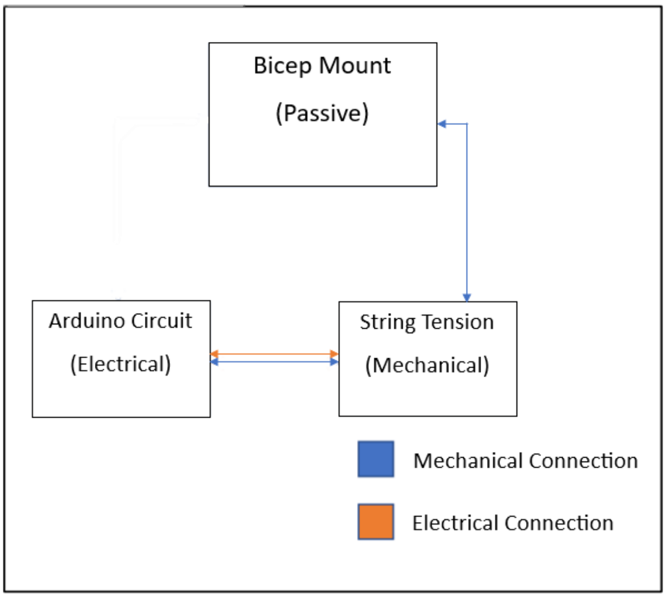


*Figure 4: Block diagram of interactions between subsystems*

Likewise, the electronic subsystem determines the amount that the motor rotates by, so that the string is never loose and conversely does not break. The mechanical subsystem will respond by opening and closing the hand relative to the amount of rotation. This feature is activated by a switch within the electrical circuit that automates the opening and closing of the hand. Thus, by implementing a switch, the prosthesis must first be manually activated for the two subsystems to interact.

The mechanical and electronic subsystems both interact with the passive subsystem as their respective components are secured through the passive subsystem. The mount connects the mechanical fingers to the wooden body, the saddle fastens the motor, which is a component of both the electronic and mechanical subsystems, and screws are used to secure the other mechanical and electronic components onto the prosthesis.

## 2.3 Component Design

In this section, we will describe the details of each component involved in our final design and explain how the component functions. We will also demonstrate how the performance of each component was verified and indicate any modifications that were made because of testing.

### 2.3.1 6V Metal DC Geared Motor

The DC motor is a geared motor with a gear ratio of 75:1 that is capable of 0.64N/m of stall torque. Despite being rated at 6V, it can be powered by just 1V, although it would operate with reduced power. It weighs only 96g and is 54mm long with a diameter of 24.4mm, as seen in Figure 5 from the manufacturer DFRobot. It operates through the principle of induction, where a magnetic field is generated around a wire when an electric current is run through it. Motors feature a magnet that is alternately attracted to or repulsed by the coils of wire around it, which results in circular motion. This motion allows the shaft to spin (NYU ITP Physical Computing n.d.). This motor is secured to the prosthesis using a saddle and screws. Its wires are screwed to the output pins of the motor driver that supply power and control the motor. There is also a shaft coupler bolted to its shaft, which turns with the motor. We verified the performance of the motor by calculating the torque we would require, and hence comparing it to the torque output by the motor. Our calculations, which can be seen in Appendix 2, show the torque produced by a 10kg bag held perpendicular to the ground is approximately 0.40N/m. Thus, this motor should allow our prosthesis to carry a 10kg bag without difficulty.

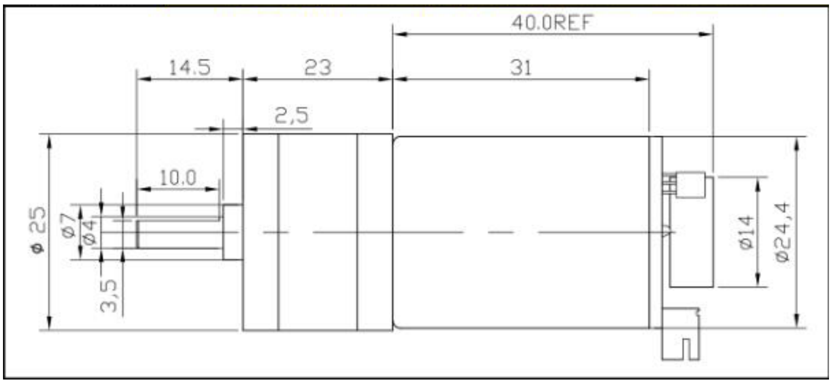


*Figure 5: Dimensions of DC Motor (DFRobot)*

### 2.3.2 Shaft Coupler

The shaft coupler is a 0.75-inch-long open cylinder with two more holes on the side, allowing two shafts to be connected. This coupler has a 4mm opening on one side, and a ¼ inch opening on the other. It includes set screws, so the coupler is firmly attached to the shafts. These characteristics are clearly visible in Figure 6. The 4mm side is fastened to the shaft of the motor, whilst two strings have been threaded through the other end and tied firmly. The motor turning will cause the strings to wrap around the shaft and thus loosen or tighten. Although we had planned to use a 3D printed pulley attached to the motor shaft, our testing showed the pulley was not strong enough to withstand the torque applied to the string. As a result, we used a shaft coupler instead since metal was much stronger than the ABS the pulley was printed with, and the set screws meant the coupler could be more securely attached. We initially verified that this component was suitable by comparing the size of the hole and the size of our motor shaft, which were both 4mm according to their respective listed specifications. This was confirmed to be correct when we were able to successfully attach it onto the motor shaft when constructing our prototype.


