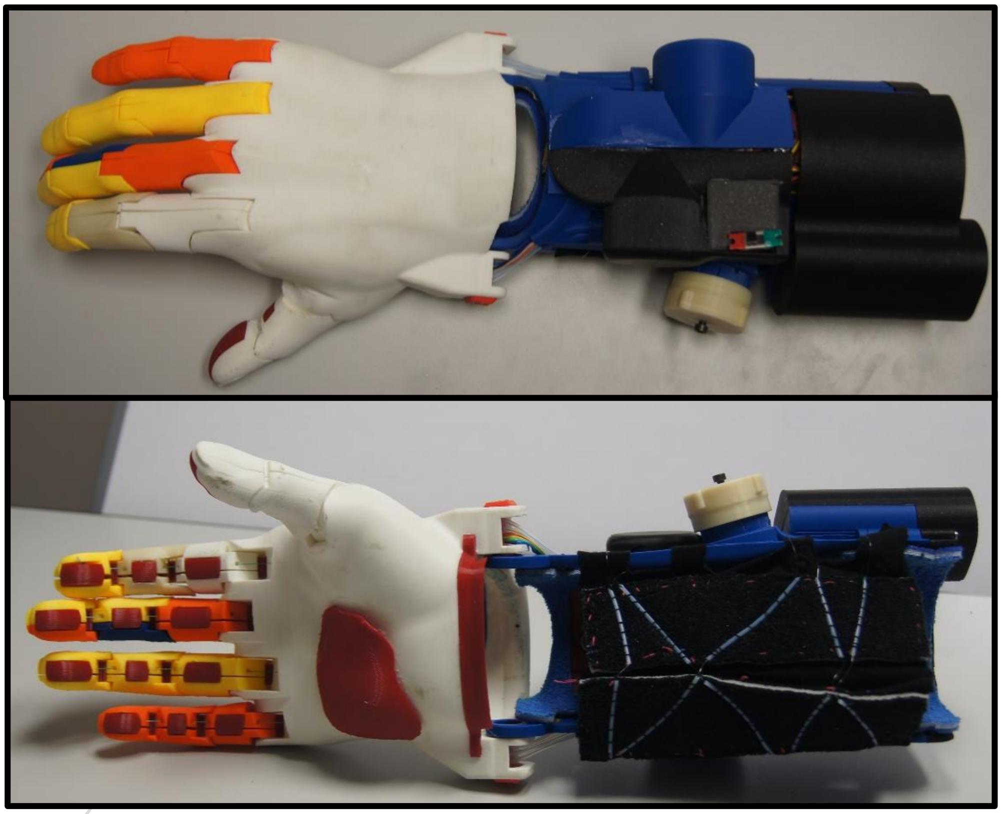
28/06/19

RESPONSIBLE DESIGN

ELECTRONICALLY ASSISTED PROSTHESIS



Abstract

This report presents a design for an electronically assisted, upper-limb prosthesis for a trans-radial amputee. The brief laid out at the start of the project required the prosthesis to be 3D printed, low cost, electronically actuated and controlled. The approach taken was a combination of experimental testing, rapid prototyping and user testing. The final prototype is actuated using two servo motors that contract fingers using fishing line. It is controlled using a joystick attached to the user's residual thumb joint. A pressure sensor in the finger communicates how much force is applied to an object by activating vibration motors on the residual arm. Force testing and mechanical analysis was used to decide on a design for the fingers, and furthermore used to optimise their function.

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1 Introduction

Prosthetic design has existed for millennia with some of the oldest, most basic prosthesis on record originating from Egypt almost 3000 years ago during the Pharaonic Period where prostheses were made commonly from wood and leather [1].

In the modern age, the technologies associated with prost
hetic design have advanced greatly from the Pharaonic Period. Today the most advanced prostheses involve the use of complex electronics and materials. The advent of 3D printing technologies has made it easier than ever for individuals to design, test, and build their own 3D printed prosthetic devices. 3D printing allows the manufacturing of prostheses to occur in remote environments so long as a 3D printer is available, making prosthetic devices cheap and accessible to individuals in need, who would otherwise never be able to obtain such a device.

The project, which is titled “Responsible Design”, involves students from the GI-NOVA Laboratory (part of the school of Génie Industriel at Grenoble INP) working in collaboration with the Gre-Nable community to design, test and build an electronically assisted prosthesis for a user who only has a residual palm. The Gre-Nable community is part of the much larger e-Nable community, an independently funded, community driven organisation, who match makers with access to 3D Printers to individuals in need of a prosthetic device. The sole purpose is to help those with disabilities access 3D printed prostheses that could improve the quality of their lives.

1.1 User Persona

This user persona is representative of the individual who was involved in this project and the type of individual who could benefit from the device created.

Name: Florence Bernard
Age : 50
Interests: Gardening, Cooking, Painting, Cards, Hiking
Disability: Trans-radial Amputee

Florence has the need of a prosthesis for her right hand as she has no fingers and only a small portion of her thumb on her right hand, Figure 1-1. She solely uses a mechanical prosthesis because she finds her current electronically controlled prosthesis to be to inaccurate and heavy. Therefore, a lighter and more reliable electronically assisted prosthetic is required to be developed for her.

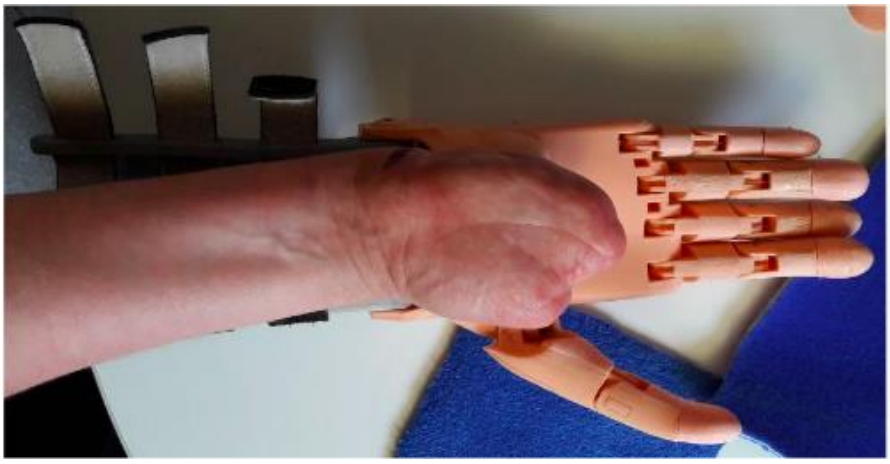


Figure 1-1: User's Residual Limb [2]

1.2 Initial Requirements

Several key initial requirements were outlined in the brief at the beginning of the project stating that the device should be:

- 3D printable.
- Electronically assisted.
- Open-Source.
- Maximum materials cost of €200.
- Maximum weight of 500g.
- Universal for multiple users.

Therefore, the aim of this project is to develop an electronically assisted trans-radial prosthetic for a specific user. However, this product should also be open source and accessible to the rest of the community, meaning the product should be versatile to allow it to be adapted for other users.

2 2018 Design

A group of university students from the University of Bath and other international institutions worked on this project in 2018. They produced the device seen in Figure 2-1.
They used an existing model of a prosthetic hand called the 'Kwawu Hand' and tried to combine it with electronic components mounted on the Gauntlet. Their aim was to use a linear actuator controlled by an Arduino Micro to actuate the movement of the fingers. However, they failed to get the system functioning. There were several key issues with the design listed below:

- The fingers were very stiff and required a large force to contract.
- There was a large amount of friction in the system due to poor routing of the wires through the palm.
- The fishing wire used had a low Young's Modulus, meaning they could stretch easily. This resulted in a lot of energy loss to elastic potential energy in the actuation system.

All the issues associated with the 2018 design and the lessons learned from them would be used to influence the design choices of this project. It was established that the best way to proceed would be to do extensive testing of current technologies and elements of prosthesis design which were most suited to our project.

The overarching aim of this project was to create a fully functioning, electronically controlled prosthesis that improved upon all the flaws of the prosthesis developed by the 2018 group.

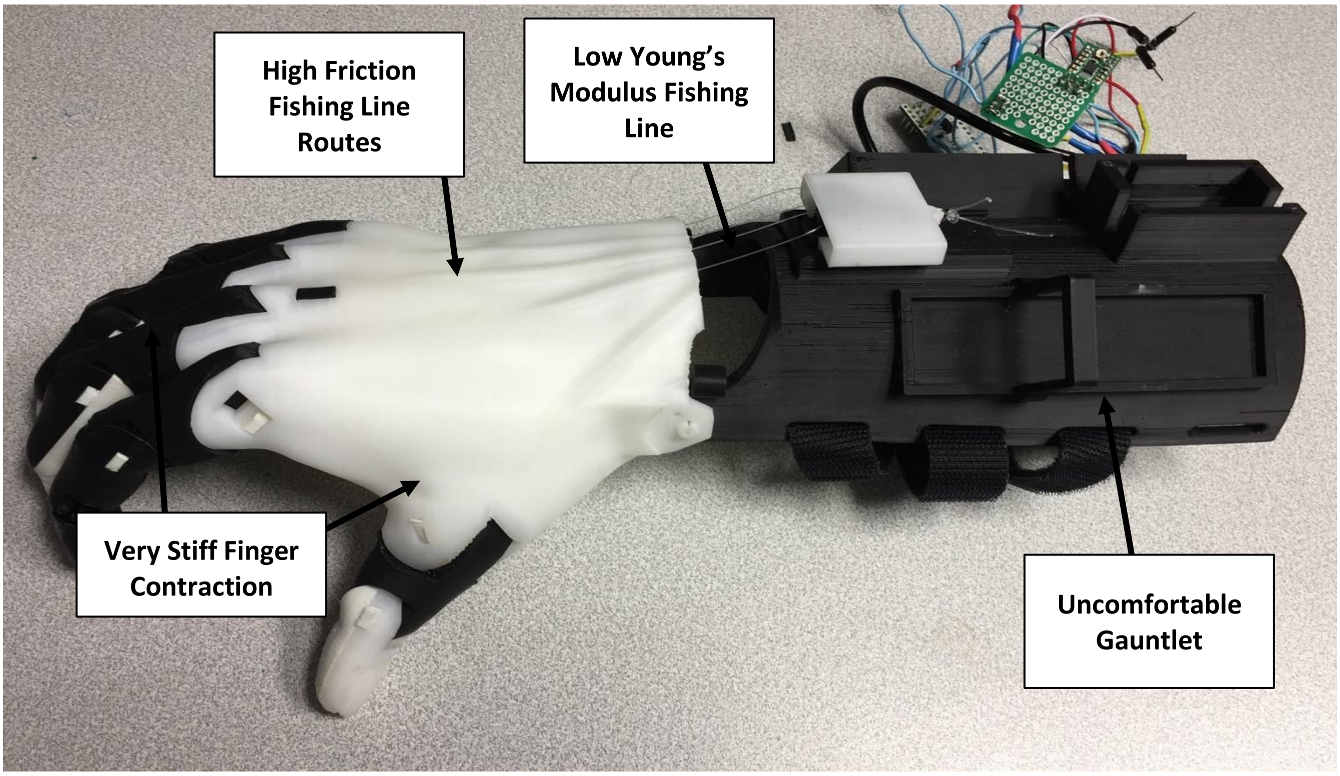


Figure 2-1: Prosthesis Designed by Students during the 2018 Semester

3 Initial Specification

The initial specification, Table 3-1, was constructed from the information given in the project brief, the initial requirements and the description of the user. The initial specification has several specification points that were initially non-quantifiable due to the limited information at the beginning of the project. These specification points have "Quant?" beside them. However, as the project proceeded it was possible to quantify these criteria.

Design Specification: Responsible Design				
D/W	**Wt**	**Requirements**	**Source**	**Kano**
		Physical Characteristics		
D	H	• Weight to be <500g	Brief	Basic
D	H	• As small as possible	Initiative	Performance
D	H	• Universal fit	Brief	Excitement
		Performance Requirements		
D	H	• Power Grip	Brief	Basic
W	M	• Can perform secondary grips (pinch)	Initiative	Performance
D	H	• User does not have to provide constant force to maintain grip	Brief	Basic
		• Allow wrist movement		
W	M	• Battery Usage Length (Quant?)	Brief	Performance
W	M	• Use of Myoelectric/Pressure sensors (avoids user providing	Initiative	Performance
W	M	constant force)	Initiative	Performance
		• Max weight that can be lifted (Quant?)		
D	H		Initiative	Performance
		Product Safety		
D	H	• Encasement of electronics	Initiative	Basic
D	H	• Voltage regulators	Initiative	Basic
W	H	• Waterproofing	Initiative	Performance

		Maintenance		
W	M	• Easy to disassemble/assemble if required	Initiative	Performance
W	M	• Easy connection to Arduino	Initiative	Performance
W	M	• Easy to clean	Initiative	Performance
		Manufacture & Design		
W	M	• Efficient use of 3D/Laser printing	Initiative	Basic
D	H	• Parts easily assembled	Initiative	Performance
W	M	• Suitable materials used	Initiative	Basic
D	H	• Minimal amount of material used	Brief	Basic
W	H	• Reduce no. of parts to minimum (Quant?)	Initiative	Performance
D	H	• Open-source	Brief	Basic
D	H	• Use existing available parts	Brief	Basic
D	H	• Max price €200	Brief	Basic
W	M	• Recyclable materials used	Initiative	Excitement
D	H	• Design completed by 14th June	Brief	Basic
W	H	• Easily Replicated	Initiative	Performance

Table 3-1: Initial Specification

4 Project Management

Project management is the management of all techniques, knowledge, tools and skills used in the project to meet the time, budget and quality constraints (which are also called the "triple constraints") [3].

To properly manage the project, the phases of the project life cycle are needed to be specified. To carry out a successful project the team should select a suitable management process by clearly defining the projects requirements. By having good communication with the stakeholders, which are the user and the supervisors of the project, the needs and expectations should be specified in each stage of the life cycle [3].

4.1 Management Styles

At the beginning of the project multiple styles of project management were researched so that an effective method could be implemented that would suit the needs of the project. These were:

Stage Gate (Waterfall)

A stage gate process is a project management technique in which an initiative or project (e.g new product development) is divided into distinct stages separated by decision points known as gates. At each gate, continuation is typically decided by a manager, steering committee, or governance board. The decision is made on forecasts and information available at the time, including the business case, risk analysis, and availability of necessary resources (e.g., money, people with correct competencies).

The traditional stage gate process in Figure 4-1 has five stages with four gates. The stages are typically:

1. Scoping
2. Build business case
3. Development
4. Testing and validation
5. Launch

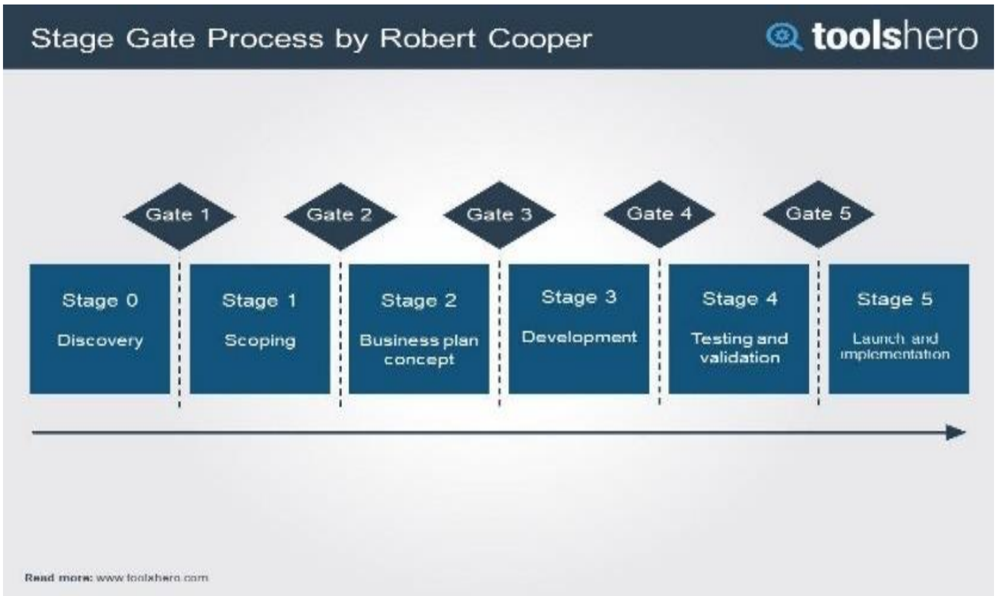


Figure 4-1: Traditional Stage Gate Process [4]

Before the beginning of this process there is often a preliminary ideation/discovery stage. The number of stages and gates may change depending on the length, size and risk associated with the project.

Stage 0 - (Discovery/Ideation): Idea generation and ultimately deciding on what projects the company should pursue.
Stage 1 - (Scoping): Evaluate the product and its corresponding market. Recognise the strengths and weaknesses of the product and the potential customer offering. As well as competition. Determining the level of market threat allows a judgment to be made on whether to precede.
Stage 2 - (Building Business Case): In this stage the company must put together a product definition and analysis, build a strong business case and project plan, as well as a feasibility review.
Stage 3 - (Development): During the development phase plans from the previous steps are carried out. The ultimate deliverable of the development phase is the prototype, which will undergo extensive testing and evaluation in the next phase of the process.
Stage 4 - (Testing + Validation): This phase provides validation for the entire project. Areas that will be evaluated include: the product itself, the production/manufacturing process, customer acceptance, and the financial merit of the project.
Stage 5 (Product Launch)*:* At the launch the product will have passed all the previous gates. The company must come up with a marketing strategy to generate customer demand for the product.

Gates provide a point during the process where an assessment of the quality of an idea is undertaken. It includes three main issues:

- *Quality of execution*: Checks whether the previous step is executed in a quality fashion.
- *Business rationale*: Does the project continue to look like an attractive idea from an economic and business perspective.
- *Action plan*: The proposed action plan and the requested resources are reasonable and sound.

Gates have a common structure and consist of three main elements:

- *Inputs*: What the project manager and team deliver to the decision point. These deliverables are decided at the output of the previous gate and are based on a standard selection of deliverables for each gate.
- *Criteria*: Questions or metrics on which the project is judged to determine a result (go/kill/hold/recycle) and make a prioritisation decision.
- *Outputs*: Results from the gate review. A decision (go/kill/hold/recycle), along with an approved action plan for the next gate, and a list of deliverables and date for the next gate [5].

Strategic Project Management (SPM)

Strategic Project Management consists of selecting, managing and measuring project outcomes to ensure optimal value for an organization. All projects undertaken by an organization must meet a set of criteria setup by the organizations' leadership to ensure alignment with the strategic vision of the organization [6].

Breakdown of the Strategic Management Process:

1. Selection of the corporate mission and major corporate goals.
2. Analysis of the organization's external competitive environment to identify opportunities and threats.
3. Analysis of the organization's internal operating environment to identify the organization's strengths and weaknesses.
4. The selection of strategies that build on the organization's strengths and correct its weakness to take advantages of external opportunities and counter external threats.
5. Strategy implementation [7].

This breakdown is also applicable to the smaller scale cases of a small business or simple team of individuals.

Agile Project Management

Agile Project Management (APM) is an iterative approach to planning and guiding project processes. An agile project is completed in small sections and these sections are called iterations.

An iteration refers to a single development cycle. Each section or iteration is reviewed and critiqued by the project team. Insights gained from the critique of an iteration are used to determine what the next step should be in the project.

The main benefit of Agile Project Management is its ability to respond to issues as they arise throughout the course of the project. Making a necessary change to a project at the right time can save resources and, ultimately, help deliver a successful project on time and within budget.

Agile Project Management breaks down projects into small pieces that are completed in work sessions that run from the design phase to testing and quality assurance (QA). These sessions are often called sprints. Sprints are generally short, running over days or weeks; they are typically two to four weeks long.

The Agile methodology enables teams to release segments as they are completed. This continuous release schedule allows for teams to demonstrate that these segments are successful and, if not, to fix flaws quickly. The belief is that this helps reduce the chance of large-scale failures, because there is continuous improvement throughout the project lifecycle.

Agile Project Management does not require the presence or participation of a project manager. Although a project manager is essential for success under the traditional project-delivery methodologies, such as the Stage-

Gate model (where the project manager manages the budget, personnel, project scope, quality, requirements and other key elements), the project manager's role under APM is distributed among team members.

Given the shift in work from project managers to Agile teams, Agile Project Management demands that team members know how to work in this new fashion. They must be able to collaborate with each other, as well as with users. They must to be able to communicate well to keep projects on track. And they should feel empowered to take appropriate actions at the right times to keep pace with delivery schedules [8].

Extreme Project Management

Extreme Project Management helps organizations manage the unknown by allowing alterations in plans, budgets, and final outcomes at any project stage. Unlike other project management approaches, Extreme Project Management offers an open-ended, flexible, and deterministic way to handle complex business problems. Businesses that rely on scientific discovery/invention, or organizations (e.g. Apple) that are pushing the envelope of known technical capabilities, will often employ this method due to its tolerance for uncertainty.

Extreme Project Management works best for complex and uncertain projects that involve frequent changes to conditions as the project progresses. This approach is commonly used when it is not possible to fully understand a project's requirements and guidelines are driven by market changes. The project team must be willing to make several attempts to achieve the desired result [9].

Critical Chain Project Management (CCPM)

The Critical Chain Project Management Approach (also known as Critical Path) was developed in response to poorly executed projects that resulted in longer than expected durations, frequently missed deadlines, budget overruns, and missed deliverables. CCPM focuses on the use of resources required to execute project tasks. The "critical chain" of the project is the longest sequence of tasks that are constrained by the availability of a resource (which could be a team member, a natural resource, a time window, a budget, etc.). To address potential resource availability issues, the project manager builds in safety buffers to ensure projects are on-time.

The 3 types of safety buffers are as follows:

***Project buffer*:** A project buffer protects the project completion date, which might be variable due to changes in activity durations on the critical chain.

***Feeding buffers*:** A feeding buffer is any path of activities merging into the critical chain. To protect against delays on critical paths, feeding buffers are inserted between the last task on a feeding path and the critical chain.

***Resource buffers**:* Resource buffers can be set alongside the critical chain to ensure that the renewable resources are available to work on critical chain activities as soon as they are needed.

CCPM should be used when projects are concerned with resources. Ultimately, this approach is effective in sending quality deliverables on time by proactively removing constraints [9].

4.2 Chosen Management Style

For this project the team felt that the most applicable project management style would be something in line with the stage-gate process. From the beginning of the project a set of deliverables had been requested from the supervisors which immediately led to the creation of clear milestones that had to be worked towards.

Stages

For this project it was felt necessary to divide the stages up as follows as they corresponded well with a new product development endeavour:

1. Discovery
2. Scoping/Research
3. Testing
4. Prototype Development
5. Final Design

Stage 1 - (Discovery)*:* At the beginning of the project the team was issued with a project brief, outlining that the project was to design an "electronically assisted prosthesis", and a list of deliverables and requirements by the project supervisors. This provided an insight into what the project was going to entail, and it allowed the team to develop a plan of how to move forward.

Stage 2 - (Scoping/Research)*:* It was then necessary to do extensive research in the field of prosthesis design and to discover all the possible technologies that could be tested and hopefully implemented in the final design.

Stage 3 - (Testing): After the research had been conducted it was possible to test the designs and technologies that were most applicable to this project and of most interest to the design team. It was necessary to determine what designs could be carried forward to the prototype development phase, but it was necessary to have justified reasoning on why the component selection was made. During this stage it was also possible to interview the user which provided the team with more design direction.

Stage 4 - (Prototype Development): Using the findings from the testing stage it was possible to design and build several initial prototypes by iterating and continuously improving the design of individual components. This stage was concluded with a 2nd meeting with the user where they highlighted their likes and dislikes of the design and it was also possible to see where improvements had to be made for the final design.

Stage 5 - (Final Design): Using the knowledge and insights acquired from the 2nd meeting with the user and the prototype development stage it was possible to make the final improvements to the prosthesis before product issue.

Gates

The gates consisted of team meetings where we would assess the progress of the current stage and its outputs, and whether it was time to move onto the next stage. At the end of a stage it was necessary to determine what tasks were going to take place and to divide these tasks among team members. The decision-making process implemented was not comparable to the standard stage-gate method of appointing a project manager who would have the final say. Instead, an agile approach was used for decision making and task delegation where the whole team worked together to determine the best course of action.

A task board see Figure 4-2, was set up to delegate the tasks among the team and monitor the progress of the tasks throughout the stage. It ensured each group member was aware of what everyone else was working on.
Regular meetings and interactions with the supervisors also allowed us to make informed decisions on the progress of the project.

Therefore, a combination of regular team meetings, group discussions and supervisor support allowed for an agile approach to project management that served the team well and allowed there to be a natural flow between stages.

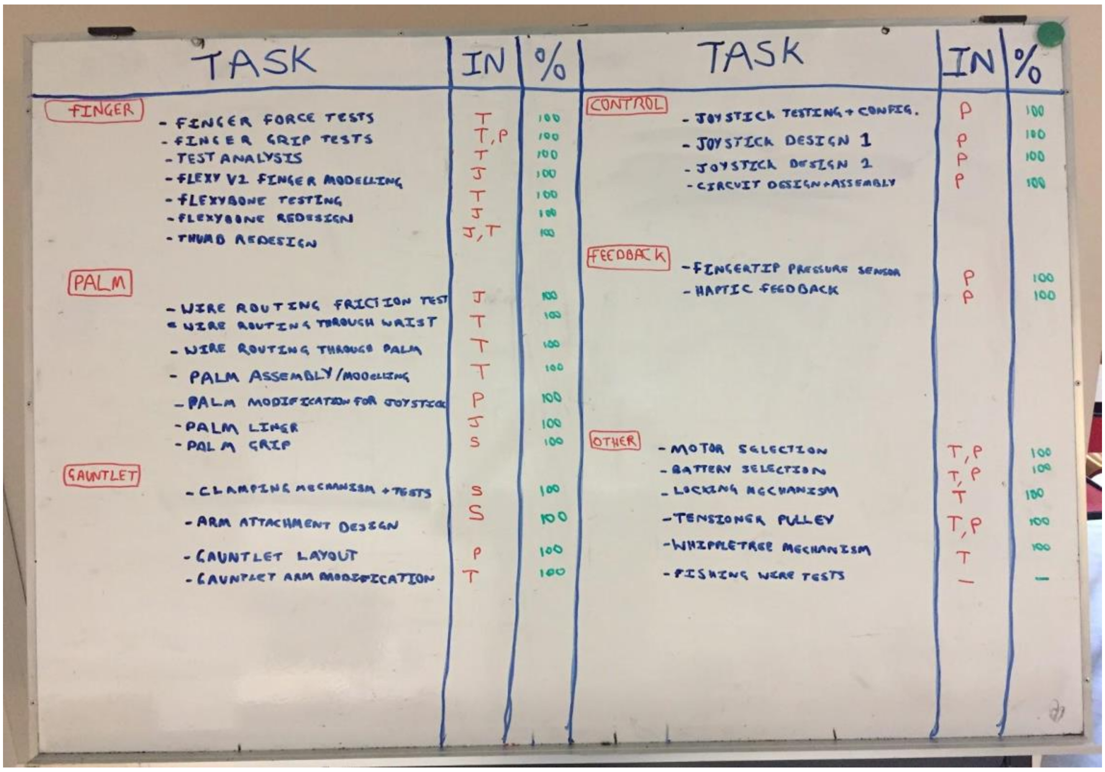


Figure 4-2: Task Board

4.3 Organization Structure

The project falls into the cross-functional matrix structure. In a cross-functional matrix, team members are from different organizational functions. Within the matrix structure all team members learn how to collaborate with colleagues and supervisors from different cultures. In this project, the team members were studying different subjects, which lead to different divisions. Two of the team members were studying Integrated Design Engineering; One of the team members was studying Aerospace Engineering; and lastly one of the team members was studying Mechanical Engineering with Manufacturing and Management. To have a successful project the skills of each member of the team were taken into consideration to initially allocate the tasks and to encourage the sharing of experience and knowledge. After the initial period of the project the tasks were allocated based both on experience of the team members, such as worked previously with 3D printers or electronics, and each member's desire to do further research and learn a topic that they are not familiar with. This structure puts the customer, in this case the user, first by bringing the team members together with different perspectives, thereby improving the problem solving and innovation during the process [10]. The team followed the agile management as defined previously in section 4.1 so each member can participate in other tasks and roles.

The team implemented a working schedule of 9am until 5pm, with overtime carried out when necessary or by the choice of a team member. Weekly group meetings were held allowing the team to plan what should be done for the upcoming week, discuss progress made and help solve any problems the members faced. To avoid the overlapping of tasks, they were all defined and allocated amongst the team during the weekly meetings. The tasks were then documented on a whiteboard so that a clear outline for the week could be presented, while having a visual monitor of task progression by using a percentage completion score as seen in Figure 4-2.

4.4 Logbook

Alongside team meetings, a logbook (Appendix A) was used throughout the project to document the daily activities of each group member. It was extremely beneficial to refer to later in the project as it kept track of all the team's decisions and made it simple to justify why an action was taken. It also made it easier to write the final report because of this concise documentation. Additionally, it was used to monitor what other group members were working on during the week, making it easier to keep track of individual progress. The log book was sent on a fortnightly basis to all the supervisors, so they were aware of the progress being made with the project.

4.5 Supervisor Correspondence

At the beginning of the project there were fortnightly meetings with one of the French supervisors. This allowed the supervisor to witness the current progress made with the project and it allowed the supervisor to voice their opinions and any concerns they had with the direction being taken.

Fortnightly reports were produced throughout the duration of the project outlining its progress. These were sent to both the Bath and Grenoble supervisors.

As the project proceeded almost daily face-to-face encounters were had with supervisors in Grenoble as the team had questions that had to be answered and deliveries of electronics and different components had to be given to the team.

4.6 File Sharing

To keep the project as collaborative as possible, all files developed by the team were kept in an online shared drive. This meant that any member of the team could access and view what was being done by the rest of the team. This included all Arduino code, schematics, test notes, daily logs and photos and videos. In addition to this, all CAD files were also shared and accessed using the collaborative CAD software Onshape.

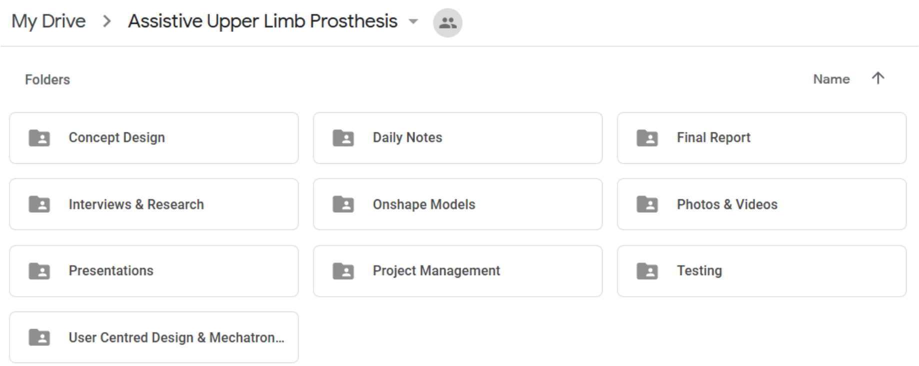


Figure 4-3: screenshot of shared drive folders

File sharing also allowed peers to review each other's work, which was an important part of the process, as when a single person works on a certain aspect of the design tunnel vision can occur, whereby they cannot always see the bigger picture. A fresh pair of eyes can often identify problems that would have otherwise gone unnoticed. As members of the team also worked on different aspects of the design, it helped the different aspects of the project integrate and improve communication.

4.7 Timeline

Figure 4-4 represents a timeline of the project highlighting the main milestones and deadlines along the way. The first month was spent doing a considerable amount of research into the different products currently on the market, and the different technologies available that could be implemented into an electronically assisted prosthesis. The next two months were spent extensively testing the different technologies that were felt to be of use in this project and testing aspects of current prosthesis designs that were felt could be improved upon. Rapid prototyping was also undertaken allowing the design team to do a large amount of testing on 3D printed parts. Then towards the end of April, using the results and conclusions drawn from the testing phase, it was possible to begin building and iterating the designs, quickly developing and iterating through various prototypes, before finishing the final prototype before the last meeting with the user towards the end of June.

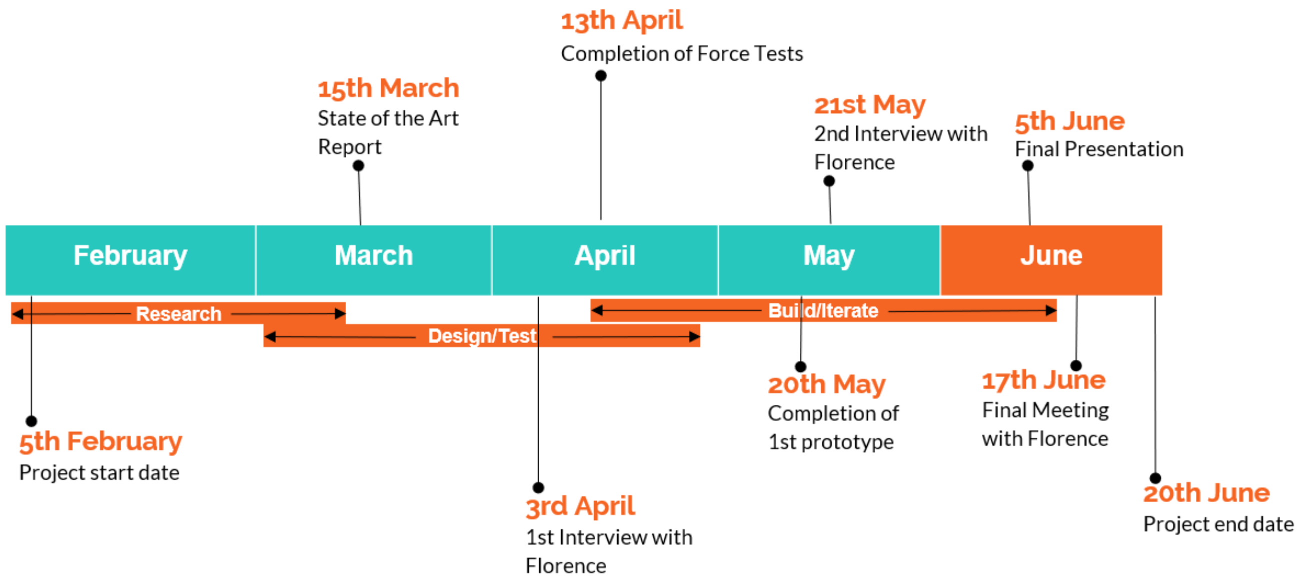


Figure 4-4: Project Timeline

5 State of The Art

The first deliverable of the project was a 'State of The Art' report. This entailed the dividing up and research into specific areas of project's scope. Areas of each section have been included as these embody most of the research conducted and therefore guided the paths and technologies that were investigated and tested throughout the project.

5.1 Mechanical Operations (JP)

5.1.1 Introduction (JP)

The design of a prosthesis, and in the context of this project an upper limb prosthesis, encompasses many different technical fields. However, this section will discuss and primarily focus on aspects of mechanical, anthropometric and ergonomic design. In addition to how prosthesis design can affect individuals psychosocially. Reiterating how important both the mechanical design is for functionality, but equally how important the aesthetic design is for social acceptance. There's a plethora of different prosthetic devices currently on the market, as well as countless models that have been made by passionate individuals looking to help people in need. Four of these will be summarised in this section.

The optimal prosthetic device for this project will fulfil the following criteria:

- Cheap to manufacture
- Light weight
- Durable
- Maintainable
- Aesthetically appealing
- Ergonomically & anthropometrically designed
- Open-source
- 3D Printable
- EMG sensor control
- Customisable case/non-stigmatising

5.1.2 The Human Hand: Anthropometric design (JP)

The human hand is an essential part of human form, function, and communication, capable of complex, expressive articulation. It is a complex set of bones, muscles, tendons, nerves and other biological material that allow it to function with such great dexterity. It's complicated neuro-physiology makes it a formidable challenge for roboticists and designers of prosthetics to emulate [11]. The fine motor skills performed by a human hand are learned over a long period of time; essentially being calibrated and fine-tuned from infancy to perform tasks requiring a high level of dexterity. Millions of years of evolution has perfected hand design and it has proved extremely difficult to mimic such fine motor control using man-made hardware and computer algorithms.

In a human hand (Figure 5-1, Figure 5-2) there are 27 degrees of freedom and 5 different categories of bone . Each finger has 4 DOF, 3 for extension and flexion and 1 for abduction and adduction; the thumb is more complicated and has 5 DOF, leaving 6 DOF for the rotation and translation of the wrist [11]. The Distal, Interim, and Proximal Phalanges of the finger provide most of the dexterity in the hand.

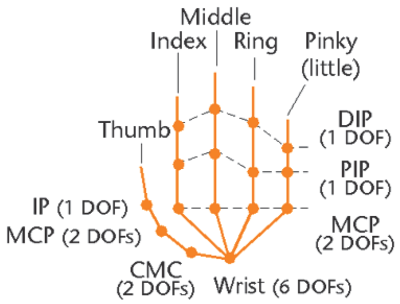


Figure 5-1: Degrees of Freedom – Human Hand

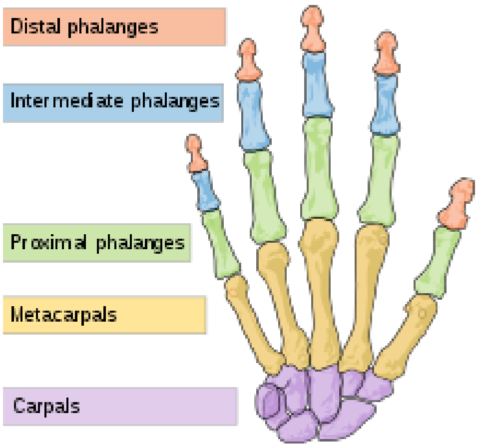


Figure 5-2: Bones in Human Hand [12]

Most robotic and prosthetic hand designs will have the same number of joints as a biological human hand. However, on most of the basic prosthetic hands the joints cannot be controlled independently, thus limiting the number of degrees of freedom [11].

Due to the lack of fine motor control of the fingers the prosthetic hands are normally limited to a small number of simple gestures. The most common of which is the cylindrical grasp (Figure 5-3) were the thumb and fingers contract around an object.

Figure 5-3: Cylindrical Grasp [13]

5.1.3 Complexity: Degrees of Freedom vs Size – Trade Off (JP)

Mechanical complexity determines the number of degrees of freedom. However, as the mechanical complexity of the system increases a trade-off ensues, as increasing complexity typically leads to an increase in the size of the device and a reduction in its robustness and durability.

5.1.4 Prosthesis Research (Table 5-1) (JP)

Prosthesis	Product Summary
 *Figure 5-4: Flexy Hand 2 [14]*	- Open Source (e-NABLE) - 3D printed - Wrist movement tensions wires providing finger contraction force - Flexible filament in hinges - 1 degree of freedom - Lightweight
 *Figure 5-5: Open Bionics 'Hero Arm' [15]*	- Commercial product (Open Bionics) - Myoelectric sensors - Motorised actuation - 6 different grip settings - 6 degrees of freedom - Adjustable thumb position - <1kg weight - Haptic Feedback - Themed covers
 *Figure 5-6: e-NABLE Phoenix Hand [16]*	- Open Source (e-NABLE) - 3D printed - Uses dental bands to provide tension in joints. - Wrist movement tensions wires providing finger contraction force. - 1 degree of freedom - Lightweight - Whippletree mechanism used to distribute force according between fingers.
 *Figure 5-7: Bebionic Hand [17]*	- Commercial product (Bebionic) - Myoelectric sensors - Motorised actuation - 14 different grip patterns - 7 degrees of freedom - Adjustable thumb position - Anti-slip functionality - Expensive - Heavy

Table 5-1: Existing Prosthetic Models

5.1.5 Summary of Devices (Table 5-2) (JP)

1. E-NABLE Flexy Hand 2
2. Open Bionics - Hero Arm
3. e-NABLE Phoenix Hand
4. Bebionic

Criteria	**1**	**2**	**3**	**4**
Cheap to Manufacture (<€200)	✔	✗	✔	✗
Light Weight (<1kg)	✔	✔	✔	✔
Durable	✔	✔	✔	✔
Easily Maintainable/Repairable	✔	✗	✔	✗
Aesthetically Appealing	✔	✔	✔	✔
Ergonomically and Anthropometrically Designed	✔	✔	✔	✔
Open-Source	✔	✗	✔	✗
3D Printable	✔	✔	✔	✗
EMG Sensor Control	✗	✔	✗	✔
Motor Actuation	✗	✔	✗	✔
Customisable Casing	✗	✔	✗	✗

Table 5-2: Device Comparison

5.1.6 Ideal Design (JP)

None of the designs will result in 100% transfer of input power to output power in the digits. There will always be a loss due to motor inefficiencies, friction within the joints, and elastic potential of the wire. The ideal solution will be a combination of high efficiency motors, non-flexible wire and joints that have been sufficiently smoothed and polished to reduce friction.

A 3D model of a hand that has been obtained using a method such as 3D laser scanning would be ideal. It must be easily scaled and manipulated to create a functioning prosthetic hand, that is also life-like in geometry and appearance. The design must be open-source and 3D printable. It must be cheap to produce, be durable, easily maintainable, and light weight.

The optimal design that would conform to the project requirements would be a combination of Open Bionics' Hero Hand and the e-NABLE Flexy Hand 2. The simplicity of the 'Flexy Hand' hand design coupled with a more basic version of the Hero Arm's myoelectric motorised control and adjustable gauntlet would be an ideal solution.

5.2 Input Control Techniques (SS)

5.2.1 Introduction to Upper Limb Prosthetics (SS)

The purpose of an upper hand limb is to replace the function of the hand which may be lost because of a disease, trauma or congenital disorder and mimic the appearance. There is wide range of prosthetics which range from aesthetically appealing cosmetic ones to primarily functional mechanic ones.

5.2.2 Human Hand and Forearm Anatomy (SS)

The muscles in the forearm is shown in Figure 5-8 as inner (intrinsic) and outer (extrinsic) forearm and in Figure 5-9, it shows the anterior forearm muscles closely. For the sensors or mechanical designs to work, a force or a flexion of the hand or muscles is needed. As the muscles flex, with different patterns and signals, the fingers, wrist can be curled, or gripping can be made.

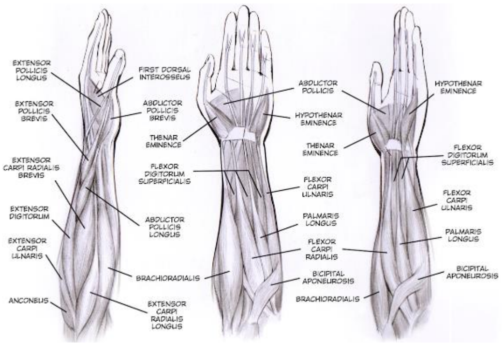


Figure 5-8: Muscles in Forearm

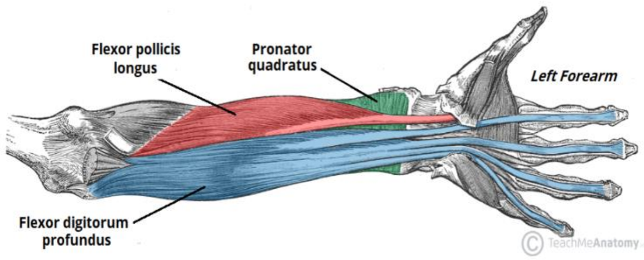


Figure 5-9: Deep Flexor Muscles of Anterior Forearm

For the flexion, the two muscles are mainly taken into consideration. Flexor pollicis longus attaches to thumb and primary function of it is to flex the joints of the thumb which are called 'interphalangeal and metacarpophalangeal'. Flexor digitorum profundus pronates the forearm and the function of it is to flex the other four fingers [18].

Other muscles that are also important to take into consideration for prosthesis are pronator quadratus, pronator tere, extensor carpi radialis longus and extensor carpi radialis brevis. Pronator quadratus works in collaboration with pronator teres help to turn the palm in different directions. Extensor carpi radialis longus is an extensor muscle located posterior of the forearm. It helps the wrist movement and its function is to abduct the hand at the wrist so that the hand can move towards the thumb. And extensor carpi radialis brevis moves the hand away from the thumb. It is also located posterior of the forearm.

5.2.3 Different Input Controls for Prosthesis (SS)

To measure and collect data and information from a prosthetic hand, sensors and mechanical solutions can be used. There are different types of sensors which can work with or without any external power supply to operate, these can be called passive and active respectively and work in closed loops. For this report the input control devices and sensors are researched and analysed below. Besides the sensors, for the movement of the fingers and the wrist, mechanical solutions are also analysed.

5.2.3.1 Micro Switch

This is a gripper thumb terminal device which is developed by Skip Meetze and replaces the axon hook. This device is analysed for the mechanical switch control. This works without a cable and harness. The gripping object can be replaced in to the hand with the other hand, however this doesn't really work when the patient is missing both hands. Afterwards, a motorised gripper is developed. Electronic devices are considered as too complex to assemble for E-NAble users. Motor gripper has no electronics in this development. It uses parts from an inexpensive flashlight. Three triplet batteries, battery hold, and a push button switch which can be obtained from the flashlight. These can be put in to the motor gripper.

Switches can be used to activate the motor mechanism. In the motor gripper there is a crank shaft on a small gear motor that operates the mechanism to open and close the thumb. There is a second microswitch which allows the motor run in one direction. User can press the switch against any place like a table and start it running. It grips and opens in a certain period. If the patient double clicks it will open ones and needs to be double clicked again to discard the material that was gripped. This is a motorized gripper thumb that uses switch system to maintain the gripping. The main objective of this switch is to solve the complexity problem that other prosthetic upper limbs have and make it easy to use [19]. The design of the hand and the switch can be seen in Figure 5-10.

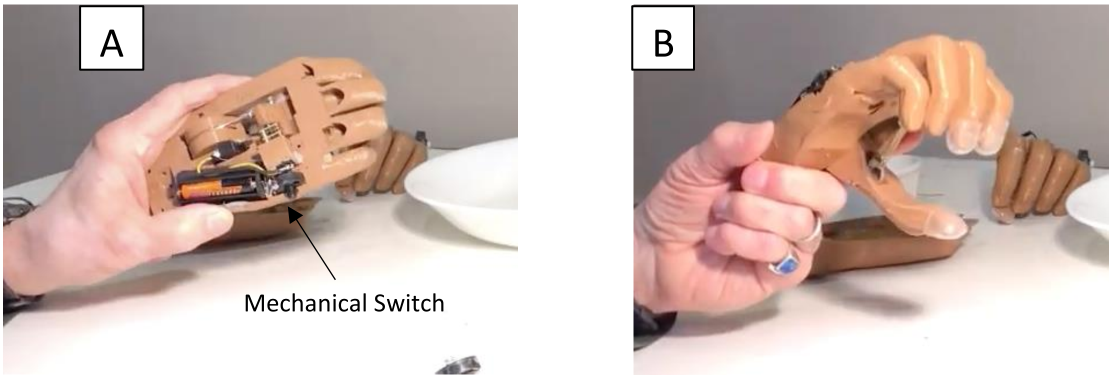


Figure 5-10: 'A' shows the mechanical design and the switch of the prosthetic hand. 'B' shows the prosthetic hand's open version [19]

5.2.3.2 Myoelectric EMG Sensor

Myoelectric sensors use electromyography signals generated from muscles while in contraction. It measures the muscle activation via electrical potential. The sensors can be placed on the forearm, and the patients can be taught how to contract the specific muscle to perform finger movement [20]. There is two ways to use the sensor- one way is by sockets which are generally made from epoxy resins or fiberglass or carbon fibres. Also, by using some lining made of silicon or other soft materials in the inner parts, the inner face and be made more comfortable. The second way is direct bone attachment which directly inserts the titanium rod into the bone [20].

Three different muscle groups which are skeletal muscle, smooth muscle and cardiac muscle. EMG is generally used in skeletal muscles. In the skeletal muscles, neurons work for contraction. In the resting state, nerve cell membrane is polarized because of the ionic composition differences around the membrane. Muscle tissues conduct electrical potential in a similar way to the nerve cells. Bundles of the muscle are capable of contraction and relaxation. The main function of bundles is to produce motion. Those muscle fibres depolarize by stimulus from a neuron. The signal propagates on fibres surface to cause depolarization and movement of ions to generate electric field near each field. The EMG signal is the train of Motor Unit Action Potential (MUAP) showing the muscle response to neural simulation [21]. The EMG signal amplitude ranges from 0 to 10 mV and main dominant energy ranges from 0 to 500 Hz [21].

The main concentration is on the flexion of the forearm so focusing on the inner forearm for allowing curling of fingers, gripping etc. To have movement for each finger, multiple electrodes should be used in specific parts of the forearm. By the experiment done by Backyard Brains neuroscience research group the placements of the electrodes are shown below in Figure 5-11 [22].

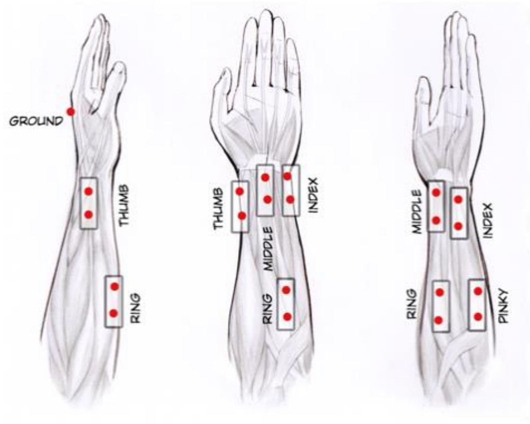


Figure 5-11: Shows the places that electrodes can be placed for multi-electrode myoelectric sensor to get an input signal for different fingers

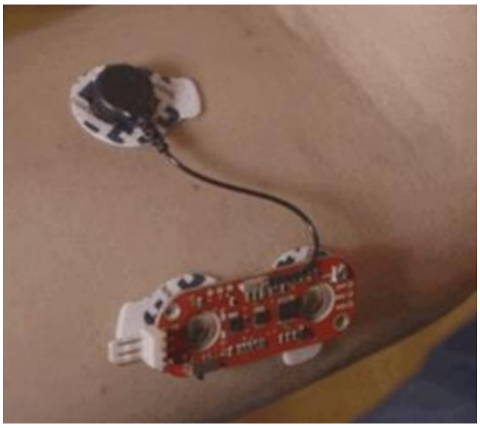


Figure 5-12: Shows the places that the electrodes can be placed for single and small myoelectric sensor

To get a multi-degree of freedom, for instance individual finger movements, the electronics can be put precisely and will maintain a grip force equivalent to the body weight of the patient. If one channel sensor is attached to the forearm, as shown in Figure 5-12, each finger cannot be controlled individually as it records the activity of many muscles. To get a response from each finger, the muscles should be isolated by using multiple electrodes and classifying signals. Arm bands can be used as well, but in this case of prosthetic hand for upper limb, the forearm is available to be used and within the gauntlet, the sensor can be easily secured.