*Figure 6: Appearance of shaft coupler*

### 2.3.3 Arduino UNO R3

The Arduino Uno is a microcontroller board which includes all the basic circuitry required to execute basic commands, such as a microprocessor, memory, and circuits. The Arduino features 14 digital I/O pins, a further 6 analog input pins, and a USB Type-B connection port to upload programming code. The layout of these features is evident in Figure 7. This code is written in a language simplified from C++, which allows inexperienced users to easily control a DC motor with minimal code (Garcia-Tudela et al. 2023). In our design, the Arduino is wired to the motor driver and a switch through jumper cables inserted into the pins, controlling the function and voltage output to the motor and thus its speed of rotation. It is screwed into the wooden body using wood screws. We verified the performance of the Arduino by first testing it with sample code by ensuring it could turn a motor which is displayed in Appendix 3, and then confirming it could recognise inputs from the switch, shown in Appendix 4. This code was executed successfully.

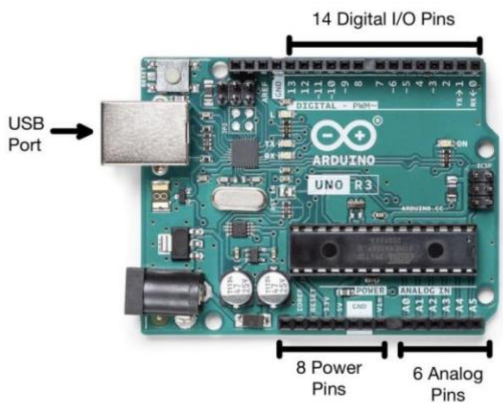


*Figure 7: Key features of Arduino Uno*

### 2.3.4 L298N Motor Driver

The motor driver can control the speed and direction of the motor's rotation. It can control two motors, although it only controls one in our design. Controlling the speed is achieved through Pulse Width Modulation, where on-off pulses of varying widths are sent. The voltage supplied to the motor is proportional to the width of the pulse. As the speed is also dependent on the voltage, the motor driver can vary the motor's speed. To change the motor's direction, the motor driver features a built in H-Bridge. This involves 4 switches arranged in the shape of an 'H', which can open and close to change the direction of the current relative to the motor (Last Minute Engineers n.d.). The motor driver interacts with other components in the electronic subsystem. Our DC motor is connected to the output pins of the driver and the battery holder is wired to the driver to supply it with power. Furthermore, it is connected to the Arduino with jumper cables not only so it can execute the Arduino's code, but also to power the Arduino. The positioning of the pins of the driver are shown in Figure 8. Wood screws are used to secure it to the body of the prosthesis. Its performance was verified alongside the Arduino by ensuring that it could power a motor, and then checking the motor was able to spin in both directions. The code written to achieve this could be seen in Appendix 3. We also tested the circuitry to ensure the driver could independently power the Arduino when the Arduino was not connected to a computer. This was confirmed by the lights on the Arduino lighting up.

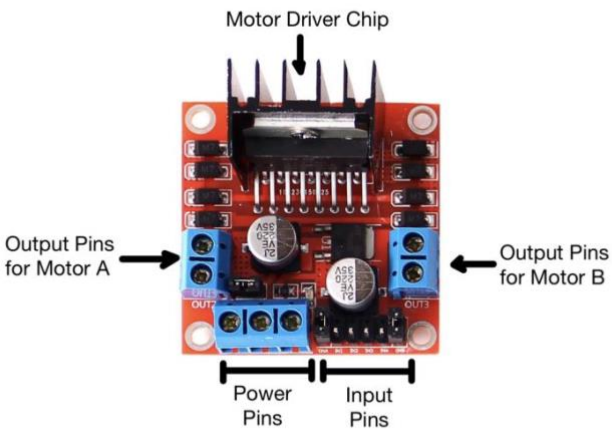


*Figure 8: Key features of motor driver*

### 2.3.5 Switch

Our switch is a single-pole, single-throw, momentary switch that is activated when it is pressed. This works as the metal needed to complete the circuit is suspended above the circuit whilst the switch is at rest. When it is pressed down, the circuit is closed, allowing current to flow. However, once it is released, a spring causes the switch to return to its initial position (Mano, n.d.). The button of the switch is rectangular with a side length of 10mm, as can be seen in Figure 9, created by the distributor Jaycar. Jumper cables were soldered onto the end of our switch, which were then inserted into the Arduino's pins so the Arduino could register input signals from the switch. The switch is secured onto the wooden prosthesis body with hot glue. To verify that the Arduino was able to read the switch, we wrote some simple code that output if the switch was pressed or unpressed based on its state, as seen in Appendix 4, which could then be read off the serial monitor of the Arduino software. When we confirmed this functioned, we modified the code to debounce the switch and tested it again using the same principle. The new code, which was also successful, is shown in Appendix 5.