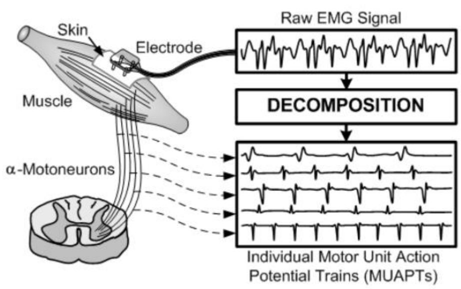


Figure 5-13: EMG signal capturing diagram

Electrodes are supposed be given special care as it can lose contact with the skin and this results in distortion in the signal. This problem can be minimalized by putting constant pressure on the surface of the electrode and using a saline gel to increase the conductivity. The patient's skin is supposed to be cleaned with alcohol, the places that electrodes are going to be put, and supposed to be lightly exfoliated [23].

Direct bone attachment, also called as Implanted Myoelectric Sensors (IMES), is developed from implanted EMG sensors. They are wirelessly powered and can provide 6-8 degrees of freedom. All implanted sensors are innervated separately with muscles to obtain independent control with minimum cross-talk and interference. The signals sensed by Telemetry Controller (TC) from those devices powers and receives the signals. Up to 32 implanted electrodes can be controlled by TC. As implanting the devices are expensive, needs further medical operation and not applicable for every patient, this sensor is eliminated [24]. The Targeted Muscle Reinvention (TMR) is also a surgical procedure like implanted sensors. The nerves from amputated limb are transferred to residual limb which targets muscles that doesn't have a biomechanical function. The TMR muscles serves as an amplifier of the motor nerves and provide EMG signals to control the arm or the hand. This method helps the patient to control the prosthesis more intuitively and can be enhanced by pairing with pattern recognition technology [25].

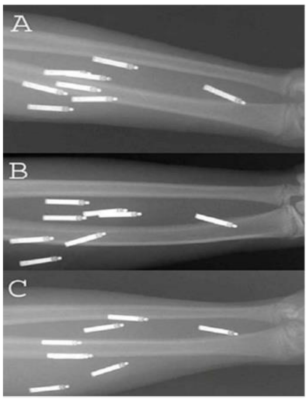


Figure 5-14: Shows implanted myoelectric sensors

5.2.3.3 Force Resistive Sensors

Force Sensing Resistor (FSR) is a type of a resistor. FSR consists of resistor and sensor technology which has conductive polymer that changes its resistance based on force applied to its surface. It is patented in 1977 by Franklin Eventoff [22]. FSR exhibits reduction in the resistance while having an increase in the force that is applied to the active surface. It has an optimised force sensibility to be used human touch control of the electronic devices [26].

When the force is applied to the surface of the sensing film, the particles touches to the conductive electrodes and deforms against the substrate which changes the resistance of the film. The more conductive area touches with the film, the lower the resistance [27]. The layers of the FSR can be seen in Figure 5-15.

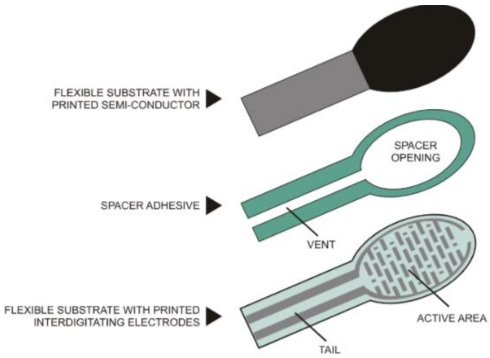


Figure 5-15: Shows Different Layers of the Force Resistive Sensor

Advantages of FSR are having a thin size, very low cost, and being a good shock resistance. The disadvantage of FSR is having a low precision. They generally have 10% difference in the measurement results [22].

FSR has wide range of applications such as car sensors, musical instruments, keypads, prosthetics, fingertips in robotics and many other. It is easy to use with all the electronics and have a simple connection with the Arduino as well. In the application for the prosthetic hand project, two types of FSR is used which are 0.5 inch and 1.5

inch for testing. In both sensors, the level of sensibility for prosthesis can be achieved by changing the sensibility variable with in the Arduino code. It is seen that application of the sensor is easy and set up for the Arduino is not complicated so the complexity of the prosthesis can be minimalized by using this sensor.

5.2.3.4 Flex Sensor

Flex sensor outputs change in resistivity due to bending. It is generally applied to skin surface and by the bending of the sensor causes a change in resistivity directly transformed to voltage change due to Ohms Law. In this way a microcomputer can recognize it by a simple amplifier circuit compared to the circuits that are used for strain gauge sensors. Amplified voltage change is used in differential input of motor and in this way operational intention is transmitted to the electrically driven prosthesis [28]. These sensors measure the amount of bending due to bending of the sensor. There are three types of flex sensors: optical, ink-based and capacitive flex sensors. The construction and working principle for all three are different [29].

Optical flex sensor is made of flexible tube which has two ends and within that reflective interior wall and a light source which is replaced on one and whereas photosensitive detector placed on the other hand. This helps the sensor to detect direct light rays when the flexible tube is bent.

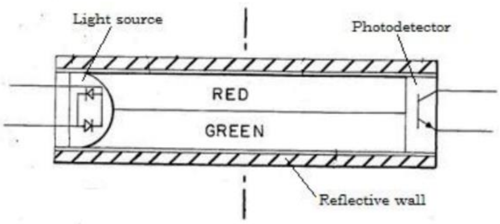


Figure 5-16: Optical Flex Sensor

Conductive ink-based flex sensor has phenolic resin with conductive ink deposited and on top, thereon a segmented conductor is placed. This will form a flexible potentiometer which will change upon deflection.

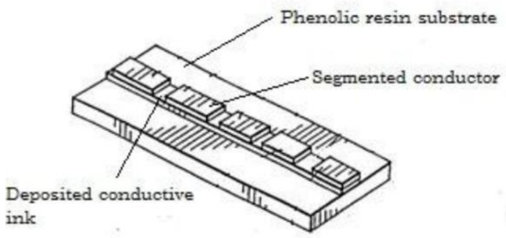


Figure 5-17: Conductive Ink-based Flex Sensor

Capacitive flex sensor consists of two conductive layers separated by a dielectric material. This material reduces the resistance between the conductive layers which changes in relation with deflection. It is generally used in goniometer in rehabilitation research. By using the glove in rehabilitation, the joint movements are measured for patients. Further, those gloves were used for human machine interfaces [29].

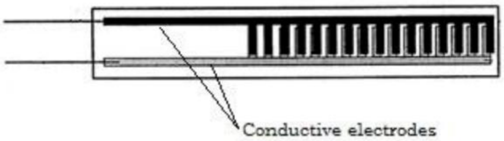


Figure 5-18: Capacitive Flex Sensor

Most of the electrical parts require a bridge circuit and multi-amplifier circuits. These increase the weight and the cost of the product. If low resistance value of stain gauges is used, surplus heat may occur. To solve this problem, sensors can be applied to the system instead of the strain gauges. By using a voltage divider, flex sensors will make a simple composition and reduce the total number of electronic parts. As a flex sensor has a huge resistance, it can avoid the overcurrent [29].

For the upper limb prosthesis project, the capacitive flex sensor is chosen to be used for testing with other sensors as it is more applicable for using on the skin and getting feedback by using wrist movements.

5.3 Feedback Techniques (PB)

Restoration of sensory function is a substantial barrier in the successful adoption and acceptance of a prosthesis design. Poor controllability and feedback often mean that prostheses are perceived as external devices by amputees and are consequently abandoned [30]. Reducing the cognitive effort required to use a prosthesis is also a considerable hurdle. It is important that amputees are provided with sensory feedback that is consistent with physiological signals to avoid cognitive overload. As a rule, sophistication of the system increases the cognitive effort required to use it, particularly if it is not intuitive to operate. Therefore, most commercially available hands (i.e. Touch Bionics i-Limb [31]) implement simple discrete ON/OFF myoelectric inputs to control opening or closing of the hand.

In this section potential methods of feedback will be proposed to determine methods that could be applicable to this project. The purpose is to determine if feedback is required, and if so what methods are most appropriate.

5.3.1 Open-loop Control (PB)

Open-loop prosthesis users receive no tactile feedback from the limb, limiting dexterity and compromising control of grip force [32]. An example of this are the E-nable hands [33], whereby users generate force from wrist flexion which offers rudimentary feedback of position in conjunction with visual feedback. In an open-loop prosthesis, the user must heavily rely on visual feedback to determine its position in space along with grip force. A feedforward mechanism is primarily used to estimate the required motion and grip force, with the user monitoring it visually during the action to adjust. This method lacks the tactile feedback that is provided by a natural limb.

5.3.2 Human Sensory Feedback Systems (PB)

The human body has a complex sensory system that encodes and transmits information to the central nervous system (CNS). Two aspects are crucial for successful feedback of a prosthesis:

1. Proprioception - knowledge of the prosthetics position in space (i.e. how flexed the fingers are) and the strength of the effort being employed by the hand.
2. Tactile feedback (i.e. information on when an object is in contact with the prosthesis and where this contact is taking place). Further feedback could include the amount of pressure on the fingertip, or the temperature of the object.

For amputees, there are two methods in which sensory feedback can be re-established:

- Invasively – by direct interface with the CNS, typically by surgical means.
- Non-invasively – sensory feedback is provided to the remaining intact CNS elsewhere on the body.

Non-invasive feedback can be fed back to the user by purely mechanical means or with the aid of electronic components such as vibration motors. Due to the nature of the project the invasive method will not be considered.

5.3.3 Sensory Feedback and Substitution (PB)

Sensory feedback should be provided to the user in the shortest time possible for effective use of the prosthetic. The human body takes approximately 14-28ms to process sensory information from the hand, therefore every effort should be made to avoid increasing this [34]. This short latency is crucial for a sense of body ownership of the prosthesis which has been found to occur with delays up to 300ms, with the optimal time lying between 100 to 125ms [35].
Sensory substitution is a means of delivering feedback by a different means or to a different location on the body. This is deemed successful when the stimulation is not perceived as an abstract signal but instead as an extension of the user's sense of touch [36]. A combination of sensors is required to replace the range of mechanoreceptors in human skin. It's been found that when vibratory feedback of grip force was displaced to a less affected arm, multiple sclerosis patients were better able to control grip force when lifting objects [37]. This also demonstrates that this displacement does not need to be on the residual limb to be successful. They can also, of course, be placed on the residual limb or stump to provide useful sensation to the user depending on the level of functioning nerves [38]. This method is preferred as it provides a greater sense of embodiment with the prosthesis.

5.3.4 Visual Feedback (PB)

The most basic means of feedback, and one that is heavily relied on by many modern prosthetics is visual feedback, whereby the user must be looking at the prosthesis to determine its position and whether it is successfully grasping an object. The main drawback of this method is that the user is required to be looking at the object a lot of the time, and this hinders usability due to significant cognitive effort. On the other hand, it is a very reliable means of feedback and is the most heavily relied on method in amputees, even for those with high-end prosthetics that offer other means of feedback.

5.3.5 Tactile Feedback (PB)

Experiments have indicated that tactile feedback offers limited practicality for grasp force control if the hand controller is predictable. This means that if the user can learn to predict the time required to, for example, trigger a myoelectric sensor to close the fingers to a certain point (known as ramp duration [32]) tactile feedback is not important, and this feedforward control is enough in conjunction with sensory cues (visual and auditory). In tests with impaired auditory and visual feedback, or with none whatsoever, the tactile feedback was found to be more useful for the participant, although only slightly. In the absence of both, the overall force measured increased for gripping the same objects, consistent with the participant over-estimating the force to provide a safety margin, however they were still able to produce economical grasps. They were also able to successfully estimate the force required to pick up objects of differing weights in this case, which suggests successful prediction in the feedforward path, and that this path therefore plays a crucial role in user behaviour.

When unpredictability of the controller is introduced (such as that of EMG sensors in the real-world [39]) and the feedforward estimate is impaired, tactile feedback is of greater use. Without tactile feedback, the performance of the prosthesis degraded, and with the addition of tactile feedback, its performance was restored. Therefore, if the user cannot successfully predict the movement of the prosthesis, tactile feedback is required.

The first test was performed in a predictable environment under ideal conditions, and therefore it is unlikely that having only visual feedback is an ideal solution in the real-world even with enough predictability of the controller. In this study, participants could learn by trial and error how much force was required for familiar objects. With unpredictable objects in the real-world, unpredictable controller behaviour, and visual distractions [40] [41], the benefits of tactile feedback are apparent.

Because of this section, the following can be deduced and are important considerations for this project:
1. The prosthesis control should be designed to minimise feedforward uncertainty, and performance should be as predictable and repeatable as possible.
2. Feedback should be provided to the user to account for any uncertainty they encounter (i.e. from force-derivative feedback [42]).
3. Reducing all uncertainty from a controller does not necessarily mean that feedback is not required in a prosthesis. It's also important to consider the importance of the prosthesis being accepted by the user as an extension of their central nervous system (CNS). Prosthesis embodiment and body ownership can only be achieved through the implementation of feedback.

Effort should therefore be made to develop a predictable feedforward controller and feedback system that mean the user can account for the uncertainty that will inevitably occur in the controller.

5.3.6 Force-Derivative Feedback (PB)

The transition between force and velocity control in natural systems is both a fluid and versatile attribute, and one that is difficult to mimic in artificial limbs. There must typically be a trade-off between speed and the ability of the system to delicately grip objects. Force-derivative feedback is a means of control that increases the dampening of a closed-loop prosthesis to reduce force overshoot when initially grasping an object [42]. Essentially, this means that the actuator can move quickly until the fingers meet an object, at which point they move slower, thus allowing the user to delicately grasp more fragile objects.

This is a simple method that can easily be accomplished with only a few lines of additional code on an Arduino and has already been achieved by the team using force sensitive resistors and a servo motor. It's therefore highly applicable to this project. The user benefits from this method as it combines both feedforward and feedback techniques. Crucially, their estimated force should not damage the object should they accidentally overshoot. However, further research has found that although this feature can be useful in some cases, having the option to turn off this feature (i.e. via a switch) is preferable for instances when automatic force control or slip detection is impractical [43].

5.3.7 Continuous vs Discrete Feedback (PB)

Traditional feedback methods have included continuous feedback such as constant vibration [44]. An issue with this method is that it leads to adaptation, and over time this feedback becomes imperceptible to the user as the brain learns to treat it as irrelevant information. Discrete feedback is therefore preferred, if it is not so abrupt that it disturbs the user.

5.3.8 Feedback Methods (PB)

There are various methods that can be implemented into a prosthesis to provide proprioceptive feedback to the user. These methods will be considered here.

5.3.9 Vibrotactile Stimulation (PB)

Information is fed to the user via mechanical vibration on the skin, typically between 10-500Hz [45]. This information could relate to position, orientation or the grip force of the prosthetic. The key features of these stimuli are the amplitude and frequency of the vibration, but the shape, pulse duration and duty cycle can also be modulated to provide additional information. The amplitude required by this method depends on the location on the body. Lower frequencies are required on glabrous skin as opposed to hairy skin. Vibration motors are small, unobtrusive and require low-power, making them highly applicable to prosthetic devices [46] and this project. Tests have already been undertaken by the team using SparkFun’s DRV2605L Haptic Driver with vibration motors and it is easy to implement.

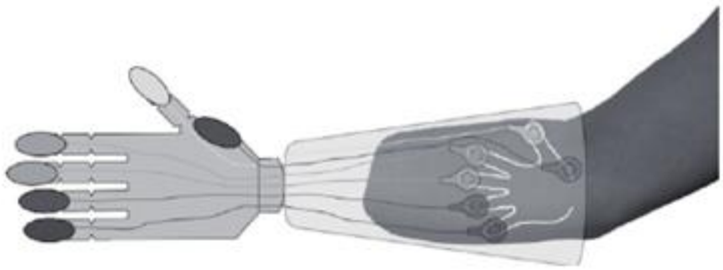


Figure 5-19: Otto Bock MyoHand VariPlus Speed with a vibrotactile feedback system that vibrates when all the fingertips are pressed and maps it onto the residual limb [37].

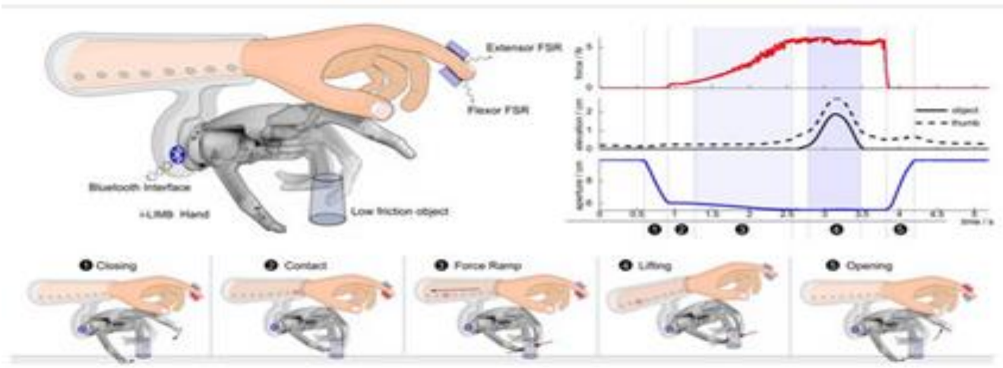


Figure 5-20: A modified i-limb Pulse prosthetic hand with only one force sensor on the fingertip. Grip-force feedback is delivered to the user using a vibrotactile feedback array that vibrates further up the forearm as the force is increased [38]. From this research, it was determined that the minimum distance between vibration motors should be 3cm – any less than this and the user will perceive the force incorrectly.

Figure 5-19 and Figure 5-20 present two different arrays of vibrotactile sensors. Figure 5-19 displays a design where the force in each fingertip is mapped to the arm in a similar pattern. It was found, however, that this method required significant cognitive effort from the user and required a learning process that took time. The second contains only one sensor placed on the index finger that maps the force in a linear pattern dependent on the force measured. This was found to be more intuitive [32].

Electro tactile Stimulation Like vibrotactile, electro tactile stimulation causes sensation on the skin by stimulating nerve endings using an electrical current [47]. If placed near nerve bundles, these sensations could spread to zones not directly beneath the stimuli to produce more complex sensation. This method has some disadvantages such as the potential for painful stimulations.
As a result, and due to recent advancements in vibrotactile stimulation, this method has been abandoned by many research projects. However, comparison between this and vibrotactile stimulation should still be undertaken to determine which is most appropriate for this project. For electro tactile stimulation, adaptation is lowest for high current stimulation (just below the pain threshold) and can also be reduced by intermittent stimulation [48].

Mechanical Haptic Feedback Skin stretching devices are novel methods in which skin on the residual limb is stretched or rotated [49] and has been proven useful for proprioceptive sensing. It is deemed to be a natural and understandable method for signalling. Testing done with rotational stretch devices has shown that it significantly improved the accuracy of the prosthesis over non-feedback conditions [50]. Despite this, there are very few prostheses available that implement such techniques, suggesting potential for further research in this project [51].
Other potential methods include:

• Tightening of a band around the arm
• 'Brushing' of the skin
• A belt to indicate slip, however in one case it was found to be less comfortable and more complex than a vibrator [52].

5.3.10 Slip Detection (PB)

When a human hand detects an object slipping it will automatically apply a force to prevent this. In a prosthesis, there is no sense of touch and therefore it is more difficult to detect. Sensors could be implemented to allow the hand to automatically grip tighter when slip is detected [53]. Force sensitive resistors and piezoelectric sensors are commonly used to detect the vibrations that occur during slippage and are to be considered for this project. Furthermore, the automation of slip prevention could reduce the required attention required by the user and subsequently cognitive effort.

Potential problems and considerations:

• Running wires through the finger can present issues such as damage to the wires over time due to repeated movement around the joints. Investigation into possible alternatives such as conductive materials will need to be investigated.
• Addition of electronic components adds complexity to the design and with this a higher chance of failure. Effort should be made to make the design as simple and durable as possible and limit the need for electronics.
• Repeatability – the sensors may not perform to the same level under different conditions and this should be considered.

5.3.11 Conclusion (PB)

Despite the proven benefits, haptic feedback has seen little implementation in modern prosthetics, opening a potential window for this project to find a novel way to implement it to improve not only performance but also user embodiment of the prosthesis. It's low cost and ease of implementation make it highly applicable to this project. Furthermore, a combination of both mechanical (i.e. skin stretching) and vibrotactile/electro tactile methods of feedback could be used to provide the user with numerous forms of proprioceptive information. For example, a wheel on the residual limb could stretch the skin depending on the flexion of the fingers, with an array of vibrotactile sensors elsewhere on the residual limb indicating pressure on fingertip(s). Investigation into the feasibility of these methods will be undertaken further into this project.

Something that has also become apparent from this research is that a significant hurdle is obtaining reliable and predictable control of the prosthesis, particularly when dealing with fragile objects. This is a difficult task when myoelectric controllers are still not entirely predictable and offer some feedforward uncertainty. Utilising the remaining CNS of the user could play a potentially crucial role in overcoming this as it is by far the most reliable means of feedback and control. Using actuator assistance in combination with the remaining wrist movement available to the user (particularly as a means of providing finer movement towards the end of a grasp) could be a beneficial method and something that should be investigated. This in combination with feedback through methods such as force derivative feedback and haptic feedback based on grip force could improve performance and embodiment of the prosthesis. The next challenge is designing a solution based on these conclusions that is simple, durable, reliable and can be easily replicated by others.

5.4 Materials (TE)

5.4.1 3D Plastics for Load Bearing Structures (TE)

Research was conducted into the most common materials used for fused filament fabrication 3D printing. The three materials chosen to be compared in Table 5-3; ABS, PLA and PETG, are all hard, stiff and strong polymers ideal for withstanding loads and create/maintain a designed shape and structure. Below gives a comparison of the different characteristics for each polymer.

PROPERTY	ABS	PLA	PETG
TENSILE STRENGTH (MPA)	27	37	53
DENSITY (G/CC)	1.1	1.24	1.27
ELONGATION (%)	3.5	6	18
FLEXURAL MODULUS (GPA)	2.1	4	2.1
GLASS TRANSITION TEMP (C)	105	60	75
BIODEGRADABLE	No	Yes	Yes
FOOD SAFE	No	Yes	Yes
PRICE PER KG ($)	21.99	22.99	45

Table 5-3: Three Primary Plastic Filaments used in FFF Printing [54,55]

All three polymers from Table 5-3 fit the attribute of light weight, with PETG having the highest density of 1.27g/cm^3 and ABS having the lowest of 1.1g/cm^3. Additionally, their tensile strength shows the strongest of the materials is PETG with a strength of 53MPa. ABS is the weakest of the materials with a strength of 27MPa, however both PETG and ABS have the characteristic of good impact resistance, which is a weakness of PLA. This is important for durability of a prosthetic in constant use, which is susceptible to outside forces and impacts.

An important point for consideration is which of the materials is deemed as food safe. Due to the fact a prosthetic arm has a high probability of encountering food or liquids, a plastic like ABS could be dangerous due to the toxic chemicals in its makeup. Therefore, the primary purposes of the arm would have to be considered if ABS is the plastic chosen. PLA or PETG are therefore more suitable materials for the application of a prosthetic arm.

Looking at just PLA and PETG, the later has a large benefit with that it has a higher glass transition temperature of 75^{o}C compared to the 60^{o}C of PLA. This temperature is the threshold which, if the polymers temperature is greater than, has an increased rate of deformation when a load is applied. This is due to the polymer layers being able to slide more easily past each other due to the increase in thermal energy to overcome cross layer bonds. PETG is therefore more heat resistant and deforms less compared to PLA. PLA could therefore cause problems during simple acts such as cooking or holding a cup of boiling liquid. However, this same characteristic can be extremely useful to produce certain parts of a 3D printed prosthetic arm. It allows the use of thermoforming, a process where the plastic can be softened by heating allowing it to be shaped by the application of a small force. This process is extremely beneficial for producing the gauntlet, the part which connects the prosthesis to the residual limb. It allows this part to be 3D printed flat to give the best finish and accuracy, and then be formed to fit the users arm. Therefore, PLA is the most suitable material for the gauntlet of the prosthesis.

The primary reasons that PLA is more popular than PETG are [56]: The price difference per kg of the materials, with PLA being half the price of PETG. The surface finish of parts printed in PLA is smoother and higher quality, which is an important characteristic for a prosthetic hand that has many interlocking and moving parts. A smooth surface finish would therefore reduce the friction experienced during use, creating a more efficient design. PLA has a larger variety of colours and variations with different properties while also being sold by more suppliers.

Finally, PLA is slightly easier to print, with it needing a lower extruder and heated bed temperature than PETG. Overall, the polymer PLA would be the most suitable material for the use of creating a prosthetic arm.

5.4.2 Flexible Filament (TE)

Another type of filament that has been developed for FFF 3D printers is flexible filament. These materials are not suitable for load bearing structures but have some useful properties to improve 3D printable prosthetic designs. The two most readily available flexible materials are shown below in Table 5-4:

PROPERTY	SEMI-FLEX	NINJA FLEX
DENSITY (G/CC)	1.176	1.19
ULTIMATE TENSILE STRENGTH (MPA)	30.44	26
ELONGATION AT BREAK (%)	543	660
PRICE PER KG ($)	57	55

Table 5-4: Flexible Material Properties [57,58]

Comparing the two materials shows that they have similar densities of around 1.18g/cm^3 and a price of $56/kg. They are both extremely durable materials, but Ninjaflex has better surface finish quality and prints faster giving it a large benefit over semi-flex. The main differences between them is that Ninjaflex has a lower ultimate tensile strength of 26MPa, making it weaker than Semi-Flex with a strength of 30.44MPa. However, Ninjaflex has the greater flexibility and elasticity, with an elongation of 660% compared semi-flex's 543%. This gives it greater potential when coming to designing for use in low budget prosthetics.