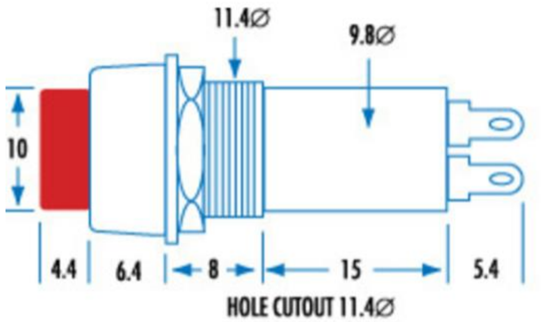


*Figure 9: Dimensions of switch (Jaycar)*

### 2.3.6 1.5V Batteries

In our project, we are utilising four 1.5V batteries, which total to 6V. This is the required amount of voltage to run our motor at full power. The batteries each store chemical potential energy, which is then transformed into electrical energy. This process occurs through an oxidation reaction where the anode releases electrons that travel through an electrolyte to the cathode. This then generates an electric current that can be used to power electronics (Bates, 2012). Our batteries are held in the battery holder, which is used to transfer the electrical energy. Initially, we planned on using a single 6V battery to power our prosthesis. However, upon testing with a voltmeter, we discovered that they did not actually produce 6V each. As it was difficult to source a battery holder that could hold the batteries we had purchased, we decided to modify our design and use four 1.5V batteries instead. Using a voltmeter again, it was verified these could produce 1.5V each.

### 2.3.7 Battery Holder

The battery holder can hold four standard AA batteries that are 1.5V each. This allows it to transfer 6V to our other electronic components. Our holder features a snap-in mount, where the plastic edges are curved to keep the batteries secure. When force is applied to pull the batteries out, the edges are pulled back, releasing the batteries. The appearance of the holder is shown in Figure 10. It is essential to ensure that the batteries are not dislodged when the user is operating the prosthesis, as the loss of power would cause the prosthesis to fail. The holder is attached to the wooden body using Velcro so it can easily be removed to change the batteries. We verified the holder was secure by inserting the batteries and moderately shaking it, mimicking the motion it would undergo when the prosthesis was being used. The wires from the holder were then connected to the pins of the motor driver. As the lights of the driver lit up, it was clear that the circuit was functional.

*Figure 10: Appearance of battery holder*

### 2.3.8 Finger Joint A

Individual finger joints have been FDM 3D printed using ABS as the material. This gives our fingers tough and durable properties, which ensures they will not break or degrade when the prosthesis is being used. Each finger features a hole running through the middle of the finger, through which the fishing line will be inserted. When the string is pulled, the joint will angle downwards, curling the gripper. The exact dimensions and appearance of the joint are shown in Figure 11. Bolts will be inserted through the holes to connect the finger to the mount on one end, and to Finger Joint B on the other end. Two of each joint have been used in our design. The performance of all the joints were verified together by connecting them into a functional finger and ensuring that pulling on the string created the required movement of the joints to close the gripper. We also ensured that the gripper was secure enough for the bag to not fall out when being carried.

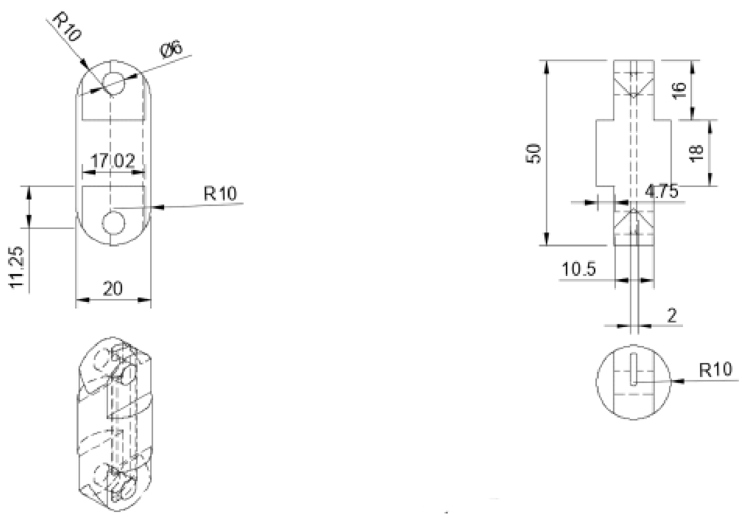


*Figure 11: Dimensions of Finger Joint A*

### 2.8.9 Finger Joint B

Like Finger Joint A, Joint B has also been 3D printed using ABS for the same reasons. A hole has also been printed into the joint, allowing the same line the be threaded through the finger. It mostly differs from Joint A as there is a hollow space at the ends of the fingers, allowing it to connect to Joint A and Joint C, making it the middle joint of the finger. This design, as well as the exact dimensions of the finger, are evident in Figure 12. Bolts are used again to secure the joints to each other, and the performance of the finger was verified with Joint A and Joint C.

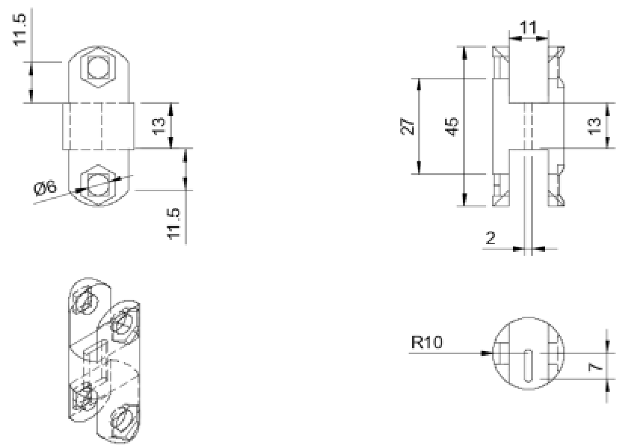


*Figure 12: Dimensions of Finger Joint B*

### 2.8.10 Finger Joint C

Joint C is the end joint of the finger, which has also been 3D printed with ABS. Unlike the other two joints, the end of the joint is rounded, mimicking the appearance of a real finger. A hole is also printed across the entire length of the joint, so the line threaded through it can be tied off and secured at the end of the finger. Its dimensions are shown in Figure 13. The inner end of the finger is bolted onto Joint B. Its performance was verified with Joints A and B.

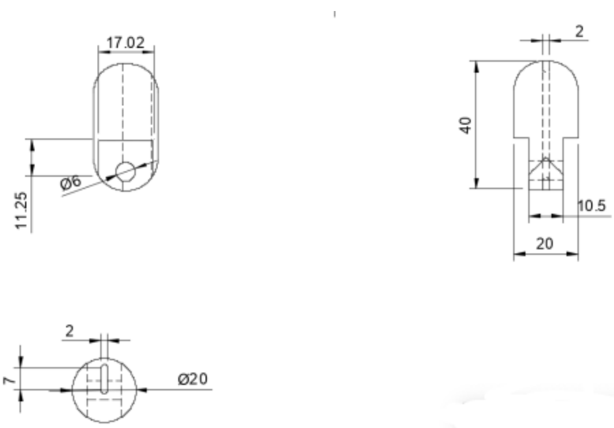


*Figure 13: Dimensions of Finger Joint C*

### 2.8.11 Finger Mount

A mount has also been 3D printed for our design. This was also printed using ABS to create a consistent aesthetic in our prosthesis. Although the mount has been printed to support up to 4 fingers, we have only connected fingers onto the middle two slots. In these slots, Joint A of both fingers has been bolted onto the mount. The mount is then screwed into the piece of wood to attach it securely to the prosthesis body. During our testing, we modified the design of the mount as it was originally modelled to be too large and protruded significantly from the piece of wood. Thus, it was remodelled and reprinted to be a more suitable size. These final dimensions are shown in Figure 14.

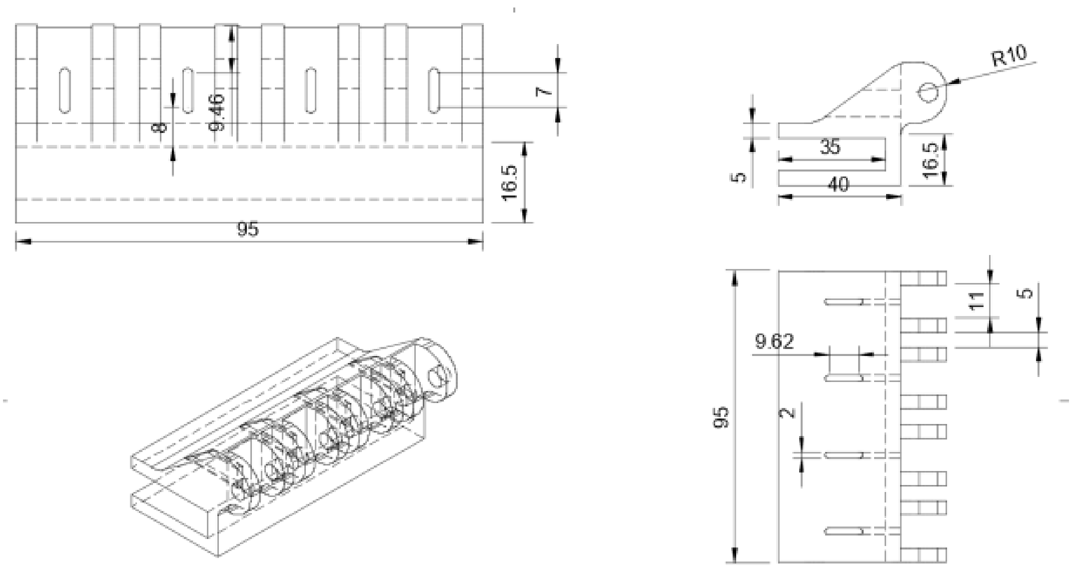


*Figure 14: Dimensions of finger mount*

### 2.3.12 Fishing line

Fishing line is made from nylon, which is a polyamide that is extremely strong due to the intermolecular hydrogen bonding that occurs between polymer chains. When drawn into line, nylon also becomes crystalline, which further increases its strength (Davis et al. 2018, p.381-p.391). According to the manufacturer, the fishing line is capable of withstanding 50 pounds of load, equating to roughly 22.5kg, which is more than double the maximum 10kg weight of the bag. The line has a diameter of 0.7mm. They further state the line does not stretch much, which allows the tension to be more easily controlled. We verified the strength of the line by tying it onto the motor shaft and through a finger and then running the motor at maximum power. As the motor stalled before the line broke, it was clear it would be able to carry the bag. In our design, one end of the line is tied onto the shaft coupler. The other end is threaded through a hole in the finger joints and knotted at the end so it will not be dislodged.

### 2.3.13 Velcro Tape

Velcro is composed of two different strips of fabric. As one side features loops of nylon, whilst the other has nylon hoops, the hooks catch on the loops when the sides are put together. This creates resistance that keeps the connection secure (Sharer 2023). Two strips each of Velcro hoops and loops are adhered to the side of the wooden plank by using the adhesive on the back of the tape. Each strip is 25mm wide and 150mm long. Thus, when connected, the straps will be able to support a maximum forearm diameter of around 280mm, since overlap of the straps is required for them to attach. We confirmed this diameter was sufficient for all members of our team by each wearing the prosthesis. We further made sure that the prosthesis would not slip off whilst being worn through freely moving the prosthesis around, emulating its standard use. Additionally, Velcro is also used in our design to secure the battery holder to the wood.