There are multiple ways that flexible materials can be implemented into the prosthetic hand design to improve its durability, reduce complexity and the ordering of external parts. The first is for it to be used as the restoring mechanism for the fingers once tension has been released in the control. Current methods use additional elastics such as dental bands or bungee cord to pull the fingers back to the open position. However, finger designs with a flexible spines/joints in the finger use the elastic nature of the material to restore the finger position. Figure 5-21 below shows how the different restoration methods are implemented:

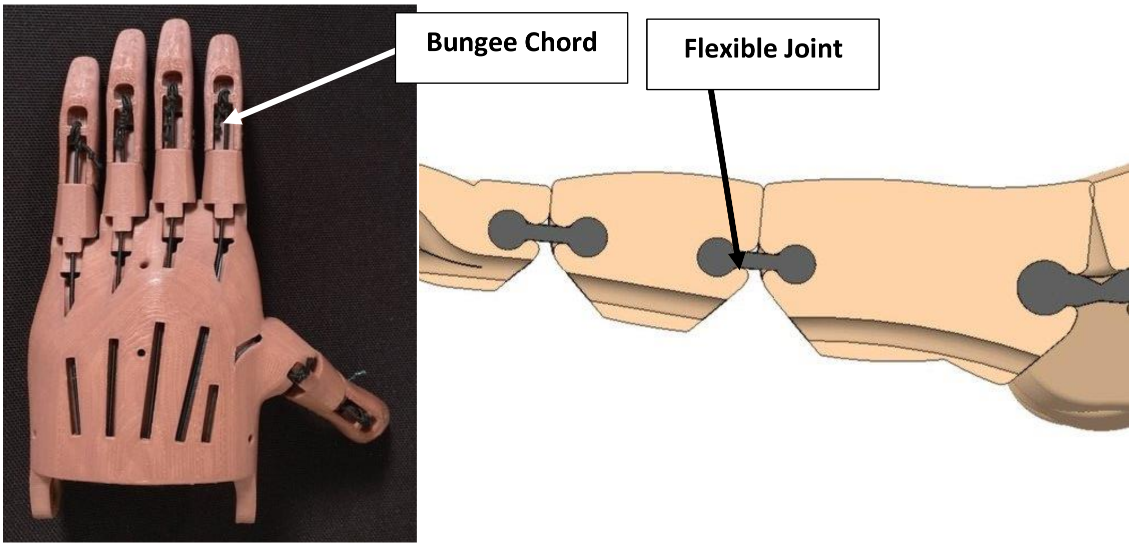


Figure 5-21: Different Finger Restoration Methods [59, 60]

An additional benefit to this mechanism is that it also simplifies the assembly, making it completely 3D printable, with no bolts or additional elastic. The durability of the flexible centre is also a lot greater than a method such as the dental bands, which must be replaced often after repeated use.

Another possibility for flexible material is to allow more movement/curvature of the palm during the finger contraction. The addition of some flexible sections could allow a more natural palm movement and fit to objects, providing more contact area and grip.

5.4.3 Conductive PLA (TE)

A material that has recently been developed for FFF printers is conductive PLA. The materials sole design purpose is to allow better integration of low voltage electronics into 3D printed parts and assemblies. The properties of this plastic are as follows [61, 62]:

- Yield Strength = 60 MPa
- Failure Strength = 83MPa
- Heat Distortion Temp = 55°C
- Density = 1.24 g/cm^3
- Volume Resistivity parallel to layers = 30Ω/cm
- Volume Resistivity through layers = 115Ω/cm
- Cost/kg = €50

As the project's specification is to create an electronically assisted prosthetic, there is a large potential for the use of this material to implement certain functionalities. Firstly, it could enable the user to have a prosthetic which enables them to interact with touch screens again, a task which is increasingly prominent within daily life. This could be achieved by rooting a path of conductive PLA to a fingertip through the finger, as a small current could then be supplied to control the touch screen.

Additionally, it could allow the addition of electronics with the fingertips, such as a touch or pressure sensor, allowing feedback systems to be implemented more reliably into the design. The conductive PLA could be used to create the force sensor itself creating a circuit when a force is experienced at the fingertip, as shown in Figure 5-22.

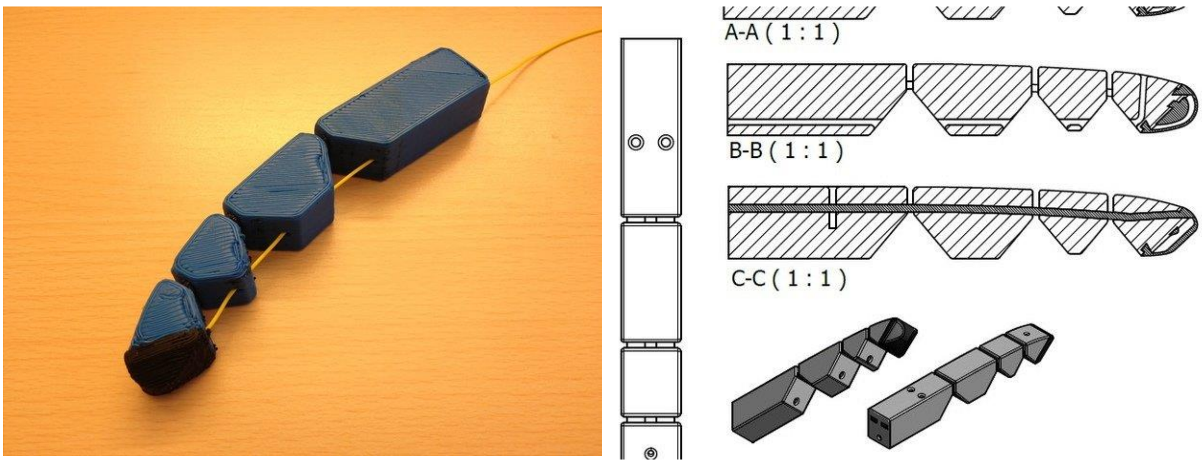


Figure 5-22: Conductive PLA Touch Sensor Fingertip [63]

Currently, wire must be run down the fingers to create the circuit for the sensors. However, a common problem with this method is the durability of the wires. Over a small number of finger contraction cycles, the thin wires fatigue breaking the circuit. This material could therefore be a potential solution to increasing durability of the product. Little testing or research has been done into the possibilities of this product, therefore there could be a large scope of applications in which it could be implemented within this project.

5.4.4 Fishing Line Finger Actuation Control (TE)

Due to the prosthetic specification points of the project being low cost and lightweight, there are limitations on the amount of electronics implementable in the device. Therefore, the most common control method for actuating the fingers in the 3D printed prosthetic hands is with the use of fishing line down the individual fingers. However, the material properties can vary with different fishing lines, for example having different Young's Modulus's and ultimate yield strength. As fishing lines are so strong the yield strength is not a concern as these forces will never be reached when actuating prosthetic fingers. However, the effect of the Young's modulus is an important consideration when designing the control of the prosthetic hand.

Wire with a lower modulus will have the ability to stretch giving the fingers an adaptive grip for picking up a range of objects with different shapes and those that need different levels of precision such as eggs [58]. This is due to a reactive force from the fingers contact with the object stretching the line instead of compressing the object. On the other hand, when the fishing line stretches, energy is consumed in the form of elastic potential energy, therefore reducing the amount of force being supplied to the fingers through the line. This could have a negative effect within a system that only has a limited energy supply to produce a force, such as small motors. In the cases of electronic actuation of the fingers it is therefore more beneficial to have a high Young's modulus line for the most efficient use of the motors. An example of a high Young's modulus fishing line is the ASSO SK60. It was designed to be high resistance with a Young's modulus of 130MPa and max weight of 16.6kg [64].

6 Tools

6.1 3D Printing (TE)

6.1.1 Machines (TE)

One of the tools made available by the department was the manufacturing method of 3D printing. This technology allowed the use of the manufacturing and design process rapid prototyping (RP), "A group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional computer aided design (CAD) data." [65] This process allowed the testing and iteration of designs throughout the development of the project. The models of 3D printers that were made available were; the Zortrax M200, Zortrax M200+ and the P3Steel printer, which all use the printing process Layer Plastic Deposition (LPD). The P3Steel printer is a structural upgrade kit for the Prusa i3 printer. As it is unclear if any other upgrades have been made to this printer, the Prusa i3 specification points have been used. Images, Figure 6-1, and technical details, Table 6-1, of these printers are given below.

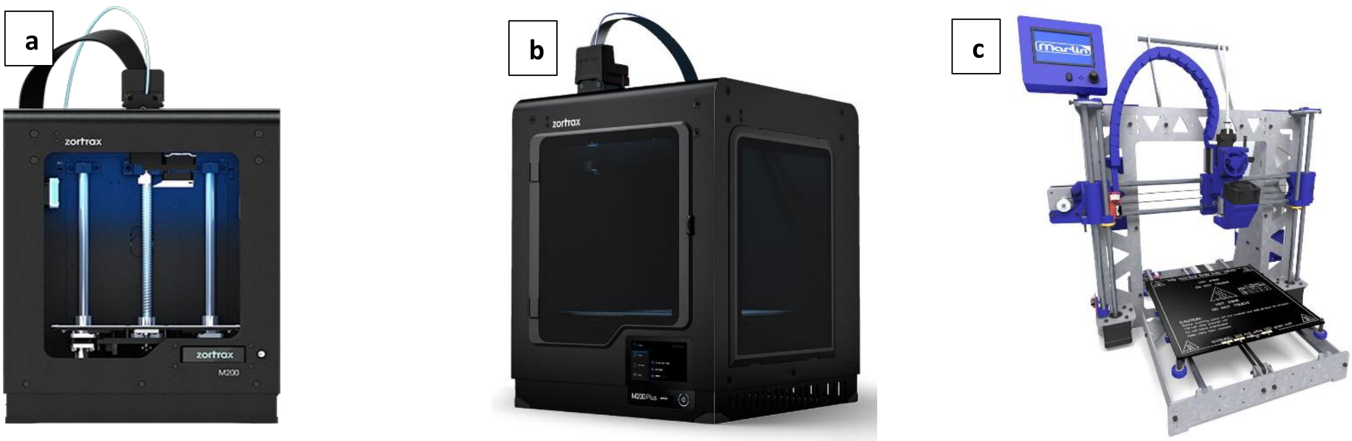


Figure 6-1: a – Zortrax M200 [66], b – Zortrax M200+ [67], c – P3Steel [68]

	M200	M200+	P3Steel
Layer Resolution (mm)	0.09 – 0.39	0.09 – 0.4	0.15 - 0.2
Minimum Wall Thickness (mm)	0.4	0.4	Dependent on Upgrade Specifications and Assembly Accuracy
Dimensional Accuracy (+/- %)	0.2	0.2	
Build Platform	Heated	Heated	Heated
Build Volume (w/l/h mm)	200 x 200 x 180	200 x 200 x 180	250 x 210 x 200
Slicer Software	Z-Suite	Z-Suite	Repetier Host

Table 6-1: 3D Printer's Specifications [67, 68, 69]

All the printers had a small layer resolution with the largest being 0.15mm. They all had good dimensional accuracy allowing for small intricate parts to be designed with a very good surface finish. Additionally, all three have heated beds, allowing for more reliable prints with less chance of the part unsticking from the build platform during the print.

The Zortrax machines had their own supported slicer software called 'Z-Suite', specific for creating the 3D print files for their machines. The P3Steel machine used the slicer software 'Repetier Host'. Both software support an input of .stl files, which are easily created from any CAD software, and provide a range of print settings to vary the quality of the printed parts.

6.1.2 Materials (TE)

Each printer model gave access to different materials that could be considered during the design of the product. The materials supported by each printer are given below in Table 6-2:

	M200	M200+	P3Steel
Materials	Z-PLA Pro Z-PETG Z-PCABS Z-ULTRAT Z-HIPS Z-GLASS Z-ESD Z-ASA Pro Z-ABS	Z-NYLON Z-FLEX Z-PLA Pro Z-PETG Z-PCABS Z-SEMIFLEX Z-ULTRAT Z-HIPS Z-GLASS Z-ESD Z-ASA Pro Z-ABS	PLA ABS PET HIPS Flex PP Ninjaflex Laywood Laybrick Nylon Bamboofill Bronzefill ASA T-Glase Carbon-fiber enhanced filaments Polycarbonates

Table 6-2: The Materials Supported by the Different Printers [66, 67, 68]

The materials highlighted above were the ones chosen by the department to have loaded in the printers. Therefore, the materials considered during the designing of the product were; ABS, PC-ABS, SEMIFLEX and Ninjaflex. The properties, some mechanical design applications, and print quality for these materials can be seen in section 5.4.

6.1.3 Design Considerations For 3D Printed Parts (TE)

When designing parts which are to be 3D printed using the process LPD, there are multiple considerations during the design and modelling stages. The key considerations that were used when designing parts for the project are highlighted below.

Tolerancing

For parts which interlock and assemble with several others it is important to tolerance correctly to achieve the desired fit. A dimensional accuracy of +/- 0.2% has been given for the machines and must be accounted for. A tolerance of 0.2mm was given for parts which required a friction or exact fit, and a tolerance of 0.4mm between surfaces for designs which required movement or little friction.

Minimum Feature Size

An additional design choice decided upon by the team was to avoid making any features, such as holes or walls, less than 1mm in thickness or diameter. Although the machine specification gave a minimum thickness of 0.4mm, it was found that these features either were too small to print or were too weak and therefore break easily. Also, the distance between features should never be less than 1mm as there is a risk of them merging and not having clear boundaries.

Supports

A setting available in the slicer software is the ability to generate manually placed or automatically placed supports in the 3D print files. These are removeable structures which are built up alongside the model during the printing process, providing support for overhang surfaces with a greater angle than 45° to be printed upon. This setting can therefore be considered during the designing of parts with more complex geometry.

Another factor when designing with supports is the material that is being used to print. The supports of the strong and hard materials, ABS and PC-ABS, can be removed easily just by snapping them off and with the use of small files, leaving a good surface finish. Whereas, the materials SEMI-FLEX and Ninjaflex merge with their supports due to their slower cooling rate, therefore requiring a knife to remove, leaving a rough and inaccurate surface finish. It is advised to therefore design flexible parts with a flat surface in mind to place on the print bed, with no faces over 45° and low complexity.

Orientation of Part on the Build Platform

Due to the technology of LPD building a part layer by layer, structural weaknesses are created in the part. Due to the plastic solidifying at the same time in a layer, there are strong bonds parallel to each layer. In the direction perpendicular to a layer, the bonds between the layers are not as strong due to the previous one having already being solidified before the next has been deposited.

For objects that require to withstand a load, they should be designed to be printed with the layers being built perpendicular to where the load will be applied. This will reduce the chance of failure occurring at a weakness on one of the layer boundary.

6.2 Electronics (PB)

Arduino is an open source electronics prototyping platform that has been used worldwide as a way of making electronics easy and accessible. An Arduino itself is a versatile microcontroller that can be used to read inputs, such as sensor values, and turn them into outputs like the movement of a motor or turning on an LED. The board is easily programmable using the Arduino IDE software, and many designs and tutorials are available online for a vast range of components and projects, making it easy to learn. Code can be quickly changed and uploaded via USB, allowing for rapid prototyping of designs. It can also be powered by USB, or battery for portable devices, making it highly applicable to this project. Furthermore, they are inexpensive, with many cheaper alternatives also on the market offering the same functionality. This project was highly dependent on the use of an Arduino, as it was used to rapidly test many different sensors and actuators.

6.3 Machines (SS)

In GI-NOVA platform the machines are all available for prototyping purposes. In this prosthesis project several machines are used for the manufacturing of the test rig besides the prototyping purposes.

Figure 6-2: available machines that were being used in this project [69][70]

- **Peugeot Energy Saw**: This is a circular saw machine to make cuts, edges or bevelled. It includes extension on the right and left to increase the volume that can be cut. Cutting height is 74mm for a perpendicular cut. The product that is aimed to be cut is manually loaded [69].
- **Epilog Laser Fusion**: This is an available laser cutting machine which allows a better flame-polished edge to cut. It has an engraving area of 812x508 mm. The viewing door is wide and has LED lightening. It moves in two axis and needs manual calibration [70]. It runs by using CorelDraw software.
- **CSI CNC**: This is a 3-axis CNC machine. It has a different version of a g-code which is run by Heidenhain. The machine powered by the Esprit software where the computer aided manufacturing is made.
- **Cincinnati Drilling Machine**: It is a bench drilling press which has a spindle speed in between 330 to 600 rpm. Maximum distance between the spindle nose to the table is 450mm [71]
- Maxi distance spindle nose/table 450 mm

6.4 Onshape (JP)

During any product development endeavour in the modern age it is necessary to use a CAD software programme. For this project Onshape was chosen for several reasons:

- Onshape allows collaboration and sharing using a cloud-based data storage system.
- Multiple users can edit a document simultaneously, with a historical record enabling the restoration of previous versions.
- Parametric Multi-Part Modelling and Kinematic Animation are two of many features available.
- The software uses the. stl format, which is compatible with most 3D printers and with most other CAD software packages, allowing the import and export of documents.
- Open source and can be continually improved by its users through the FeatureScript programming language.
- Intuitive system which can easily be learned by both CAD software novices and regular CAD users who are well-practiced with another platform [72]

As this is a project promoting open-source design, Onshape was deemed the most appropriate CAD software for the 3D modelling and design of the prosthetic hand.

7 Electronics Development and Testing (PB)

In addition to the mechanical testing, electronics testing was undertaken to assess the viability of different electronic components for this project.

7.1 Actuation (PB)

The first step was to determine how a prosthesis could become electronically assisted. Unlike a body-powered prosthesis, it had to be powered by electronic actuators. The 2018 design, for example, chose a linear actuator as their actuation method. By researching existing electronically controlled prosthesis, it was found that many use servo motors or linear actuators. These are popular methods as they can be implemented to precisely control the position of the fingers using positional feedback of the actuator.

As the user is a trans-radial amputee, there is little room in the palm for the actuators. Her existing myoelectric prosthesis, the Myohand by Ottobock, houses four actuators at the base of the fingers, allowing each finger to be actuated individually. There are two main problems with this:

1. Most of the weight is concentrated at the end of the prosthesis, causing a large moment arm. The prosthesis is then perceived to be very heavy and uncomfortable to use as a result.
2. The motors used in this case were highly expensive and not likely to be applicable to this project.

The motors would therefore need to be located outside of the palm, on the gauntlet. The method of contraction would be kept the same as the Kwawu model, contracting the fingers by pulling the fishing line used to simulate tendons. Some initial tests were carried out to understand how these motors functioned and how they could be controlled using the Arduino. At this stage in the project, it could not be determined which method of actuation was best suited to this project. Testing therefore focussed on the input control techniques needed to control the actuator.

7.2 Input Sensors (PB)

The first tests were used to help the designers learn how to use an Arduino in conjunction with a wide variety of sensors and actuators. Prior to this project, the team had little experience with such electronics and therefore time was spent learning how to apply them. The initial tests assessed different input control techniques using pressure, flex and myoelectric sensors. As determined from the state-of-the-art research, the controller should allow the user to precisely open and close the fingers and be as reliable and predictable as possible.

A basic circuit and code were created that controlled a servo motor based on the value read from a flex sensor and pressure sensor that mapped it directly to a servos position:

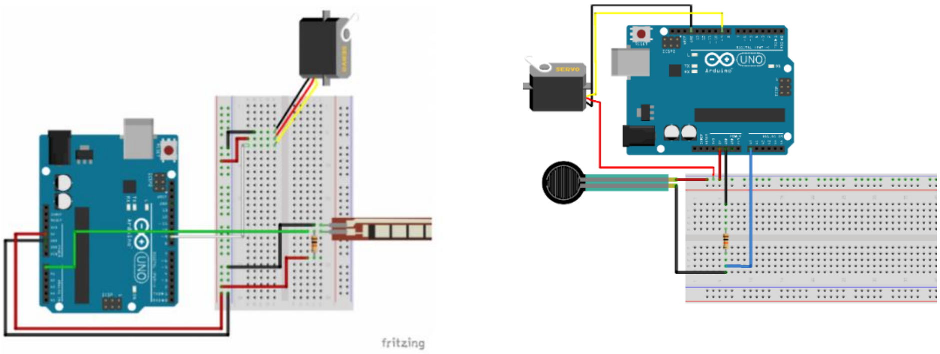


Figure 7-1: simple circuitry used to test a flex sensor (left) and a pressure sensor (right).

A circuit and code (Appendix B) were then developed using two sensors that rotated the servo motor clockwise and anticlockwise depending on which sensor was pressed. This no longer depended on the magnitude of the value read, only if the reading exceeded a threshold value.

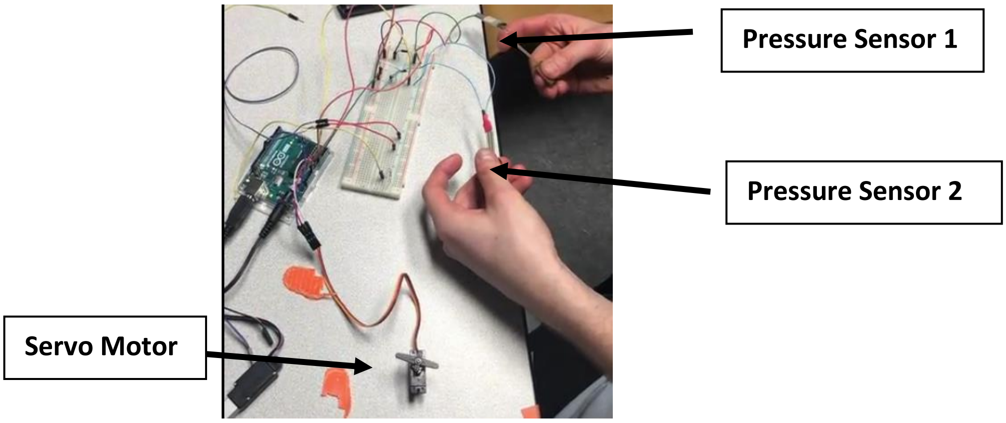


Figure 7-2: antagonistic servo control using two pressure sensors (Video in Appendix C)

A limit was placed in the code so that if both sensors simultaneously exceeded this value, the motor would remain stationary. Variable speed control was then developed with two thresholds as demonstrated by the flow diagram below. Again, both sensor types could be used.

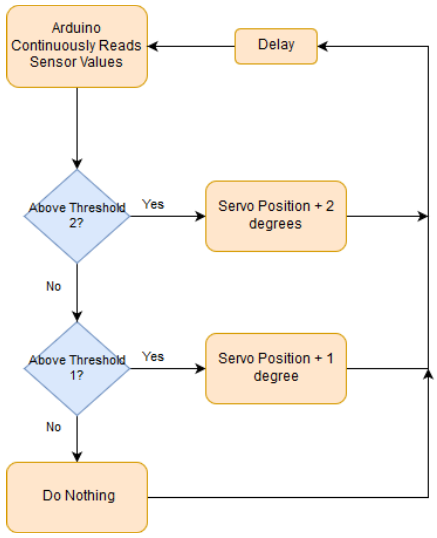


Figure 7-3: Variable servo speed flow chart

The speed can be altered either by increasing the number of degrees the servo turns through each loop, which decreases accuracy, or by increasing the value of the delay at the end of the loop. The longer the delay, the less responsive the system is. However, as specified in section 5.3 delays up to 300ms can be permitted for effective body ownership.

This configuration was further developed by adding one more pressure sensor to simulate a pressure sensor in a fingertip. When this third sensor is pressed, all movement is stopped until the pressure is released. This could be used as a means of force derivative feedback (see section 5.3.6), wherein the servo could slow down once a force is detected or stop entirely should the force be above a threshold.

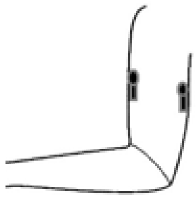
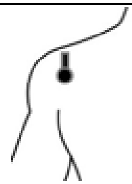
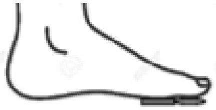
Myoelectric Sensor

The same tests were attempted using a myoelectric sensor. The sensor was similar in that it read a value to the Arduino analogue pin, however it was more difficult to test effectively for the following reasons:

- Every time it was tested it required new electrode pads to form a solid connection with the skin. These are expensive.
- A myoelectric sensor must be carefully placed on a residual muscle to find the optimal location. This is typically done by a prosthetist, and therefore when testing on the forearm the signal was unreliable and noisy.

Sensor Comparison

The next step was to find potential placement on the body for all three sensors. For successful control, the system should be reliable and predictable. For pressure sensor and flex sensor control, it must be placed in a location where a force could be applied in the correct orientation, and for a myoelectric sensor it must be carefully placed on the skin above a residual muscle. Research has shown that the control mechanism should be applied as close to the residual palm as possible to reduce the cognitive effort required to control the prosthesis. Several locations were proposed and are evaluated in Table 7-1.