### 2.3.14 Female/Male Jumper Wires

Female/male jumper wires are wires that have a hollow pin on one end and a protruding pin on the other. These are highly suitable for quickly constructing simple circuits. We have used these to form electronic connections between the motor driver and the Arduino, as well as the Arduino and the switch. Each cable is 150mm long. When we attempted to construct the circuit, it was clear that the pins were not suitable for the pins on the motor driver, as the wires needed to be screwed in. Thus, some cables have been modified by stripping off the female end of the wire to expose the copper wiring underneath. The female ends were also stripped for the switch, as the wire ends had to be soldered on. After making these modifications, we could successfully construct a functional circuit, which was tested by running some simple code when simultaneously testing the Arduino. As the code worked, there was no need for further verification.

### 2.3.15 Cup Head Bolts and Nuts

Cup head bolts feature a smooth, domed head with a square neck, which is used to stop the bolt from spinning when it is being tightened. The body of the bolt is a threaded cylinder shape. The bolts used in our design have an initial length of 110mm and an M6 diameter. Each bolt is paired with a correspondingly sized nut to keep it into place. These have been used to connect the individual finger joints, as well as to connect the joints to the mount. However, when we tested these though connecting the individual joints, it was clear that they were too long. Thus, they were sawed and filed to a shorter diameter of 65mm, which were the required length. We then made sure that the joints still maintained their mobility when bolted together by threading the line through a single finger and manually pulling on the string.

### 2.3.16 Wood Screws

Screws of 3.5mm in diameter and 10mm long were chosen to mount the Arduino and L298N motor driver onto the piece of plywood, accounting for the size of the screw holes in each of these electrical components. Similarly, these same screws were used for the mounting saddle for the DC motor. Wood screws feature a wide spaced thread and a shrank that is not threaded, which allows them to stay secured to the wood without the need for nuts. We verified that the screws were sufficiently secure by attempting to dislodge the attached components. The result was that this was not possible unless they were unscrewed, which confirmed their stability.

### 2.3.17 Mounting Saddle

The mounting saddle is used to keep our motor in place and is screwed into the wood through wood screws. Despite typically being used to secure circuitry, we have repurposed this for our needs. The saddle is a plastic loop of radius of 25mm, which is equal to the diameter of our motor. There are 10mm long tabs that extend from the sides, each with a screw hole in the centre. These are shown in Figure 15. We checked the specifications provided were accurate by using it to secure the motor to the wood and then attempting to dislodge the motor. Through this, we found that the motor was slightly too small for the saddle. However, this was temporarily solved by inserting a piece of paper under the motor, which then kept it secure.

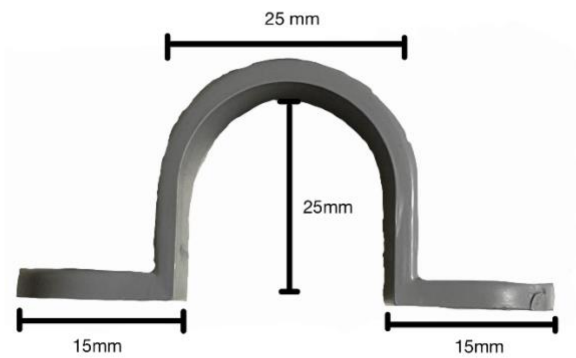


*Figure 15: Dimensions and appearance of saddle*

### 2.3.18 Wooden Prosthesis Body

We have chosen to use a piece of plywood as the body of our prosthesis. Plywood is manufactured by gluing thin layers of wood together. Each layer has its grain rotated at 90 degrees to the adjacent layers, which makes it strong in all directions (Specifier Australia n.d.). The Arduino, motor driver, switch, mounting saddle, finger mount, battery pack and Velcro straps are all mounted onto this wood through either screws or Velcro. The wood has dimensions 260mm x 75mm x 10mm, which resemble the approximate dimensions of a human forearm, determined through comparison with our own arms. In addition, plywood is not very heavy, with this plank weighing 0.13kg, making it easy to manoeuvre, which was confirmed by our own testing.

## 3. Design Performance and Reflection

In this section, we will present the results of the testing of our final design with respect to the objectives we have identified. We will then analyse any discrepancies in these results compared to our expected results and provide reasons for these discrepancies. We have also explained how our design was able to successfully meet the requirements.

### 3.1 Design Performance Results

In Table 1, we have collated our results obtained during both the preparatory testing of our final design to confirm its performance prior to testing day, and the performance of our prosthesis during the final testing day.

*Table 1: Prosthesis performance during testing*

| Criteria | Preparatory Testing Outcome | Final Testing Outcome |
|---|---|---|
| Time taken to pick up bag | 5 seconds | 16 seconds |
| Maximum weight carried | 4kg | 1kg |
| Time bag was held (maximum 10 seconds) | 10 seconds | 10 seconds |
| Distance walked with bag (maximum 20m) | 20m | 20m |
| Release bag onto table | Successful | Successful |

From these results in Table 1, it is clear our device significantly underperformed during testing with respect to how much weight it was able to carry, which was the most important criteria. Although we calculated the motor would be able to support a weight of over 10kg, we only successfully carried 4kg in our preparatory testing. It is possible the prosthesis is able to carry a higher weight than 4kg, but this was not tested as it was clear the grip had difficulty holding 4kg, and we did not want to risk damaging the prosthesis. We attempted to carry 6kg during final testing, but we were unable to grip both straps of the bag to lift it up securely. As we were certain the gripper could not support 6kg with only one strap, we abandoned this attempt.