Sensor	Locations	Description	Image	Advantages	Disadvantages
Pressure	Bicep	Tensing the muscle applies pressure to the sensor, usually housed in a tight band of fixed diameter around the arm. Controls position by using one sensor with the map function, or by combining multiple sensor locations that control opening/closing separately.		General: > Low cost > Reasonably intuitive > Easily adaptable by user	> Placing sensors further away from the prosthesis could increase cognitive effort required, and reduce the sense of embodiment. > Potentially inaccurate, especially if the muscle and sensor move in relation to each other. > Could be uncomfortable to use > Variable speed and strength unlikely
	Tricep				
	Forearm				
	Shoulder				
	Toe	Sensors placed around the big toe could be used to control movement.		> Toe control keeps all upper body muscles free from strain of control	> Unlikely that the user could walk and use prosthesis at the same time > High cognitive effort required > Could be uncomfortable to use > Accidental movements likely > Variable speed and strength unlikely
	Left Hand	Users left hand has greater dexterity, could be used to control pressure sensors.		> Intuitive > High precision > Variable speed and strength likely	> Difficult for the user to use both hands at once, and therefore they would likely just use their operational hand instead. > Need for wireless communication between controller and prosthesis, or long wires
	Residual Right Palm	Sensors could be placed in residual right palm, depending on the level of dexterity still available.		> Low cognitive effort being close to the fingers of prosthesis and objects being grasped > Potentially highly intuitive	> It is not known what dexterity is available to the user > Potentially limiting to wider market, not universal > Could be uncomfortable > Electronics in palm could be easily damaged

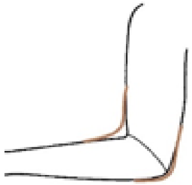
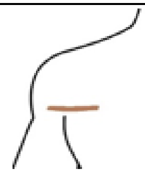
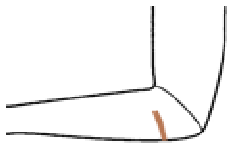
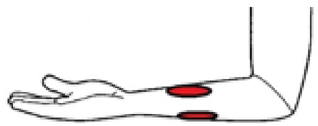
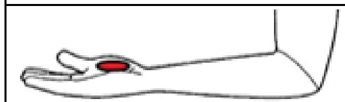
Sensor	Locations	Description	Image	Advantages	Disadvantages
Flex	Wrist	Bending at the joint flexes the sensor. Controls position by using one sensor and map function, or by combining multiple sensor locations that control open/closing separately.		> Low cost > Reasonably intuitive > Easily adaptable by user	> Placing sensors further away from the prosthesis could increase the cognitive effort required, and reduce the sense of embodiment. > Having to bend joints to control the prosthesis impairs the use of that joint and its normal function > Can be uncomfortable to use > Not much benefit over body-powered prostheses
	Elbow				
	Shoulder				
	Forearm	Tensing muscle bends flex sensor. Controls position using map function of having multiple sensor locations that control opening/closing separately.			> difficult for some people to tense their muscles >muscles move depending on rotation of arm, affecting sensor readings > Uncomfortable movement
Myoelectric	Forearm	Senses muscle signals. When a muscle is tensed, it produces an electrical signal (see section X). The magnitude of this signal depends on how hard the muscle is tensed. This is measured by the sensor and read to the Arduino.		> Detecting muscle signals > Variable speed and strength likely > Position of sensors on forearm keep system self-contained. > Highly advanced, can be used for multiple grip patterns and precise control > Used in many high-end electronic prostheses	> High cost > Requires specific electrode placement, usually by a prosthetist > Signal can be noisy and therefore inaccurate > Muscle movement in relation to sensor on skin can also affect signal quality > Complex to implement
	Residual Palm				

Table 7-1: Sensor location comparison

The team tested many of the proposed sensor locations on themselves with a servo motor. The findings were consistent with the research undertaken and the predictions made in Table 7-1. All sensors presented an element of inaccuracy, with the myoelectric sensor being particularly unreliable. This was primarily due to difficulty in finding optimal electrode placement.

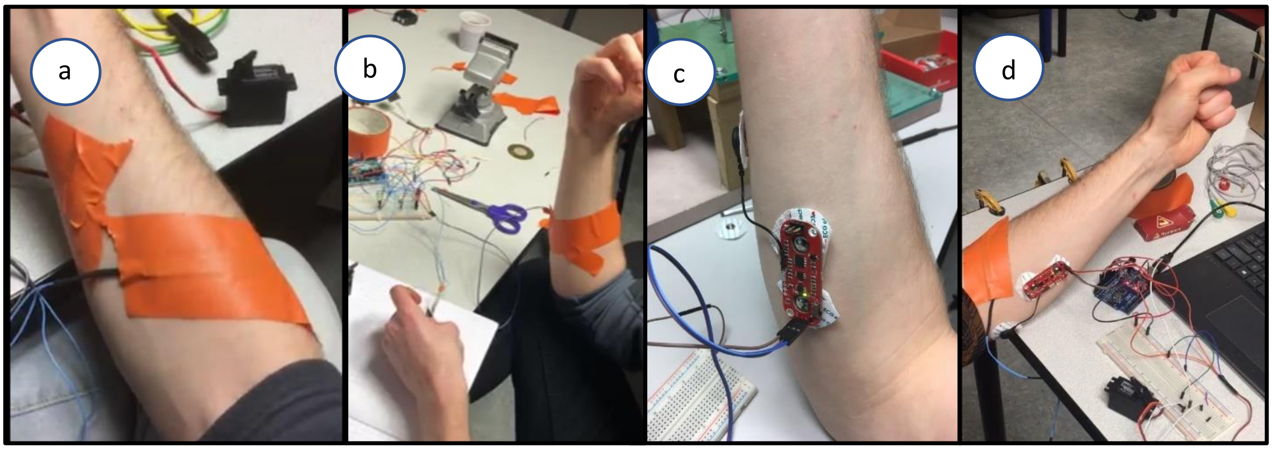


Figure 7-4: Sensor tests, A. Two flex sensors on forearm. B. One flex sensor on forearm. C. One myoelectric sensor on forearm. D. One flex & myoelectric sensor on forearm. (Video Appendix C)

To test all these locations fairly, a test was designed that could be undertaken with the user in the first interview. Unfortunately, this test was not undertaken due to an electronic fault on the day of interview.

7.3 Force Feedback (PB)

In section 5.3, it was concluded that force feedback is important when there is feedforward uncertainty in the controller. The implementation of a sensory feedback system is particularly important in an upper limb prosthesis to improve closed-loop control and prosthesis acceptance [73]. It's also difficult to determine force through visual feedback alone. As determined from the previous sections, there is considerable uncertainty from flex, pressure and myoelectric sensors. To help counteract this, methods of force feedback were investigated. Through research, vibrotactile stimulation was found to be a proven means of achieving this.

The DRV2605L haptic driver module from Sparkfun Electronics is a component capable of driving a vibration motor in 1 of 123 different vibration patterns controlled using an Arduino and haptic driver library available from the Sparkfun website. A haptic driver has the benefit of providing high quality haptic feedback using eccentric rotating mass (ERM) or linear resonant actuator (LRA) type motors over a shared I^2C-compatible bus or PWM input signal. It helps provide consistent actuator performance in terms of consistency of acceleration, start time and brake time. This is important for reliability, particularly when used to help compensate for controller uncertainty. The use of I^2C and the Arduino's SDA and SCL pins are explained in detail in the DRV2605L datasheet [74].

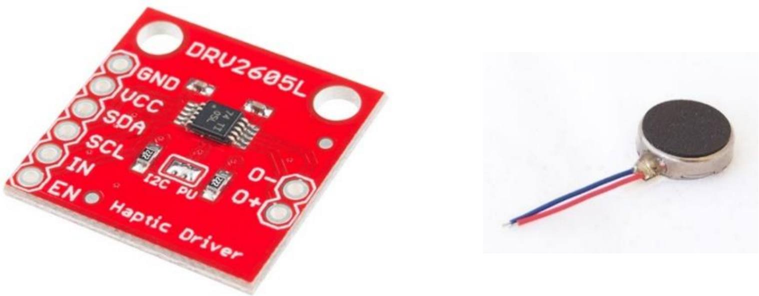


Figure 7-5: DRV2605L haptic driver and vibration motor

Pin Name	Type	Description
GND	Power	Supply ground
VCC	Power	Supply input (2 to 5.2 V). A 1-µF capacitor is required.
SDA	Input / Output	I2C data
SCL	Input	I2C clock
IN	Input	Multi-mode Input.I2C selectable as PWM, analogue, or trigger. If not used, this pin should be connected to GND.
EN	Input	Device Enable
OUT +	Output	Positive haptic driver differential output
OUT -	Output	Negative haptic driver differential output

Table 7-2: Haptic Driver Pins

Each waveform is triggered by a GO bit, which triggers processes inside the device. Its primary purpose is to initiate the playback of a specific waveform that corresponds to 1 of the 123 vibration patterns. The GO bit is essentially a software trigger, triggered by 'HMD.go()' in the code. It remains high until the playback of the waveform is complete.

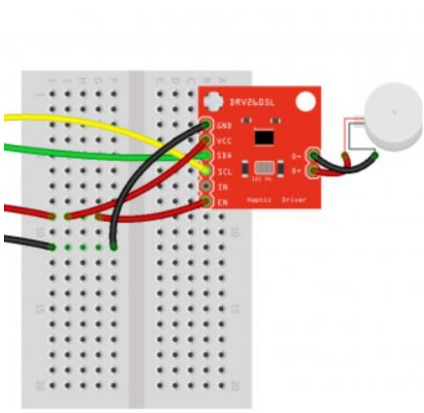


Figure 7-6: breadboard setup with driver, motor and wires leading to an Arduino

Using this driver, successful control of a vibration motor was achieved in conjunction with a pressure sensor. When pressed, the motor would vibrate until the force was removed. The next step was to obtain control of multiple motors, with the end goal being to develop a haptic array (as specified in section 5.3). In a haptic array, multiple vibration motors need to be used and activated separately. However, in the arrangement shown in Figure 7-6, all motors connected would vibrate simultaneously. Therefore, a method of connecting multiple motors to the same driver needed to be developed. NPN bipolar junction transistors were determined to be an effective solution to this problem, as using an Arduino's PWM pin the base pin can be set to high or low, acting as an electronic switch and allowing individual motor control.

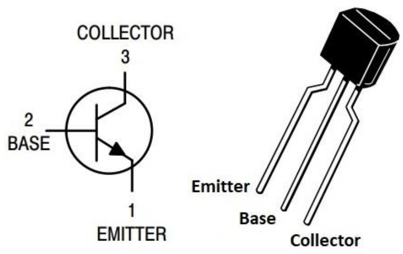


Figure 7-7: – NPN Bipolar Junction Transistor

When low, the transistor breaks the circuit for that motor, removing power. Once high, the circuit is reconnected. Part of this circuit is shown below using two vibration motors and two transistors:

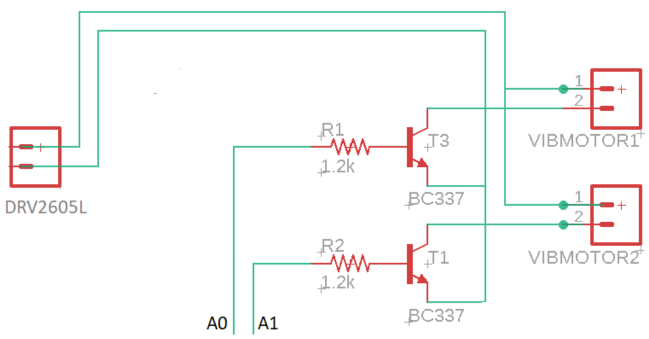


Figure 7-8: transistor and vibration motor circuit

Two transistors work as switches controlled by the PWM output of the Arduino. These control which motors are connected to the haptic driver and are easily controlled by the code. The resistor in series with the base of the transistor is a current limiting resistor, this stops the transistor being damaged from too much current. The transistor obtains the required voltage to form the short circuit, and anything else is dropped across the resistor. The value of this resistor should be large enough to limit the current, but small enough to provide the base with enough current.

Once this was successfully achieved, a pressure sensor was added to the circuit and three threshold values were specified in the code corresponding to different voltages from the sensor. A different motor vibrates depending on the pressure detected. If placed in the fingertip, this can be used to give force feedback to the user when grasping an object.

0 < *sensor value* <= **threshold 1** = vibrate motor 1
threshold 1 < *sensor value* <= **threshold 2** = vibrate motor 2
threshold 2 < *sensor value* = vibrate motor 3

Figure 7-9: Vibration Motor Thresholds

The thresholds used were arbitrary due to this being a proof of concept. In the final design, these could be chosen by calculating exact forces and what these correspond to – i.e. threshold 2 = the average force to crack and egg. The vibration pattern used (from the 123 available) was also fairly arbitrary as it was a proof of concept. In the code, number 47 is used, which corresponds to 'Buzz 1 – 100%' - a strong vibration was used to maximise perceptibility.

47	Buzz 1 – 100%
48	Buzz 2 – 80%
49	Buzz 3 – 60%
50	Buzz 4 – 40%
51	Buzz 5 – 20%

Figure 7-10: snapshot of Sparkfuns DRV2605L haptic driver waveform library effects list [74].

As the haptic array would need to interface with the mechanical design, various housings were designed, and 3D printed using both ABS and NinjaFlex to assess its viability. Below are two different configurations.

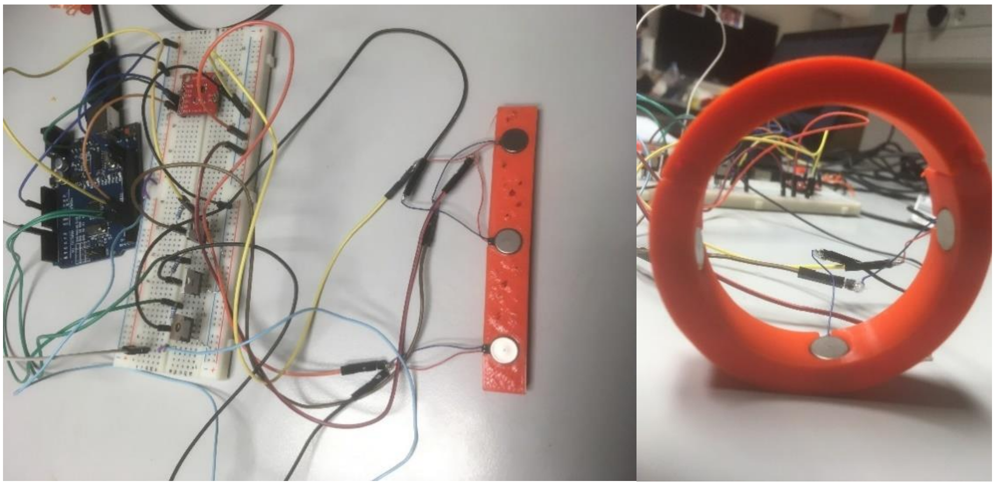


Figure 7-11: Haptic array in linear and circumferential configurations

The linear pattern is inspired by the state-of-the-art research (see section 5.3), to apply feedback to the forearm. The minimum distance between vibrations motors for effective differentiation being 30mm. In the circular design, the centre points of the motors are also located 43mm apart (arc length) and the team found them easily differentiable.

From this testing, the haptic array was deemed to be a potential method of providing force feedback to the user. However, for this to be successful some problems would need to be overcome:

- The pressure sensor used in the testing was far larger than a fingertip, and therefore a smaller sensor would need to be sourced or made.
- Wire fatigue would be a significant problem in the finger due to a high degree and rate of flexion. Other conductive materials would need to be investigated to replace standard wire.

Because of these limitations, other means of measuring force were also investigated.

<u>Current Sensor</u>

Under high loads, a motor will stall and as a result draw a high current. A current sensor can be used to measure this current, and therefore provide feedback on the force applied to an object. A current sensor was connected in a circuit with a resistor to measure the current drawn from the circuit. This was achieved along with calibration on an Arduino. The resistor was then replaced with a servo motor and the motor current was measured. Stalling the motor produced a high current spike as expected, which could be used as a means of feedback when an object is gripped by the hand.

A benefit of this method is avoiding electronics in the fingertip and palm, simplifying the system and increasing its robustness. The main drawback is that the motor current fluctuates a lot, and therefore the team found it could only be used to detect when the motor stalls, i.e. when a high force is being applied. It is not a good solution for low force detection.

<u>Piezoelectric Sensor</u>

In prosthetics, a piezoelectric sensor is typically employed as a method of measuring slip. When an object slips from the fingers, it causes vibrations through the surface. These vibrations can be detected by the sensor, which is highly sensitive to these vibrations. The team tested such a sensor using an Arduino. A graph is shown below:

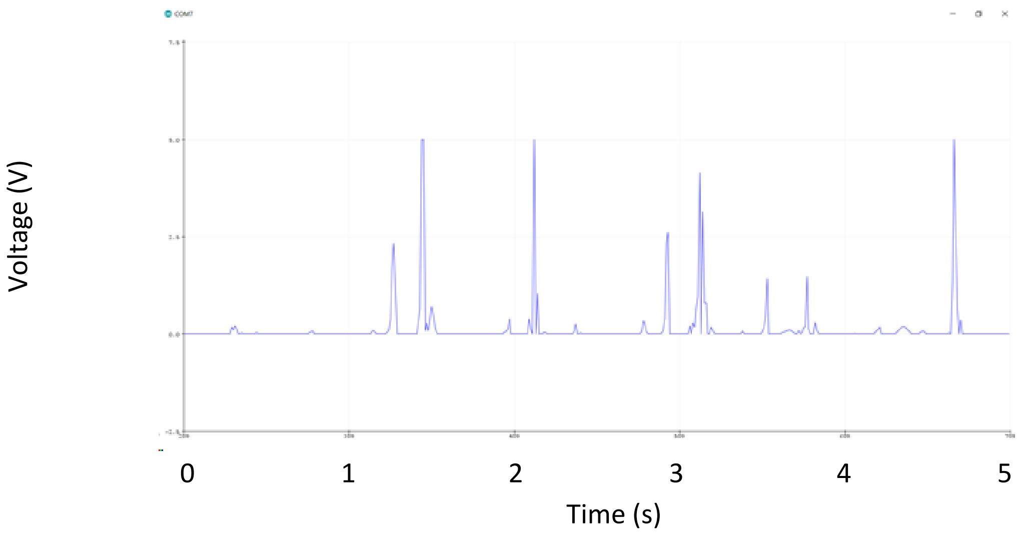


Figure 7-12: voltage spikes from a piezoelectric sensor.

Each peak indicates the sensor being jolted and creating a voltage. Although not developed, code could be made that rotated the servo motor by a certain number of degrees should the sensor value spike above a certain value or detect a certain vibration pattern consistent with an object slipping from the fingers. This rotation would hopefully catch the object before it falls. As this was difficult to test without a functioning prosthesis, it was not developed.

8 Mechanical Development and Testing

8.1 Finger Model Testing (TE)

The approach to design the mechanical system of the product was to investigate multiple models for the fingers and palm via testing. Within the e-Nable community, extensive design and development has been done into the mechanical design of effective and simple models for the fingers, palm and mechanical actuation. Therefore, it was agreed that the best approach would be to choose from one of these existing models and build a mechanical and electronic system using this as a base.

The tests chosen to be conducted to select the model were:

1. Maximum contraction force test.
2. Scaling model force test.
3. Model object grip test.

8.1.1 Test Design and Manufacturing (PB, TE, JP, SS)

A process was carried out to; choose the models that would be tested, design the rig that all the tests would be carried out on, and manufacture and assemble the rig and multiple sizes of the models.

8.1.1.1 Finger Models (TE)

Four models were chosen, and the index finger of each model would be compared throughout the tests. A section of palm for the index fingers of the models would be printed to allow contraction of the proximal joint, and to allow constraint of the finger. The four finger models chosen, and their justifications are given below.

<u>The Phoenix Hand</u>

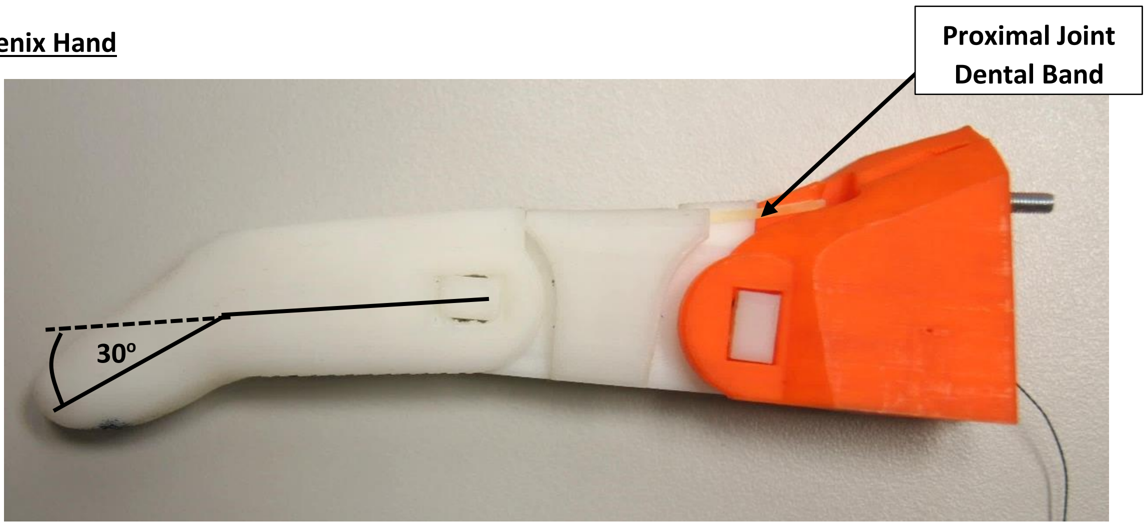


Figure 8-1: Phoenix Index Finger Assembled

The Phoenix hand was the first model chosen due to it being the flagship model for the e-Nable community. Key features of the model are:

- The model has only two contraction points, the intermediate and proximal joints. The distal bone remains at a fixed angle of 30° compared to the intermediate, see Figure 8-1.

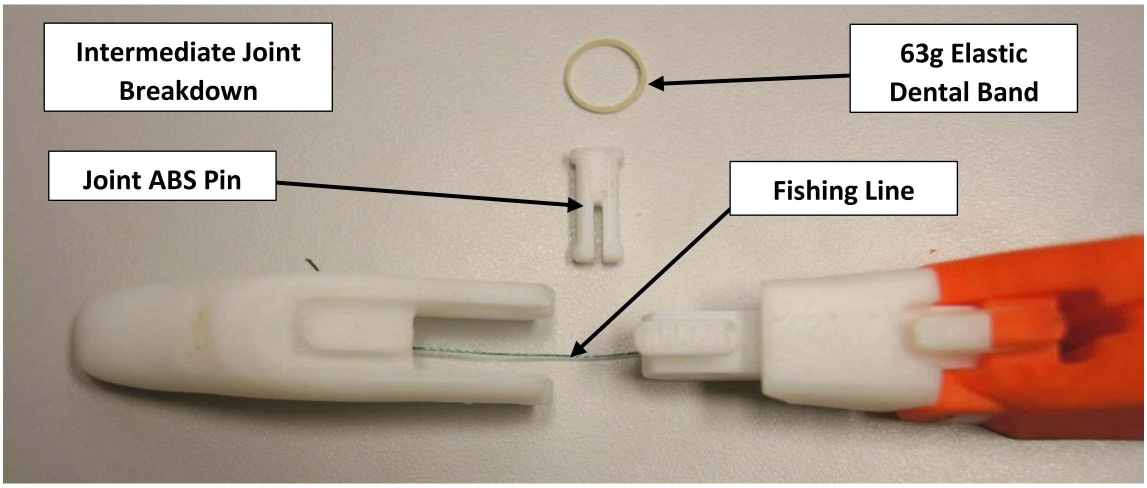


Figure 8-2: Phoenix Index Finger Disassembled

- The design is simple, with three parts being assembled with two 3D printed ABS pins through the joints to allow for rotation, see Figure 8-2.
- Two dental bands, with a force rating of 63g, are used along the outside of the finger over the intermediate and proximal joints. The extension of these bands during contraction provides an elastic restoring force to return the finger to its natural position once the contraction force has been released.
- Fishing line runs along the inside of the finger through large openings in the ABS. The fishing line is attached to the finger via a knot around a bar located at the top of the intermediate section of the finger.

The Kwawu Hand

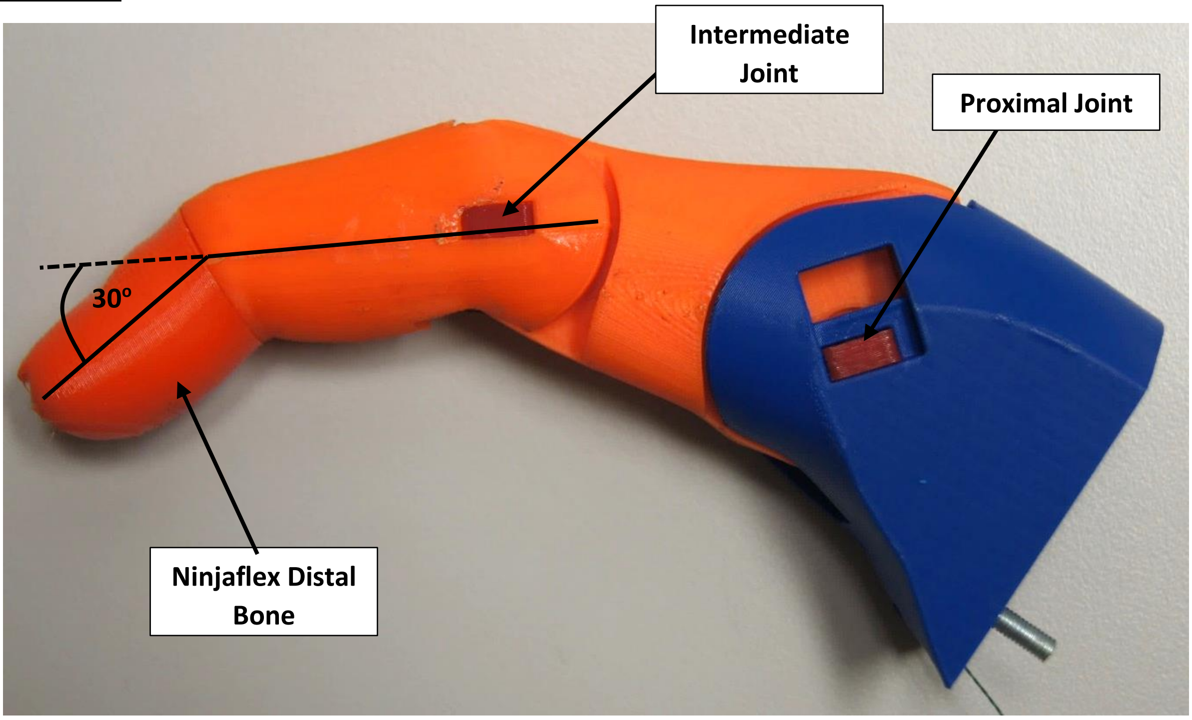


Figure 8-3: Kwawu Index Finger Assembled

The Kwawu hand is a model developed by the e-Nable community member Jacquin Buchanan. This model was chosen due to it being the hand for the user's current mechanical prosthetic and was the model chosen by the students in 2018. Its key features are:

- The model has only two contraction points, the intermediate and proximal joints. The distal bone remains at a fixed angle of 30^{o} about the intermediate, see Figure 8-3.
- The distal bone is made of Ninjaflex to allow slight deformation during the grasping of objects.