There are a variety of possible reasons that could cause this discrepancy. One cause is our mechanical system not being perfectly efficient. The friction in between the individual joints, as well as the friction between the fishing line and the joints would decrease the amount of torque that can be used to curl the fingers. Furthermore, another factor is that the strings are not aligned perfectly perpendicular to the motor shaft. Instead, as there are multiple strings, each is positioned at a slight angle. As torque is determined by the force applied perpendicular to the position vector, this would reduce the amount of torque exerted on each string. In addition, according to our research, using the motor driver can cause a drop in the voltage supplied to the motor of up to two volts (Last Minute Engineers n.d.). This would lead to the motor not operating at maximum power, which reduces the torque the motor can produce. Lastly, as two strings are being controlled by the same motor, the torque exerted would be distributed across the two strings. This could cause a significant reduction in the torque applied to each string, limiting their ability to withstand the weight of the bag. Ultimately, it is likely a combination of all the above factors contributed to the underperformance of our design.

It is also clear from Table 1 that we experienced difficulties in picking up the bag during final testing, even though we were able to meet the requirement of picking up the bag within 5 seconds during our preparatory testing. The prosthesis is programmed to close 3 seconds after the button is pressed. This should typically be sufficient for the user to pick up the bag. However, during final testing, our demonstrator had failed to press the button on the first attempt. As there was no indicator if the button had been pressed, five seconds had already passed before they reattempted to press the button. Upon the second try, they were able to pick up the bag as usual, but this led to the increased duration of 16 seconds.

Despite these unexpected results, the prosthesis was still able to perform the required minimum functions of picking up, carrying, and releasing a 1kg grocery bag identified in our problem statement. This can be attributed to the fundamentals of our design, centring around the activation of a two-fingered gripper, working as intended. Due to our rigorous testing of each individual component, we were able to make the necessary modifications required, such as by changing the dimensions of the fingers, to ensure they were able to form a secure grip whilst carrying the bag. The creation of multiple iterations of prototypes was also highly beneficial in ensuring that the circuitry of our design performed as expected, which guaranteed the gripper could successfully open and close to pick up and release the bag. The code was also extensively tested and modified to ensure our electronic subsystem was able to reliably operate and control the gripper when the switch was activated.

## 3.2 Reflection

Within this section, we will reflect on our team's performance throughout the duration of the project with regards to both our final design and our project planning. We have also included recommendations for changes that should be made in the future to increase our rate of success.

### 3.2.1 Final Design Reflection

In this section, we have reflected on the major positive and negative elements of our design, and justified how each relates to the objectives of the project. We have also assessed the impact of our team's adherence to the engineering design process.

#### 3.2.1.1 Single-press Activation

The implementation of the single-press activation and control system was the most successful part of our design. Our positioning of the switch on the side of the prosthesis body allowed it to be easily pressed by the client's opposing residual limb or leg. This fulfilled the primary request put forward by the client that the prosthesis should be simple to operate, as identified in our problem statement. Hence, it is evident that the unambiguous objectives established in our problem statement, which were used to guide our concept generation, had a positive influence on our design. Additionally, through working in combination with the Arduino and motor driver, the code ran smoothly and ensured the prosthesis was able to reliably carry out its function.

#### 3.2.1.2 Mechanical Gripper

The 2 fingered gripper was able to successfully open and close upon the activation of the switch. This guarantees that the prosthesis can perform its function of allowing the user to first pick up a bag, then carry, and finally release the grocery bag. Furthermore, the motor was able to generate sufficient torque such that the gripper would remain closed whilst carrying a 1kg bag, ensuring the user would be able to hold the bag for 10 seconds and walk for 20m. Our ability to fulfil these objectives can mostly be attributed to our team clearly determining the minimum requirements of our design and including them in the problem statement before proceeding to concept generation. This then ensured that all generated concepts would adhere to these conditions and thus fulfil the client's needs.

#### 3.2.1.3 Wooden Body

The plank of plywood used as the body of the prosthesis was an effective design choice. The wood was lightweight, which made the prosthesis easy to manoeuvre and control. Furthermore, it limited the stress placed onto the client's arm when carrying a bag, which both increased the comfort and limited the possibility of injuries. The wood was also an effective mount for the other components of the design, as they were firmly secured and could not accidentally be dislodged when the prosthesis was being used. The success of this component is due to our effective concept evaluation, where we decided to prioritise the functionality of the design over aesthetics. As a result, we chose wood over options such as metal and acrylic due to it being both easy to work with and stable.

#### 3.2.1.4 Velcro Attachment

Although the inclusion of Velcro straps did allow the user to attach the prosthesis, it did not satisfy the client's preference that the prosthesis could be independently attached and detached. In our design, external assistance is required to securely attach the prosthesis, or it is highly likely it will be dislodged from the user's arm when being used. The main cause of this design flaw comes from inadequate concept generation. Despite the attachment system being a significant component of the arm, we spent the majority of concept generation focusing on the gripper instead. This ultimately led to our team being unable to devise an effective solution due to the limited time constraints of the project.

#### 3.2.1.5 Battery Power

Our method of powering the prosthesis through batteries is also inefficient. Due to the way the circuit was constructed, as could be seen in Figure 3, the electrical components are constantly being powered when there are batteries in the battery holder. As a result, either the batteries will have to be taken out in between uses of the prosthesis, or they will be quickly depleted and will have to be frequently replaced. This is extremely inconvenient, which is especially the case when the client is a bilateral amputee and cannot perform the task themselves. It also increases the cost of using the prosthesis as new batteries will have to be purchased. This oversight was the result of poor planning and research when constructing the design. Although the issue could be easily fixed by including a second switch in our design, our time constraints meant that we were unable to correct this mistake before the prosthesis was due to be tested.