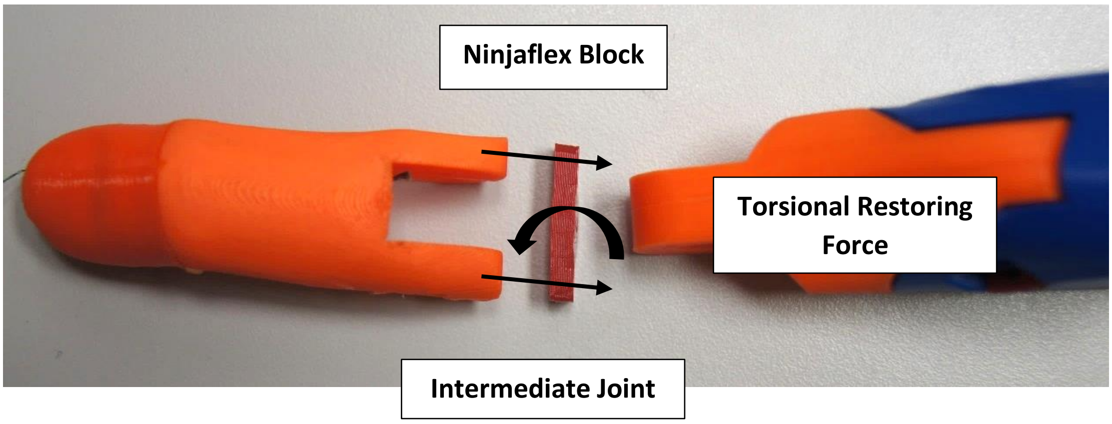


Figure 8-4: Kwawu Index Finger Disassembled

- The design uses Ninjaflex filament in the joints with 20% infill. These Ninjaflex oblongs are used to assemble the distal/intermediate section to the proximal via the intermediate joint, and the proximal section to the palm via the proximal joint.
- The Ninjaflex joints are the restoring mechanism to return the finger to its resting position once the contraction force is removed. The restoring force is produced from the torsion of the Ninjaflex oblongs, which are constrained twice by the intermediate bone on the two outside edges and once by the proximal bone in the centre. The rotation of the intermediate bone around the proximal causes torsional deformation and therefore a restoring force one the contraction torque is released, see Figure 8-4. The same force is produced at the proximal joint by the proximal bone rotating within the palm.
- Fishing line runs along the inside of the finger via large openings in the ABS. It is looped around and attached to a small bridge at the top of the intermediate bone.

The Flexibone Hand V1

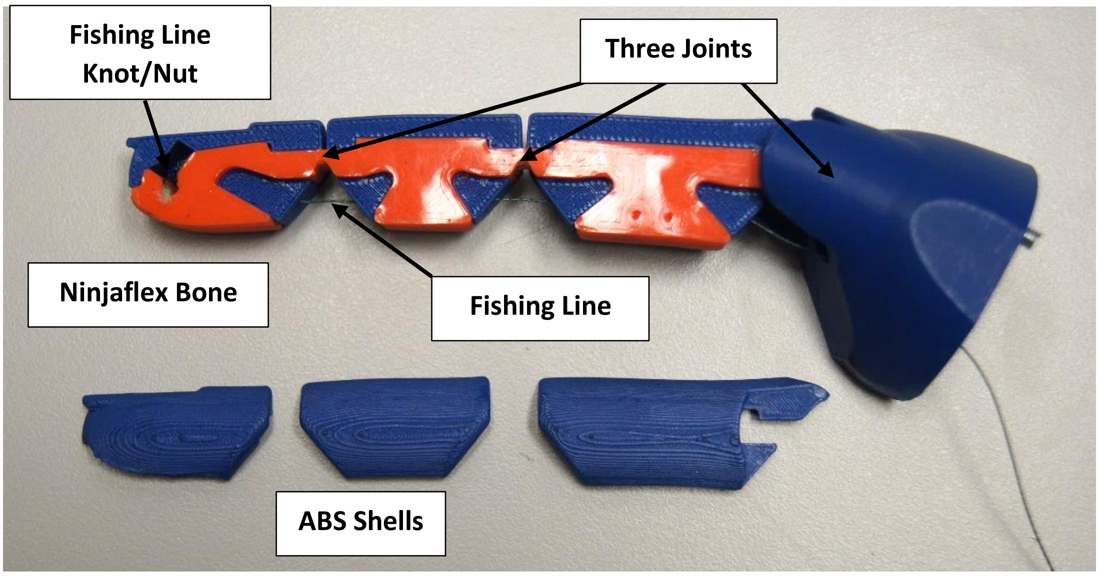


Figure 8-5: Flexibone V1 Index Finger with 3 ABS Shells Removed

This design was created by one of the supervisors of the project and e-Nable community member Philippe Marin. It was therefore by his request that this model was chosen. Its key features are:

- Three joints for rotation, the distal, intermediate and proximal joints.
- The design consists of a bone through the center made of Ninjaflex printed with 20% infill from the guidance of the designer. It is then surrounded by 6 ABS shells to create the solid finger, see Figure 8-5.
- The Ninjaflex bone provides the restoring force for the finger once the contraction force has been removed. Due to the bone being printed in its natural flat position, when the finger is contracted the ninjaflex on the back of the bone extends at the three joints creating a elastic tension force. This is the force which restores the finger to it's natural printed position once the contraction torque s released.
- The fishing line threads through a small cylindrical pathway throughout the ABS casing and Ninjaflex bone. The fishing line is secured in the distal bone with a large knot or M2 nut to restrain it from passing back through the hole.

The Flexibone Hand V2

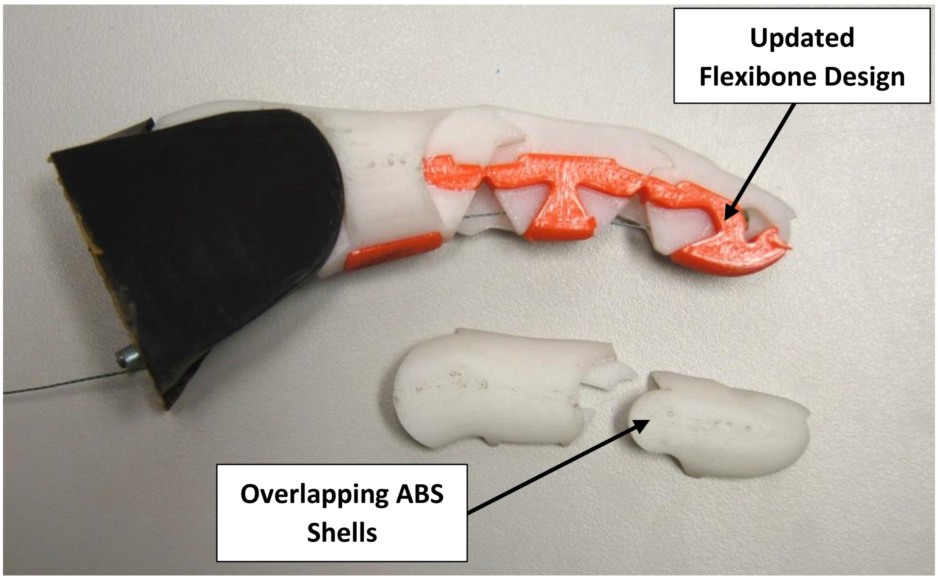


Figure 8-6: Flexibone V2 Index Finger with Two ABS Shells Removed

This design has again been developed by the e-Nable creator and project supervisor Philippe Marin. It is a new version of the Flexibone V1 design and therefore its functionality and method of restoring are very similar. However, it has some notable new features which are:

- The base model for this design is the same as the hand scan for the Kwawu model. Therefore, its aesthetics are the same but has been modeled with a Ninjaflex bone down the centre.
- The ABS shells overlap at each of the joints, making the joints invisible and more aesthetic for the user, see Figure 8-6.
- The Flexibone has been slimmed down with its width and thickness being less than the formally mentioned Flexibone V1.

This model was therefore chosen to allow a comparison between the two Flexibone designs.

8.1.1.2 Test Rig (TE, JP, SS)

The premise for the test rig was to have a moveable setup which could; accurately measure the amount of fishing wire needed to contract the fingers, and the force experienced in the fishing line throughout the contraction cycle. To achieve all these goals a rig was designed on one test bench which incorporated a servo motor, with a known diameter pulley, to accurately control the contraction length of the fishing wire. A tension load cell was placed in series with the fishing wire to capture the force readings, and a clamp was used to keep the base of the palm stationary while the joints of the finger contract. An annotated image of the test rig can be seen in Figure 8-7.

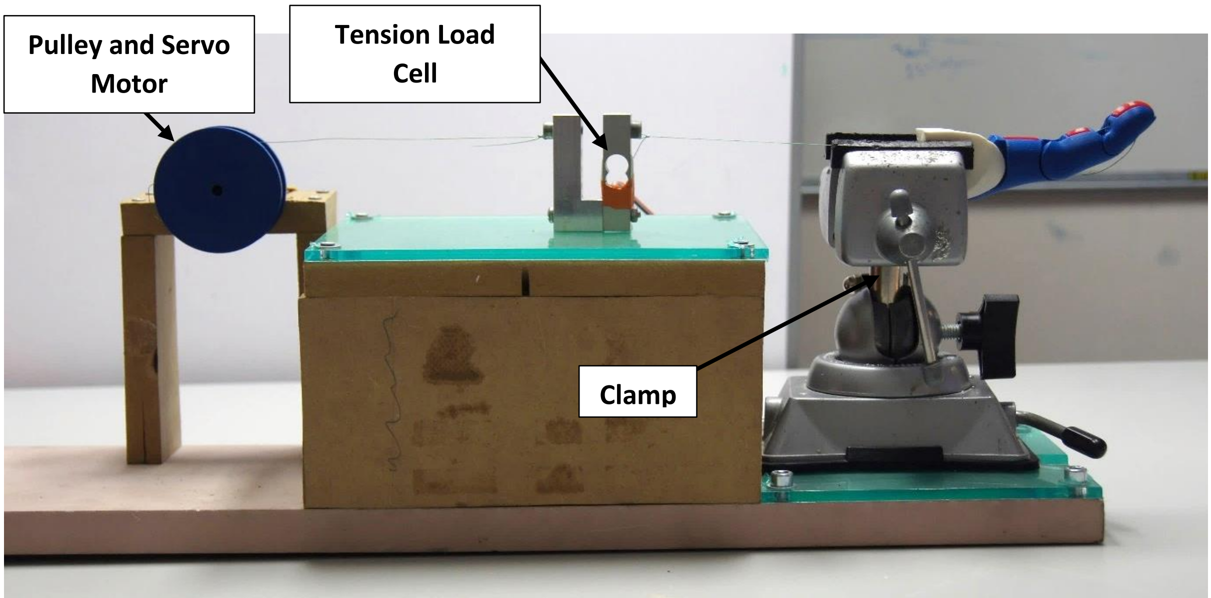


Figure 8-7: Mechanical Test Rig

Servo Motor (TE, JP)

The servo motor chosen for the test rig was the largest 180° motor available from the department. The model was the Power HD 6001 HB, which can provide 6.7kg/cm of torque at 6V [75]. However, it was only going to be powered off a 5V supply, giving a torque of 5.8kg/cm. A bracket for the motor to secure it to the rig was designed and 3D printed using the dimensions of the motor, see Figure 8-8.

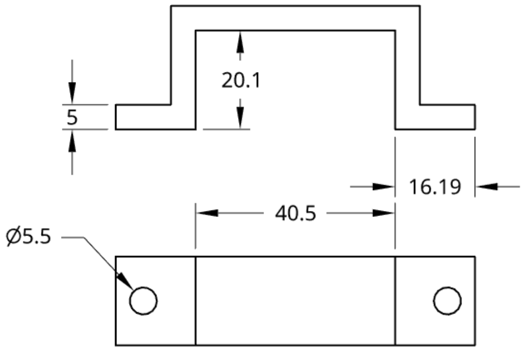


Figure 8-8: (Left) Test Rig Servo Motor 6001 HB [75], (Right) Servo Motor Bracket Schematic

Pulley (SS)

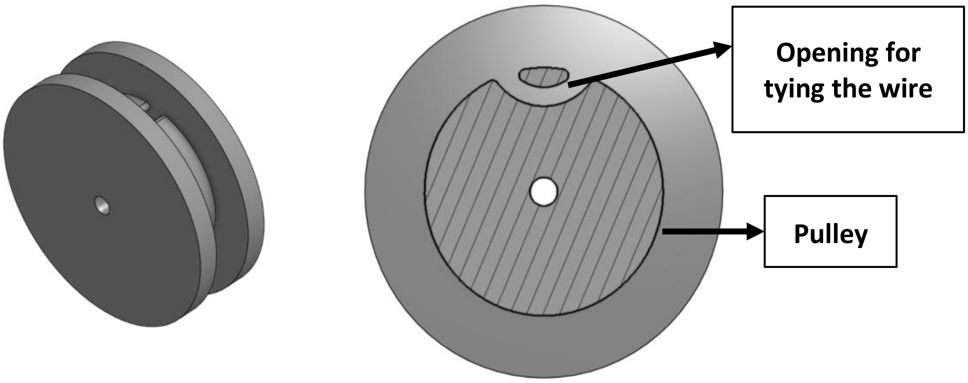


Figure 8-9: Test Rig Pulley

Before designing the pully, contraction distances for the different types and sizes of fingers were measured. Maximum contraction length in the wire was measured as 4cm. As the servo motor turns 180 degrees the circumference of the pulley needed to be minimum of 8cm. From the circumference minimum radius was calculated as minimum of 12.73mm. The pulley's inner radius was made 20mm and decided to be controlled by giving angle constraints to servomotor in Arduino.

The pully was designed on Onshape. The hole was made to be able to tie the wire around. On this hole, groove was made in the middle so that the wire would tie around it and it would be in the middle. This way the wire could be in straight line with other equipment in the test rig.

The wire was going to coil around the pulley and therefore friction was wanted to be as minimum as possible. To get a smoother surface and reduce the friction, alcohol treatment was used. The alcohol was put on the pully and then the jar's bottom was filled with alcohol. Afterwards inside the jar metal block is put so that pully won't get in contact with the alcohol. The pully was put on top of the metal block. The jar was closed and after 45min-hour the pully was taken.

Force Sensor (TE)

As the fingers being contracted are small and require a small amount of force, a load cell accurate for a low range of forces was needed to ensure the capture of reliable results. The department did not have any devices that could measure a force under 50kg, therefore a new sensor had to be ordered.

The key criteria for the sensor were:

- Had to be affordable, due to some systems being more than €500.
- Had to be accurate between a maximum of 0 - 10kg as the servo motor can provide a maximum of 5.8kg/cm of torque.
- Had to work with an Arduino, as the servo motor position and the force sensor readings could both be captured using the software Arduino IDE.
- Had to be from one of the departments listed suppliers.

Using one of the given suppliers, gotronics.fr [76], a new load cell was ordered, being the CZL635-5 5kg compression load cell, Figure 8-10, whose specification can be seen in Table 8-1. The SEN-13879 Force sensor amplifier was also ordered with the load cell, otherwise the signal from the load cell was not strong enough to be read by the Arduino.

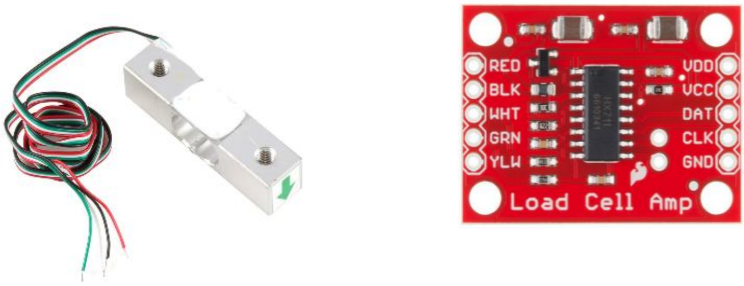


Figure 8-10: CZL635-5 5kg Load Cell (Left) [77] and SEN-13879 Force Sensor Amplifier (Right)

Power Supply	5V
Measuring Range	0 – 5kg
Accuracy	0.5% of Full Scale
Dimensions	55.25 x 12.7 x 12.7 mm

Table 8-1: CZL635-5 5kg Load Cell Specification [77]

A problem with the load cell was that it had been designed to measure compressional forces by being clamped at one end. However, all tensional load cells were far too expensive. Therefore, the compressional load cell was ordered with the aim to convert it to a tension load cell by using a designed additional attachment.

The attachment design is based on the shape of common tension load cells, this being the shape of a ‘S’ or ‘U’. The force sensor must go in series with the fishing line to capture the tension force while having one end of the load cell constrained. Therefore, as Figure 8-11 shows, an L-shaped attachment would allow the sensor to be attached to the fishing line in series at the same height either side. The tension in the fishing wire would create a moment in the load cell to try and rotate it. However, the equal tension acting on the L-shape bar would create the same moment in the opposite direction and therefore counteract and constrain the other end of the load cell.

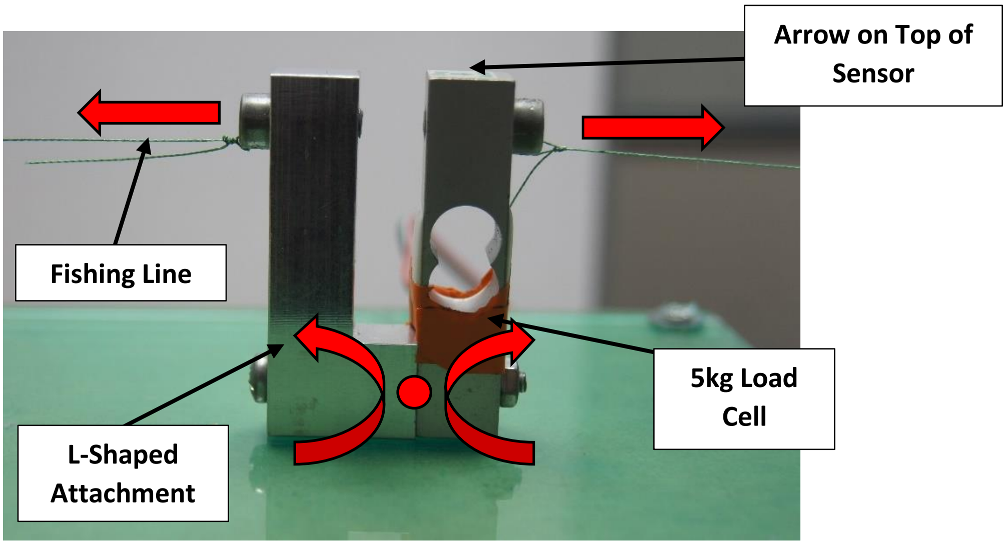


Figure 8-11: Moment Diagram of Force Sensor with L-Shaped Bar Attachment

A schematic for the L-shaped attachment is given below in Figure 8-12. It was designed to have the same dimensions as the load cell, see Table 8-1, and made from the same material Aluminium. It would therefore have the same stiffness and transfer the shear force through the bar to the load cell instead of bending. It was machined on the departments CNC machine.

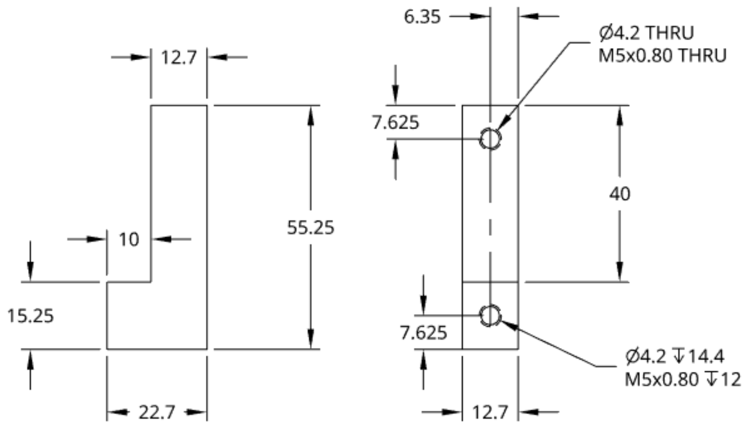


Figure 8-12: L-Shape Force Sensor Attachment Schematic

To assemble the attachment to the load cell a M4x20 nut and bolt were used to secure it tightly in the correct orientation. Two M5x15 bolts were inserted to attach the fishing wire to the sensor, both were fixed with maximum torque where a hole was drilled into each of the bolts to ensure that the fishing line could be attached at the same height.

Force Sensor Calibration (TE)

Before use, the force sensor must be calibrated using a code supplied by Sparkfun [78], see appendix D. The calibration was conducted by attaching fishing wire from the L-shape bar to a fixture and a water bottle, with a known weight, to the load cell so the whole system was freely hanging. The calibration factor in the code was then changed until the reading from the sensor matches the weight of water in the bottle. The process was repeated 3 times to find an average calibration factor. Finally, increase the weight of the bottle and test the calibration factor across its full range.

Clamp

The clamp used for constraining the index finger's palm was the PanaVise, supplied by the department. It was fully adjustable and could constrain all the fingers. It had a vacuum suction base to attach itself to smooth surfaces.

Test Rig (TE, JP)

During the designing of the rig a layout had to be planned to ensure the rig would work effectively for all the tests being conducted. The rig had to be portable so that it could be moved to locations with the best lighting for filming and with access to a power supply for the Arduino and laptop. Therefore, the rig was made on one test bed with all the platforms assembled on top.

Firstly, the clamps height was measured to be 158mm. This is therefore the height the fingers are clamped at. The clamp needs an additional surface that would allow its suction base to fix to. It is therefore is placed on a 6mm thick piece of Acrylic. The fishing line leaves the base of the palm horizontally to attach to the force sensor, therefore the force sensor had to be raised on a platform. This would bring the attachment bolt into horizontal alignment with the fishing wire. Additionally, this would remove one degree of freedom from the force sensor and therefore ensures the weight of the sensor does not create tension in the fishing line. A platform with a low friction surface was designed at a height of 120mm, considering the 44mm distance of the to the fishing line attachment bolt from the base of the sensor. This would minimise the friction created by the force sensor moving across the surface. The platform was designed to be 200mm long to give the force sensor space to move throughout the full finger contraction, while creating a rig more versatile for different tests. Finally, the platform for the motor was designed so that the top of the pulley groove was in line with the fishing line leaving the force sensor attachment. This would ensure the fishing line would always be pulled from the same height. This platform had a height of 135mm, taking into consideration the 20mm radius of the pulley and thickness of the servo motor. It was also 52mm wide so that the pulley was in the centre of the test rig, in line with the clamp and force sensor. See Figure 8-13 for a full schematic of the test rig and appendix E for the materials and assembly guide to create the rig.

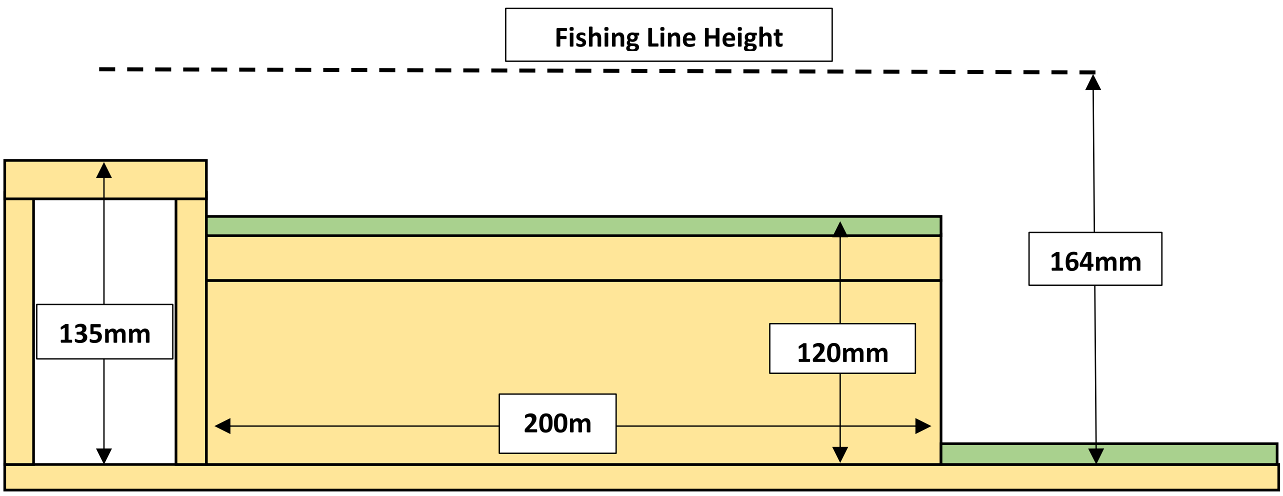


Figure 8-13: Mechanical Test Rig Dimensioned Diagram

Selection of Materials (SS)

Two types of materials were used in the force test rig manufacturing. Acrylic plate was chosen to be used under the clamp as it was easier to fix the clamp to the acrylic plate as vacuuming was used to fix the clamp. Also, it was used underneath the force sensor as the coefficient of friction was so low, dynamic coefficient of friction of aluminium on acrylic is 0.15 [79].