#### 3.2.1.6 Electrical Wiring

Although our electrical circuit was functional and could carry out its required function, the wiring was clumsily implemented. Wires were often tangled and not properly secured, resulting in a uncompact design. Additionally, the jumper cables were simply placed into the pins of the Arduino and motor driver and were not otherwise secured. This could easily result in wires being accidentally dislodged by the user, causing the prosthesis to malfunction. Furthermore, our wiring is uncovered, so the prosthesis is not waterproof. This not only mean the prosthesis is easily damaged and cannot be used when it's raining, but also poses a significant safety risk, especially when it is being worn. This issue arose from not considering the circuitry during earlier iterations of prototypes, which led to the final iteration featuring this unorganised design.

### 3.2.2 Design Recommendations

- Include a second switch that allows the user to turn the prosthesis on and off
- Solder wires to Arduino and motor driver so they are more secure
- Create a covering for the arm that protects the electrical components, preventing water damage and accidental removal of wires
- Use zip-ties to organise loose wiring
- Evenly focus on all elements of the design during concept generation
- Construct more prototypes and begin construction at an earlier stage to solve unexpected issues before the final design

### 3.2.3 Project Plan reflection

Our project planning consisted of creating a work breakdown structure, a Gantt chart and a budget for this project. Overall, our project planning had both positive and negative influences on the success of our project. These will be discussed in this section of the report.

#### 3.2.3.1 Work Breakdown Structure

The work breakdown structure both positively and negatively influenced our team's performance. The main successful aspect was that we were able to accurately identify all the tasks that had to be completed across the project's duration. We were also able to give a detailed description of what each individual task entailed, which allowed us to better understand the process involved in completing the project and thus plan for these tasks.

However, the major fault of our work breakdown was that tasks were poorly divided amongst team members. This was especially evident during the prototype construction stage, as only two of our six members were able to make significant contributions through either constructing the gripper or by constructing the circuit as well as writing the code. Naturally, this was highly unproductive and increased the time taken to develop a prototype. This increased time lead to us being unable to fix some issues discovered in our prototyping, as were discussed in Final Design Reflection.

#### 3.2.3.2 Gantt Chart

The Gantt chart was developed based on our work breakdown structure. The most successful aspect was the inclusion of contingency time at the end of the project to account for unexpected delays and still ensure our team would be able to complete the project within the time constraints. This proved to be vital when we experienced delays such as the shaft coupler being delivered a week later than expected or the 3D printing of the gripper requiring four days rather than two.

Although the contingency time proved to be extremely important, this was partly due to our estimated durations for each task being rather inaccurate. For instance, during the prototype construction stage, we had anticipated that constructing the circuit would only take one day to complete. However, Jordan, who was assigned to this task, was unable to complete it within four days. The task then had to be delegated to Kevin, who took another day to finish the task. On the other hand, we had estimated it would take seven days to code the motor. In reality, this task was completed within a day. Such inaccurate estimates resulted in a lot of time being wasted, as some tasks were yet to be completed whilst others had already been finished for a long time, and the dependencies between these tasks prevented us from moving onto the next stages. Once again, this limited the amount of time spent on creating further iterations of prototypes, preventing us from discovering and resolving many issues until there was not enough time remaining.

#### 3.2.3.3 Budget

The budget was the most successful part of our project plan. It was extremely accurate and identified all the costs involved the project except for the unanticipated purchase of cuphead nuts and bolts. The creation of a budget allowed us to compare prices between suppliers and find the most effective option, which prevented the need for uninformed, last-minute purchases. This also allowed to identify that some components could be acquired for free, such as sourcing wood and screws from the UNSW Makerspace which reduced our total costs. Ultimately, the total cost of our project was $132.90, which was $17.10 under the budget constraint.

### 3.2.4 Project Plan Recommendations

There are several recommendations for our project planning that could be implemented into future projects to significantly increase their chance of success.

Firstly, the work breakdown structure should be created with a much larger emphasis on the person performing the task, as opposed to just the task itself. This would allow us to notice that there were periods where several members of the group were not contributing to the project and hence modify the breakdown to correct this. Furthermore, we could more strongly account for our individual strengths and weaknesses and assigned tasks accordingly, in contrast to our method of members volunteering themselves for tasks. If we ensure that everyone performs the tasks that they had experience with, they could be completed in a shorter timeframe and with more success.

In addition, it would be beneficial to identify the dependencies between tasks more clearly. For instance, this would involve identifying the prerequisites that need to be completed before each new task. This would then ensure that we do not overlook any tasks that are linked together. As a result, we would be able to assign these dependent tasks to one person, so they could proceed to the next task without the need to wait for other members to catch up. This eliminates a significant amount of time spent waiting, and naturally decreases the time required to complete the project.

Lastly, our team would benefit from using a wider range of tools to estimate the duration of tasks. Most of our estimates came from group decision making, where we simply came to a consensus regarding the length of the task. However, it is clear this was not very accurate. For future projects, we should consider tools such as analogous estimating based on our prior experiences, three-point estimation to account for unexpected delays, and asking other people more familiar with the task for their opinion. By obtaining more accurate estimates, this would allow us to create a schedule where all members will be able to always contribute.