Medium Density Fibreboard (MDF), which is a composite of hardwood [80]. Compared to other wood plates, MDF has better surface quality. As it is made from fine particles it doesn't have big surface grains. The manufacturing of MDF was easy; however, the screws won't be hold properly [81]. This material was chosen in the bases of the surface quality as the surface wanted to be as flat as possible to put and assemble the parts properly on top of it. Also, it was a cheap material as the cost of it is £1.8 for a 6mm plate.

Manufacturing Process (SS)

For the manufacturing of acrylic plate, the Epilog Laser Fusion machine was decided to be used. The laser cutting machine gets the codes from the CorelDraw software. This software is a vector-based drawing program and creates vector files which is needed for the machine to move. Parts were drawn on Onshape according to the design of the test rig and saved as dxl file to have them in 2D version. While creating the part on CorelDraw, the plate size and thickness were selected which was loaded into the machine. made sure the primary colour mode is 'RGB'. Afterwards, dxl files were imported into the software and located starting from upper left corner. In the object properties it was set to hairline to perform cutting. File was saved in a flash drive and put it into the machine. The venting system was started. The calibration was made manually by selecting the top left corner of the loaded acrylic plate and the laser cutting machine is started.

For the medium density fibreboards, a plate was taken and dimensions that were needed for the test rig were drawn on the wooden plate. Afterwards, the table saw machine, Peugeot Energy Saw, was used to machine the blocks into proper dimensions. As this machine is not automatic, the dimensions slightly varied and in some parts the cut was not properly straight. As the medium density board is not the best option to use screws, to avoid splitting of the parts before using hand drilling machine and directly using screws to assemble it, the places of the holes were first drilled and then assembled.

Test Circuit (TE)

Figure 8-14 gives the layout of the circuit needed to conduct the testing. It uses an Arduino Uno with the load cell amplifier to receive an input from the load cell. There is a switch attached to pin 6 to start the test. Finally, there is a servo motor attached to pin 9 to contract the fishing line.

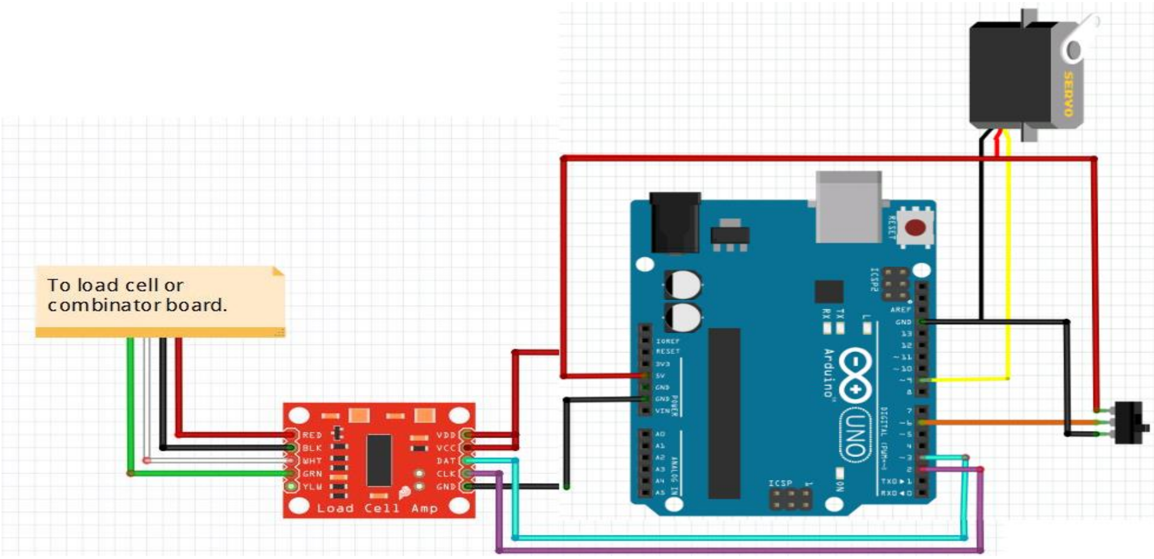


Figure 8-14: Mechanical Rig Circuit Diagram

8.1.1.3 Finger Scaling (TE)

For the model scaling test, multiple sizes of each of the 4 index fingers were needed. The base model size was the Kwawu hand as it was the user's current prosthetic size. This was therefore set as the baseline size for all the fingers and was the size chosen to carry out the primary force test analysis on. From this baseline, the test was investigating the effects of scaling the model greater than and less than this size. Therefore, the models were then scaled to +/- 10% of the original size.

As each finger model had a different geometry, and the original models were different sizes, they firstly all had to be scaled to the original Kwawu model size. To achieve this, the length of the index finger had to be defined first. It was defined as the distance from the centre of the proximal joint to the end of the distal bone along the route of the finger. This means that if the distal bone is permanently set at an angle to the intermediate bone, the total length of both bones would be included in the index finger length, see Figure 8-15.

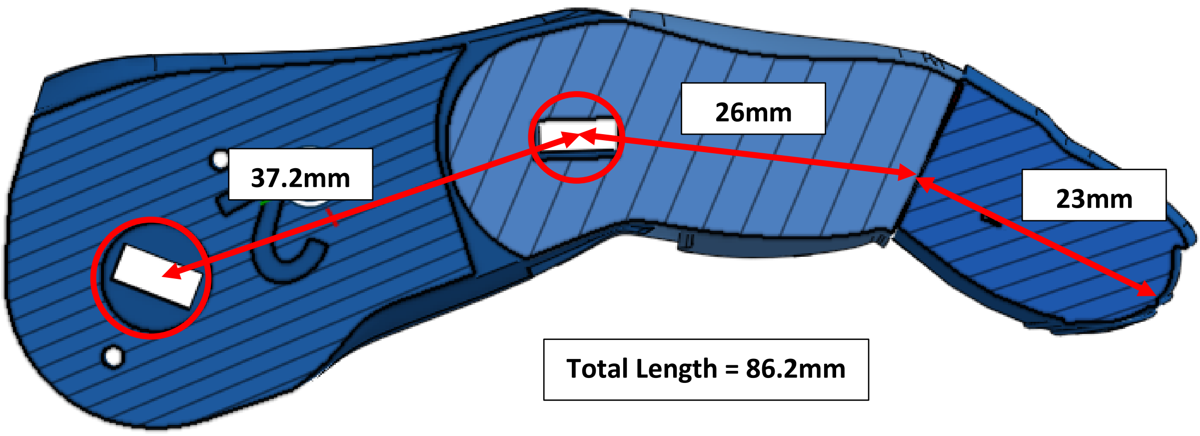


Figure 8-15: Finger Length Measurement

The length of the original Kwawu index finger was 86.2mm as seen above, therefore the other three models were measured and scaled to this length. Each scaling factor was then scaled by 90% and 110% to get the three sizes of finger for each model. The scaling factors for each of the fingers are given in Table 8-2 below.

Model	**Kwawu**	**Phoenix**	**Flexibone V1**	**Felxibone V2**
Original Size (mm)	86.2	57.9	63.9	89.8
Small Scaling Factor	0.9	1.34	1.21	0.86
Medium Scaling Factor	1	1.49	1.35	0.96
Large Scaling Factor	1.1	1.64	1.49	1.05

Table 8-2: Finger Model Scaling Values

8.1.1.4 Grip Test Attachment and Objects (PB &TE)

Clamp Attachment (TE)

For the grip test, the test rig had to be adapted to allow the fingers to hold objects. Therefore, an attachment that the fingers could attach to, which could also be fixed to the clamp, was created, Figure 8-16. As the gripping geometry for the thumb and index finger will be different for every sized object, a rudimentary attachment was designed for the fingers to press the objects against. The radius of the curve was based of the diameter of a 50cl bottle. This would allow objects up to at least this size to be gripped against the support. The height of the arc was based off the distance from the tip of the thumb to the base of the index finger. Finally, an angled wedge was added to the attachment as the index finger does not protrude from the palm at 90°. From measurements of a hand, it was found to be roughly 60°, therefore a 30° wedge was added to reduce to protrusion angle. The fingers are secured to the attachment using 3 location bolts, and then compressed within the clamp. The location holes must be drilled into both the attachment and the palms of the fingers. Ensure that the edge of the palm lines up with the inside edge of the attachment.

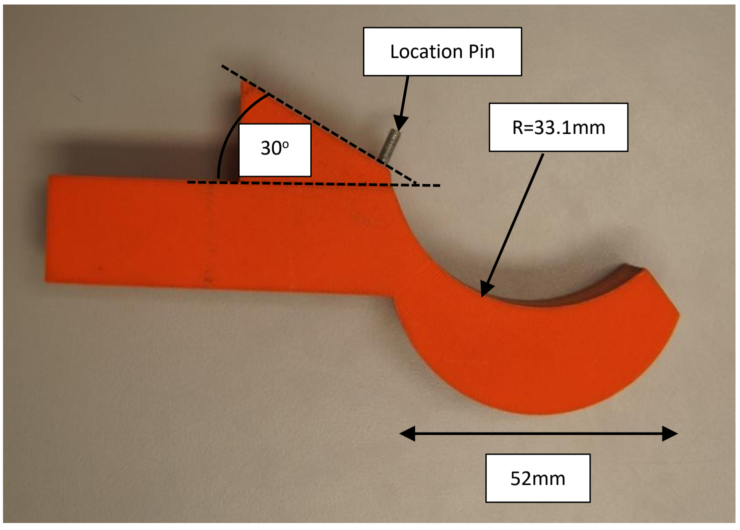


Figure 8-16: Grip Test Attachment

Test Objects (TE & PB)

As multiple sizes of objects were to be tested, the objects to grip had to be decided. Firstly, the everyday object of a water bottle was to be tested. Two sizes were chosen; the 50cL and 1L. This allowed the fingers to be tested to the extremity of their capability. Figure 8-17 shows the two brands; Cristaline and Evian, and their bottle shapes.

Figure 8-17: Grip Test Objects Evian 1L Bottle and Cristaline 50cL Bottle

Additionally, smaller sized objects were to be tested. Therefore, a range of cylinders were created out of wood foam, each with a different diameter, see Figure 8-18 . As the 50cL bottle has a diameter of 66mm, the diameters of the cylinders were chosen to be 20, 30, 40 and 50 mm. Each cylinder had a M4 wood screw in the base with fishing line attached for masses to be hung off.

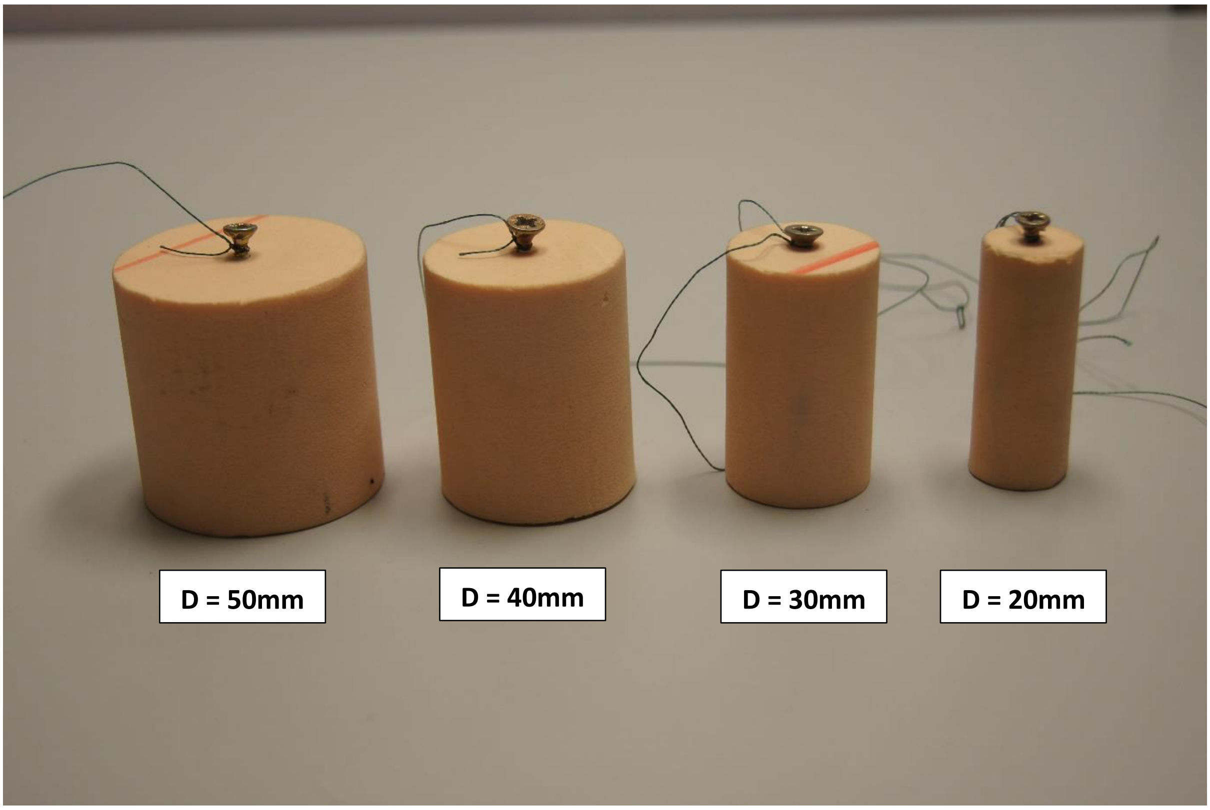


Figure 8-18: Grip Test Objects; 20mm, 30mm, 40mm and 50 mm Diameter Cylinders

8.1.1.5 Test Design Conditions/Assumptions (TE)

These are the conditions that the tests were carried out in and the assumptions made throughout.

- All the fingers have been printed on the same model of 3D printer, the Zortax M200. However, they were printed on three different machines, meaning that parts may have minute differences in surface finish and quality due to the machine setup. Additionally, the material used for all the fingers was ABS, but there may be variations between the filament on the different machines causing some discrepancies in the model finish from each machine.
- All the parts were printed off with the same settings:
  - Layer thickness – 0.14mm.
  - Infill Density – 30%.
  - Surface Quality – High.
  - Supports – On overhanging surfaces.
- No additional edits have been made to the models as only the effects of scaling the model were being analysed.
- The same 'Asso SK71 (green string-like fishing wire)' will be used as the contration wire in all the test fingers.
- An attempt has been made to make all the fingers a comparable size but due to differences in geometry there may be some small discrepancies.
- None of the fingers have been altered after the printing process via sanding, filing or polishing. The exception being if there are supports on the model.
- None of the fingers have additional gripping material on the fingertips.
- All fishing wire has been routed through the fingers so that it comes out approximately parallel to the finger resting position.
- Due to the pulley only being a tight friction fit there might be some slipping causing errors in the data.

8.1.2 Force and Scaling Test (TE)

8.1.2.1 Introduction (TE)

An evaluation was carried out on the 2018 prototype, based off the Kwawu model, produced by the University of Bath team. One of the main takeaways was that the linear actuator chosen to contract all four fingers and thumb, could not produce enough force to contract them. One of the areas of the prototype which was highlighted as causing a large resistive force, was the finger's joints. The reason for this large force is because the hinge joint also provides the restoring force for the fingers to return to their resting position once the fishing wire contraction force has been released.

As the specification of the project requires the system to be electronically actuated, the system designed can only provide a certain amount of energy dependent on the motor choice. As fingers that require more force to contract therefore require more energy, it results in less energy being available for gripping the users target object. Therefore, this investigation has been carried out to find the amount of force taken to contract Kwawu model fully.

In the e-Nable community a multitude of models have been developed which involve different finger joint mechanisms and restoration methods. Therefore, in addition to the Kwawu model, three other hand designs have been chosen to allow a comparison of how these methods impact the force taken to contract the designs. The outcome of this investigation will then be used to make an informed choice on what hand model is most suitable for the prototype being developed.

<u>Fishing Line Contraction</u>

Firstly, the method by which the fishing line tension force contracts the fingers is by having the fishing wire constrained to the finger in the distal bone with a perpendicular offset to the rotation axis of the joints, see Figure 8-19. This offset creates a moment arm for the fishing line tension to produce a torque around the joints. The fishing line therefore provides the torque needed to overcome the stiffness in the joints causing them to rotate and the finger to contract. The fishing line runs through this offset path and tends to contract the top surface of the path.

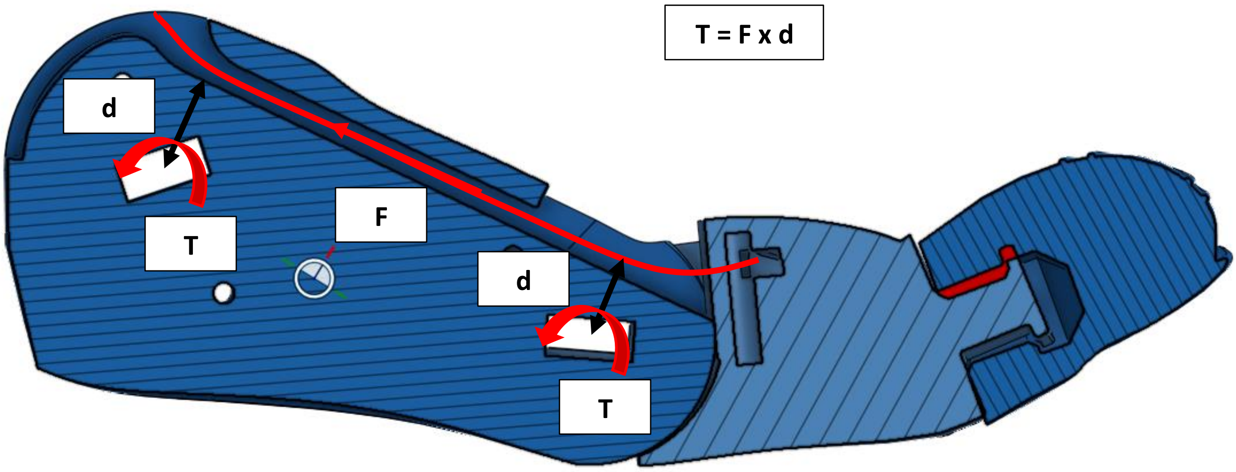


Figure 8-19: Fishing Line Path and Moment Diagram for the Kwawu Model

From the four models being tested there are three different types of joint designs. These are:

1. Torsion Joint

The Kwawu model's joints consist of a torsion bar made of Ninjaflex to restore the fingers. As the Ninjaflex bar has a low stiffness of 12MPa, it is easily deformed and allows rotation of the joints by twisting the bar. The bar is constrained by the intermediate bone at the two ends and then once in the middle by the proximal bone, see Figure 8-20.

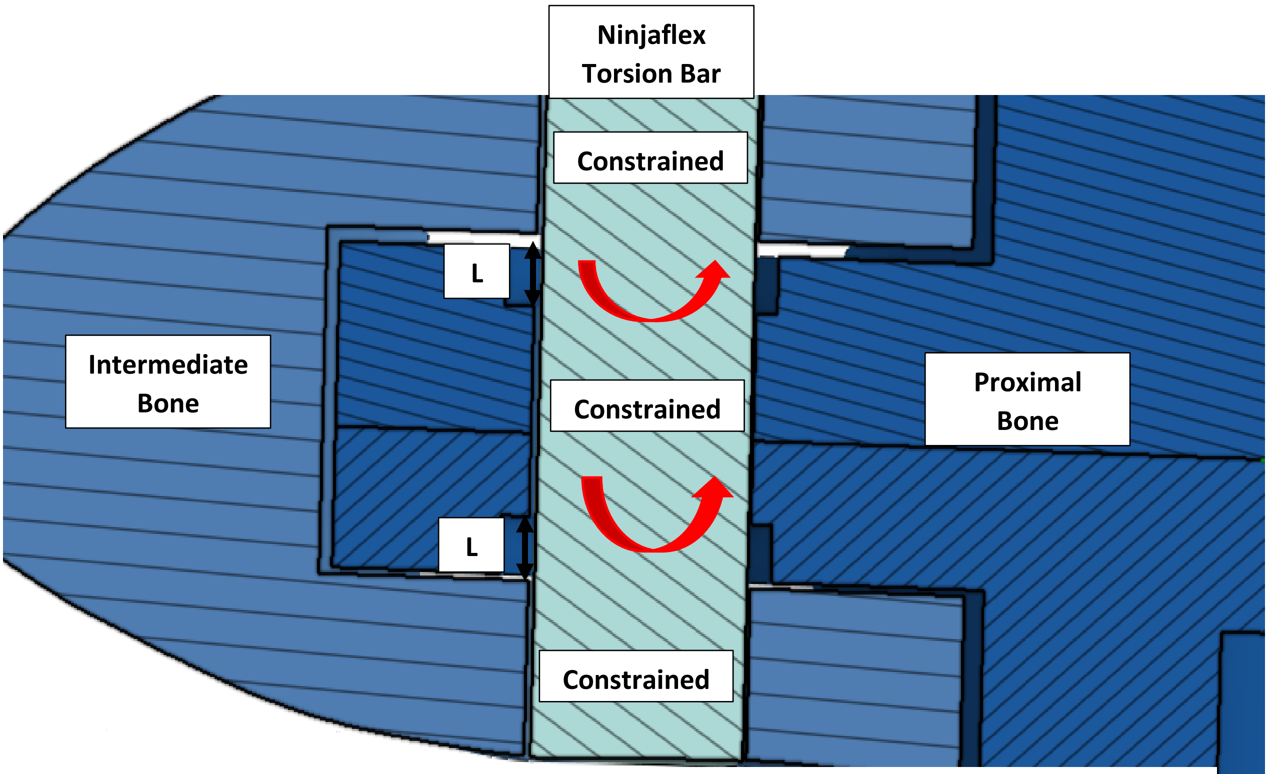


Figure 8-20: Kwawu Torsion Bar Joint Mechanism

To twist the torsion bar a torque is applied from the tension in the fishing wire. To twist the bar through a greater angle a greater torque is needed. The relationship between angle and torque is given below in Equation 8-1.

$$T = \frac{\theta * J * G}{L}$$

Equation 8-1: Torque [82]; θ = Angle turned through, J = Polar Moment of Inertia, G = Shear Modulus (equivalent to stiffness and Young's Modulus), L = Length of bar the force is applied to.

The polar moment of inertia for a rectangle cross section bar, seen in Figure 8-21, is given by Equation 8-2.

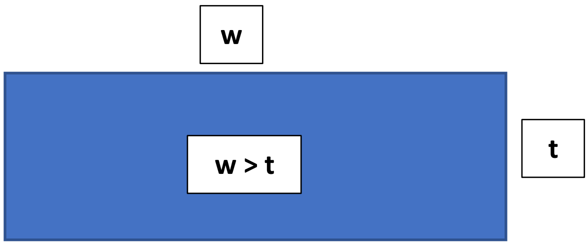


Figure 8-21: Torsion Bar Cross-Sectional Area

$$J = w * t^3 * \left[\frac{16}{3} - 3.36 * \frac{t}{w} * \left(1 - \frac{t^4}{12 * w^4}\right)\right]$$

Equation 8-2: Polar Moment of Area [82]; w = width of cross-section, t = thickness of cross-section.

As the torsion bar is constrained at both ends, this torque needs to be doubled to twist the bar on both sides.

2. Pin Joint with Elastic Restoration

The Phoenix model has a simple pin joint which allows the intermediate bone to rotate around the proximal bone, and the proximal inside the palm, see Figure 8-22. The restoration method for this model is a dental band which stretches as the finger contracts, therefore providing an elastic restoring force when the fishing wire tension is released. The dental bands are located along the back side of the finger and are therefore offset from the joint's axis of rotation. When the joint contracts, it increases the distance the elastic is stretched across, therefore increasing the bands tension. This additional tension in the elastic is what provides the restoration force for the finger once the contraction torque is released.

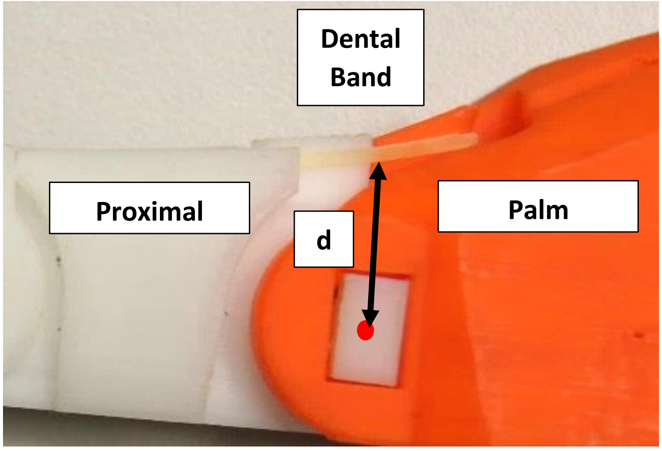


Figure 8-22: Phoenix Model Elastic Contraction Method

3. Flexibone Joints

Both the Flexibone V1 and V2 use the same joint mechanism, which is, cut-outs in the Ninjaflex at the joint locations allows contraction in the finger when a torque is applied from the fishing wire. These locations are the only areas along the Flexibone which are not constrained by the ABS casing therefore giving it the freedom to rotate. The cut-outs contract due to bending theory which states that a certain stress must be produced within the object to allow it to bend, see Figure 8-23.