## 4. Conclusion

Our solution is a hand prosthesis with two controllable fingers that can open and close, allowing the user to pick up, carry, and release a grocery bag. This mechanism will be operated by a motor, activated with a button press, that controls the tension in strings threaded through each finger. Our prosthesis is attached by using Velcro strapping. This is an effective final design, as it is most importantly able to perform the required function dictated by the design brief. It also highly successfully addresses the client's principal need of a device that is 'simple to operate' through its innovative, automated activation method that only requires the press of a button. However, the design underperformed during testing, as it was only able to carry 4kg of weight, compared to the expected 10kg and also failed to include some of the client's desired features. Ultimately, our team recommends that further iterations of the design should be developed to increase the amount of weight carried, as well as address the design's inability to be independently attached and detached for greater client satisfaction to be achieved.

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# 6. Appendices

## Appendix 1: Final code used to control the prosthesis

```
#include <Bounce2.h>

//Button
const unsigned char switchInput = 4;
Bounce debouncedSwitch = Bounce();

bool switchClosed;
bool switchClosedSetup;

// Motor connections
int enA = 7;
int in1 = 8;
int in2 = 9;

//Modes
enum {handIdle,handClosing, handClosed, handOpening};
unsigned char handState;

void setup() {
  //Button
  Serial.begin(9600);
  debouncedSwitch.attach(switchInput);
  debouncedSwitch.interval(5);

  pinMode(switchInput, INPUT_PULLUP);

  // Set all the motor control pins to outputs
  pinMode(enA, OUTPUT);

  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);

    // Turn off motors - Initial state
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);

}

void loop()
{
  // Update Button:
  debouncedSwitch.update();
  unsigned char switchValue = debouncedSwitch.read();

switchClosed = (!switchValue and switchClosedSetup);
  switchClosedSetup = switchValue;

// Initial state: Hand is open and waiting for input from switch
  switch(handState){
    case handIdle:
     Serial.println("Idle");
      if (switchClosed){
       handState = handClosing;
        break;
    }
      else{
        Serial.println("Idle");
```

```
            break;

    }
    // Second State: Button has been pressed and hand closes after delay
  case handClosing:
   Serial.println("Closing");
   delay(5000);
   closeControl();
   handState = handClosed;

    //Third State: Hand remains closed whilst in operation
  case handClosed:
     Serial.println("Closed");
      analogWrite(enA, 255);
    digitalWrite(in1, LOW);
    digitalWrite(in2, HIGH);
   if(switchClosed){
     handState = handOpening;
     break;
   }
   else{
     break;

   }
   //Fourth State: Hand reopens when switch is pressed again and returns to initial state
  case handOpening:
    Serial.println("Opening");
    delay(5000);
      openControl();
      handState = handIdle;
      break;

    default:
      delay(1000);
      handState = handIdle;
      break;
  }

}
// Sets motor to close the hand
void closeControl() {
  analogWrite(enA, 255);

  digitalWrite(in1, LOW);
  digitalWrite(in2, HIGH);
  delay(5000);


}
//Sets motor to open the hand
  void openControl() {

  analogWrite(enA, 255);

  digitalWrite(in1, HIGH);
  digitalWrite(in2, LOW);
  delay(1500);

  // Now turn off motors
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);

}
```

**Appendix 2: Calculation of torque caused by carrying a 10kg bag**

$$\tau = Fs$$

$$F = ma$$

$$F = 10(9.8)$$

$$F = 98N$$

$$s = 0.004$$

$$\tau = 98(0.004)$$

$$\tau = 0.4Nm^{-1}$$

## Appendix 3: Code used to verify motor performance

```
// Motor A connections
int enA = 9;
int in1 = 8;
int in2 = 7;


void setup() {
  // Set all the motor control pins to outputs
  pinMode(enA, OUTPUT);
  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);

  // Turn off motors - Initial state
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);
}

void loop() {
  directionControl();
  delay(1000);


// This function controls the spinning direction of motors
void directionControl() {
  // Set motors to maximum speed
  analogWrite(enA, 255);

  // Turn on motor A
  digitalWrite(in1, HIGH);
  digitalWrite(in2, LOW);
  delay(2000);

  // Now change motor directions
  digitalWrite(in1, LOW);
  digitalWrite(in2, HIGH);
  delay(2000);

  // Turn off motors
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);
}
```

## Appendix 4: Code used to verify switch performance

```
#define BUTTON_PIN 4
void setup()
{
  Serial.begin(9600);
  pinMode(BUTTON_PIN, INPUT);
}
void loop()
{
  byte buttonState = digitalRead(BUTTON_PIN);
  //Shows detected state of button
  if (buttonState == HIGH) {
    Serial.println("Button is pressed");
  }
  else {
    Serial.println("Button is not pressed");
  }
  delay(100);
}
```

# Appendix 5: Code used to test the switch when debounced

```
#include <Bounce2.h>

//Button
const unsigned char switchInput = 4;
Bounce debouncedSwitch = Bounce();

bool switchClosed;
bool switchClosedSetup;

//Modes
enum {handIdle,handClosing, handOpening};
unsigned char handState;

void setup() {
  //Button
  Serial.begin(9600);
  debouncedSwitch.attach(switchInput);
  debouncedSwitch.interval(5);

  pinMode(switchInput, INPUT_PULLUP);

}

void loop()
{
  // Update the Bounce instance :
  debouncedSwitch.update();
  // Get the updated value :

  unsigned char switchValue = debouncedSwitch.read();

switchClosed = (!switchValue and switchClosedSetup);
  switchClosedSetup = switchValue;
if(switchClosed){
  Serial.println("closed");
  delay(200);
}
else{
  Serial.println("open");
  delay(200);
}
}
```