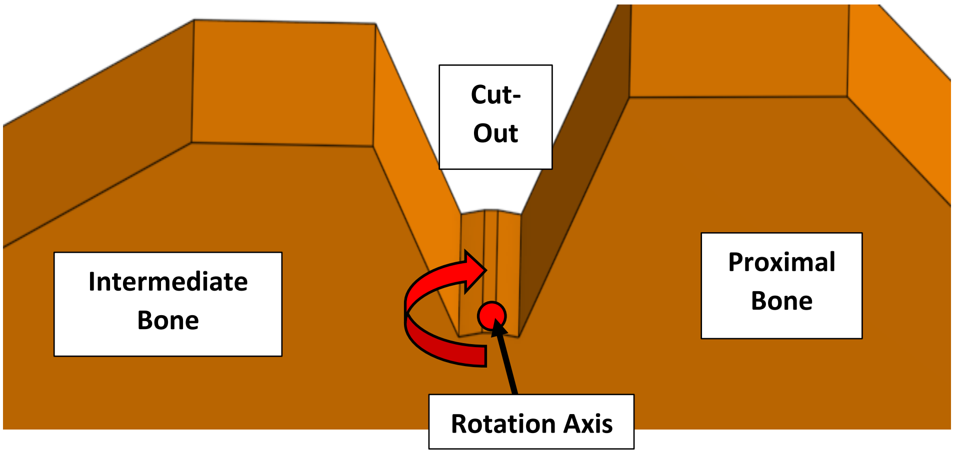


Figure 8-23: Flexibone Bending Joint Mechanism

This stress is governed by the relationship between the Young's Modulus and the strain seen in Equation 8-3, with the strain in this situation being related to the angle rotated through by the joints. Therefore, a larger angle of rotation will require a greater stress to be overcome as Ninjaflex's Young's Modulus remains constant.

$$\sigma = E * \varepsilon$$

Equation 8-3: Stress Formula; σ = Stress, E = Young's Modulus, ε = Strain.

The stress in the object is produced by the torque in the fishing line creating a bending moment in the Ninjaflex. The relationship between the torque required to produce a certain stress while bending is governed by Equation 8-4.

$$T = \frac{\sigma * I}{c * t}$$

Equation 8-4: Bending Torque Formula [84]; I = Second Moment of Area, c = Distance of Surface from the Neutral Axis.

The cross-sectional area for the joints is a rectangle, Figure 8-24, which governs it's second moment of area, the formula for which is given in Equation 8-5.

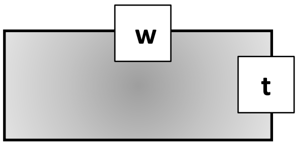


Figure 8-24: Flexibone Joint Cross-Sectional Area

$$I = \frac{w * t^3}{12}$$

Equation 8-5: Second Moment of Area of a Rectangle.

When the tension in the fishing line is released, the stress produced with the object creates the restoring force for the fingers to return to their natural position.

A secondary objective for this investigation is to see the effect of scaling the model on; the different joint methods, and the tension from the fishing wire applied to the models. The reason for this is due to the projects criteria of making the prototype suitable for a range of users. As each user will have a different physique, such as height and broadness, the size of the prosthetic for the user would have to be modified to be proportionate to the physique. The model chosen would therefore have to be scaled both larger and smaller depending on the user. Therefore, understanding the scaling effects on the different hand models will allow for a model choice which has greater user adaptability.

The final objective for this investigation is to understand the distance of fishing wire that is needed to be retracted to cause full contraction of the different finger models. An additional reason that the linear actuator could not fully contract last year's model could be due to the contraction distance of the linear actuator not being great enough to fully contract the fingers. Therefore, to allow a suitable motor to be chosen for the prototype, the length of fishing wire it needs to contract must be known. Additionally, a model that requires a smaller length of fishing wire to contract would require an actuator which retracts a smaller distance, therefore allowing for a smaller and lighter actuator. This could therefore increase space and reduce weight on the gauntlet to improve the comfort and aesthetics of the prosthetic.

The aims for this investigation are as follows:

1. To find the effect of joint mechanics on total contraction force.
2. To find the effect of scaling the model on the force to contract each model.
3. To find the length of fishing wire retracted to fully contract each model.

8.1.2.2 Materials (TE)

Part	Number
Test Rig (Section 8.1.1.2)	1
Kwawu Index Finger Small	1
Kwawu Index Finger Medium	1
Kwawu Index Finger Large	1
Phoenix Index Finger Small	1
Phoenix Index Finger Medium	1
Phoenix Index Finger Large	1
Flexibone V1 Index Finger Small	1
Flexibone V1 Index Finger Medium	1
Flexibone V1 Index Finger Large	1
Flexibone V2 Index Finger Small	1
Flexibone V2 Index Finger Medium	1
Flexibone V2 Index Finger Large	1
Asso Dyneema SK71 0.21mm Fishing Line Reel	1
Laptop Running Arduino IDE	1
Code 'Force Test' (Appendix F)	1
Force Sensor Circuit (Section 8.1.1.2)	1
Force Test Spreadsheet (Appendix G)	1
Camera	1
Scissors	1

Table 8-3: Force Test List of Materials

8.1.2.3 Method (TE)

1) Launch Arduino IDE on the laptop, connect the Arduino to the laptop and run the code 'Force Test'
2) Check that the force sensor is calibrated correctly by using the method described in section 8.1.1.2.
3) Do an initial test to measure the friction caused by the force sensor.
   a) Attach the force sensor with the arrow facing towards the pulley using the fishing line, see Figure 8-25.

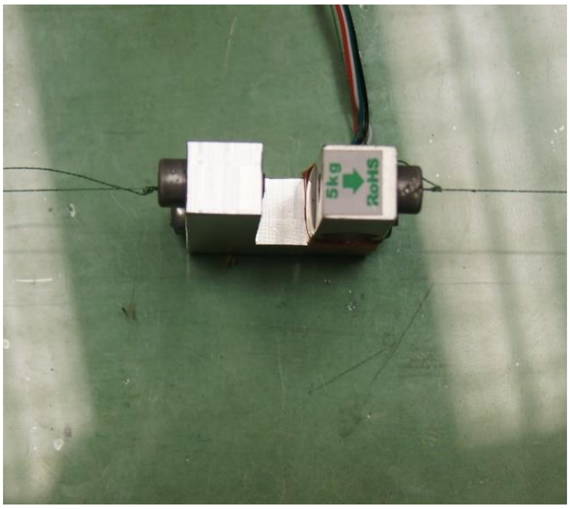


Figure 8-25: Force Sensor View from Above

b) Open the serial monitor in Arduino IDE.
c) Turn the switch on.
d) Turn the switch off once the pulley has returned to 0^o.
e) Copy the data from the serial monitor into the post processing spreadsheet, see appendix G.
f) Repeat 2 more times.

4) Remove the force sensor by untying the knots (using the needle) or cutting the string.
5) Reverse the force sensor so the arrow is facing the clamp and attach the opposite end to the pulley using the fishing line.
6) Clamp the finger in place by the palm. Make sure the palm is as far back in the clamp as possible, so it does not obstruct the contraction of the finger. Clamp the palm so it lays as low in the clamp as possible, so the fishing line comes out at the correct height.
7) Attach the fishing line, which is attached and threaded through the finger, to the arrow side of the force sensor, making sure there is no tension in the fishing line.
8) Open the serial monitor.
9) Turn on the switch and press record on the camera.
10) Turn off the switch and stop the recording once the servo motor has fully rotated and then returned to 0^o.
11) Copy the results from the serial monitor to the next tab of the post processing spreadsheet.
12) Repeat the test two more times.
13) Untie the finger from the force sensor and remove from the clamp.
14) Repeat from step 6 for each of the 12 fingers.

Use triple knots to attach the fishing line to the fingers, force sensor and pulley to reduce slipping.

Never loosen the bolts on the force sensor as it will change the sensors calibration factor.

Post Processing

Once all the data is collected post processing needs to be carried out within the spreadsheet to ensure that the repeated data sets all match up, and so that the data collected once the motor has stalled can be removed. To carry out the post processing the video footage taken for each test is used to analyse frame by frame using the video analysis software 'Tracker' [84]. The friction of the force sensor does not need to be removed as it was found to be negligible. The post processing steps are:

1) Choose a finger to analyse.
2) Find the first cell where a force is recorded for each of the three attempts.
3) Use the cell above as the starting point of the force data.
4) Zero the fishing line distance and time data using the values corresponding to the starting point of the force data.
5) Load the video for the first attempt into the tracker software.
6) Find the first frame in which movement is seen in the finger and set the time to zero on that frame.
7) Find the frame at which there is no movement seen in the finger and record the time. This is when the finger is fully contracted.
8) Find the closest time in the zeroed spreadsheet data and delete all the rows after it.
9) Load the next two attempts and repeat stages 6 to 8.
10) Find the average of the three data sets to give the final data for the finger.

8.1.2.4 Results (See Appendix G for the Results Spreadsheet and Videos) (TE)

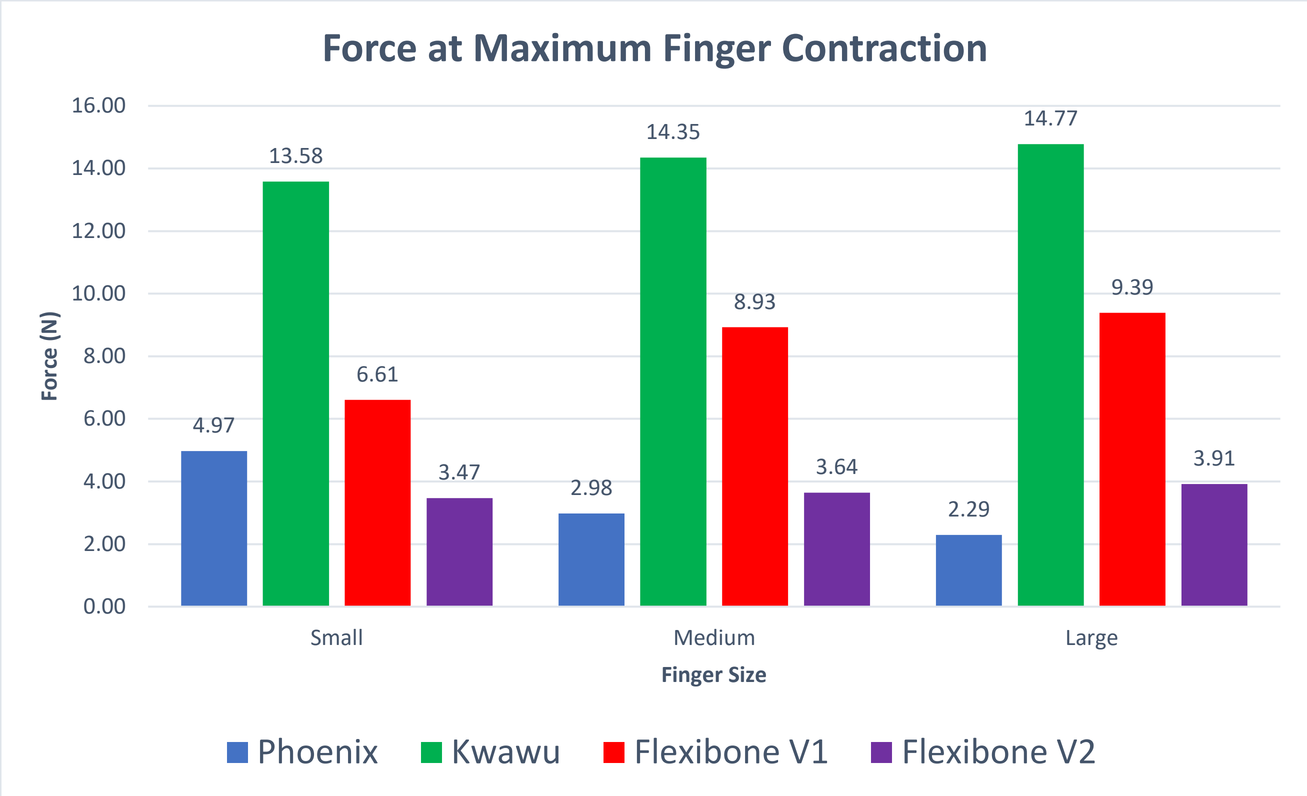


Figure 8-26: A Bar Chart Showing the Maximum Contraction Force Experienced by each Model for Three Different Sizes

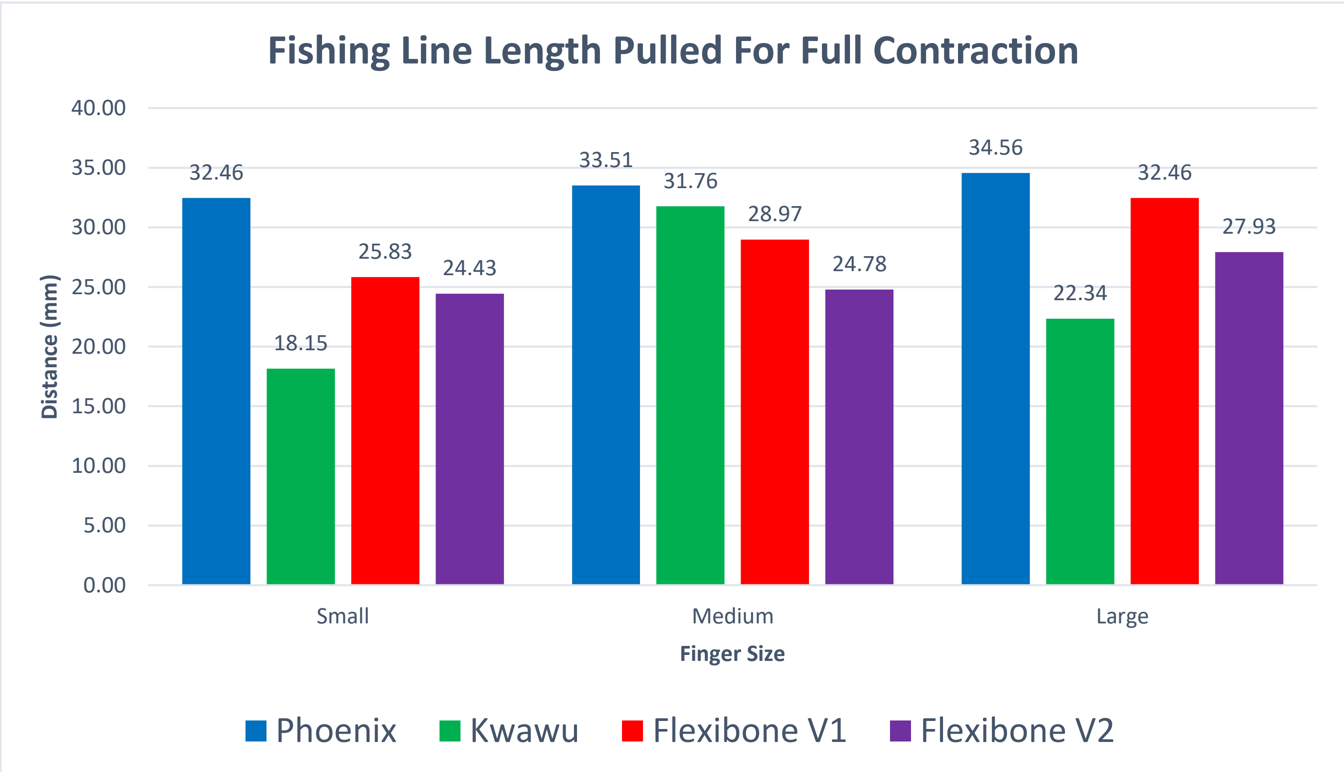


Figure 8-27: A Bar Chart Showing the Distance of Fishing Line Taken to Contract each Model at Three Different Sizes

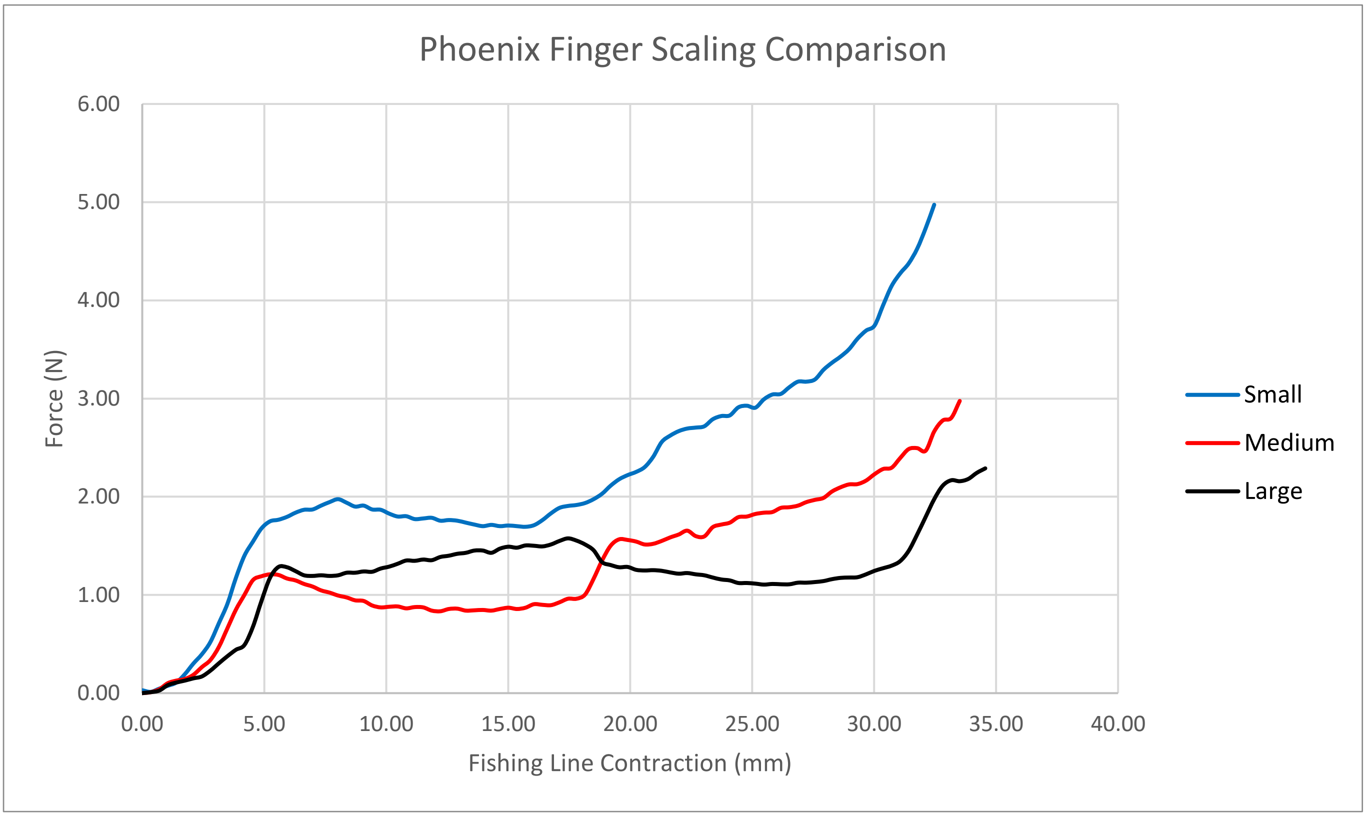


Figure 8-28: A Graph Showing the Phoenix's Force to Contract Over Its Contraction Cycle for Each Size of Finger.

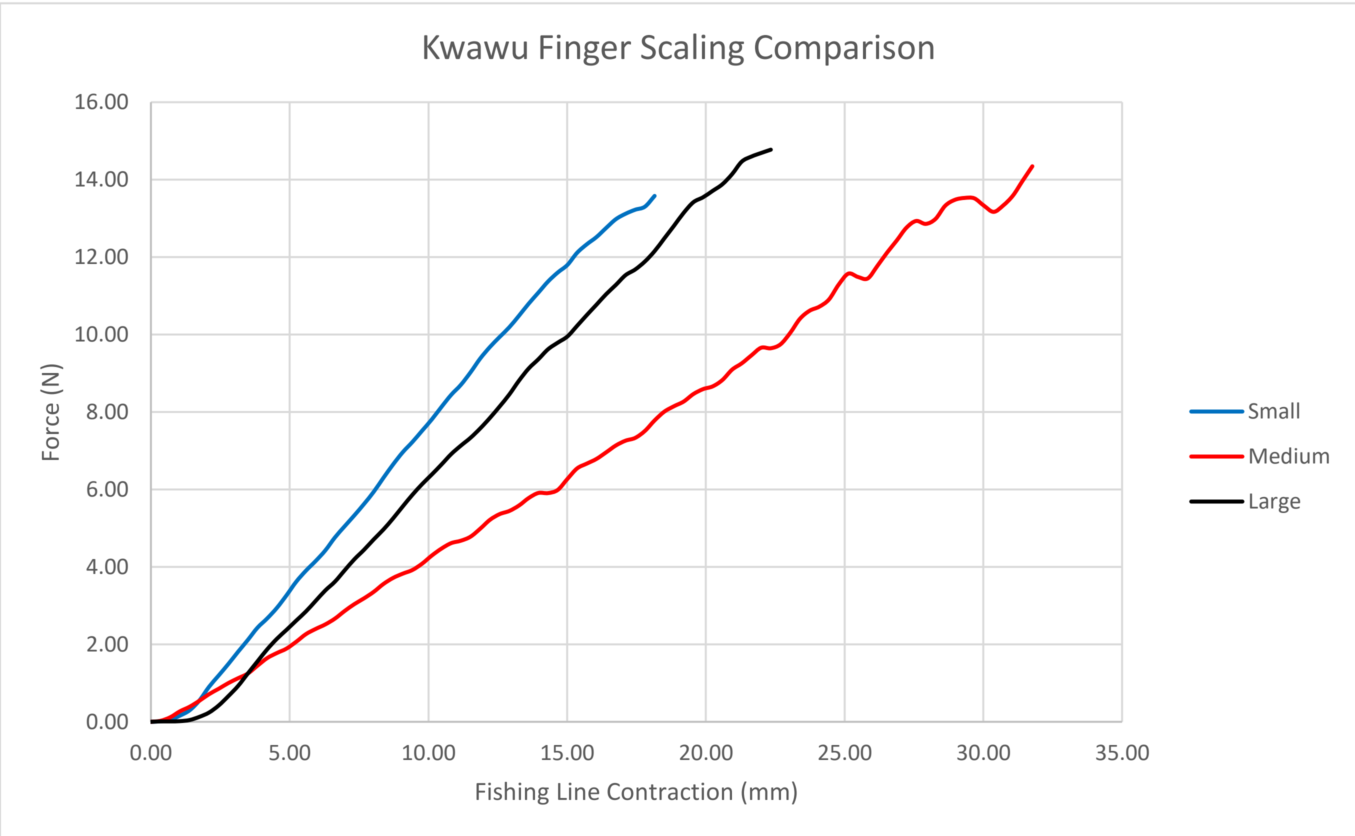


Figure 8-29: A Graph Showing the Kwawu's Force to Contract Over Its Contraction Cycle for Each Size of Finger.

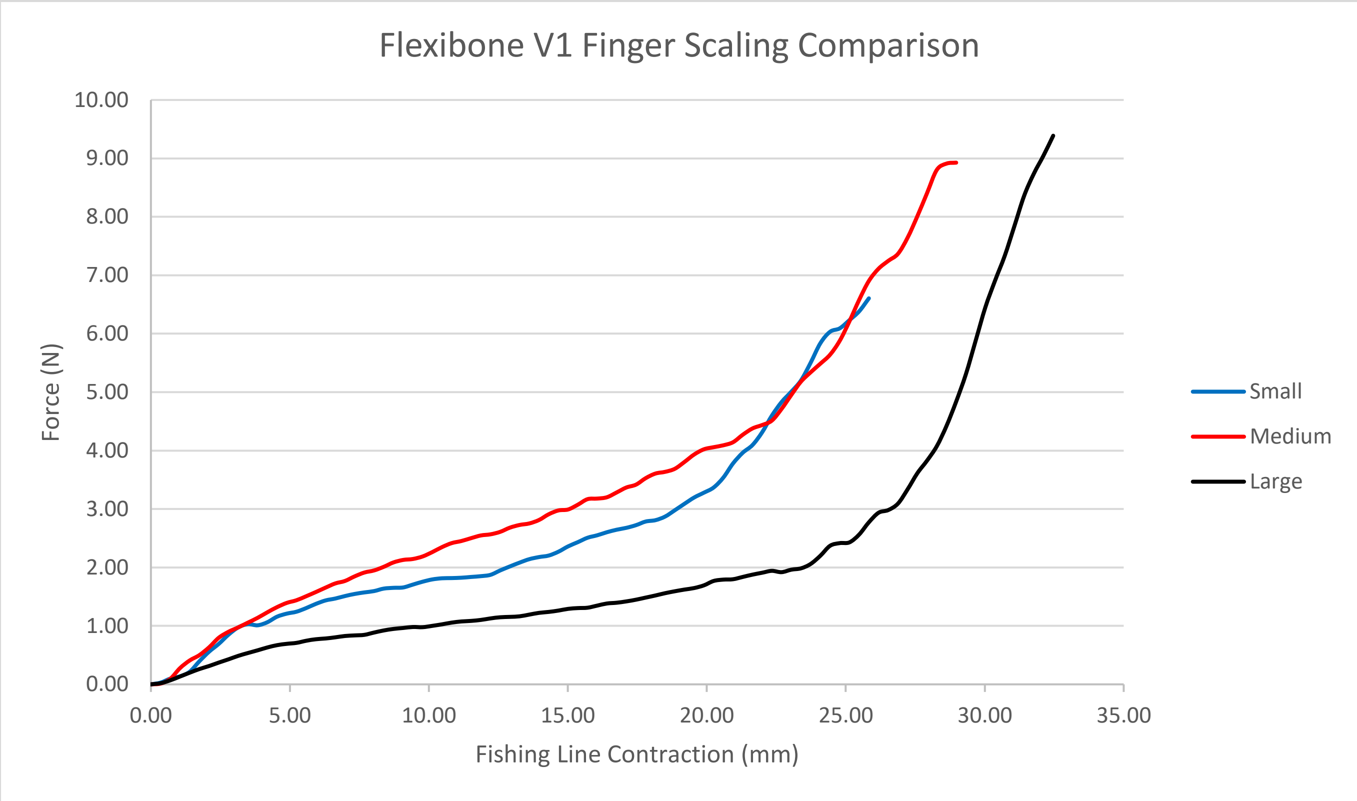


Figure 8-30: A Graph Showing the Felxibone V1's Force to Contract Over Its Contraction Cycle for Each Size of Finger.

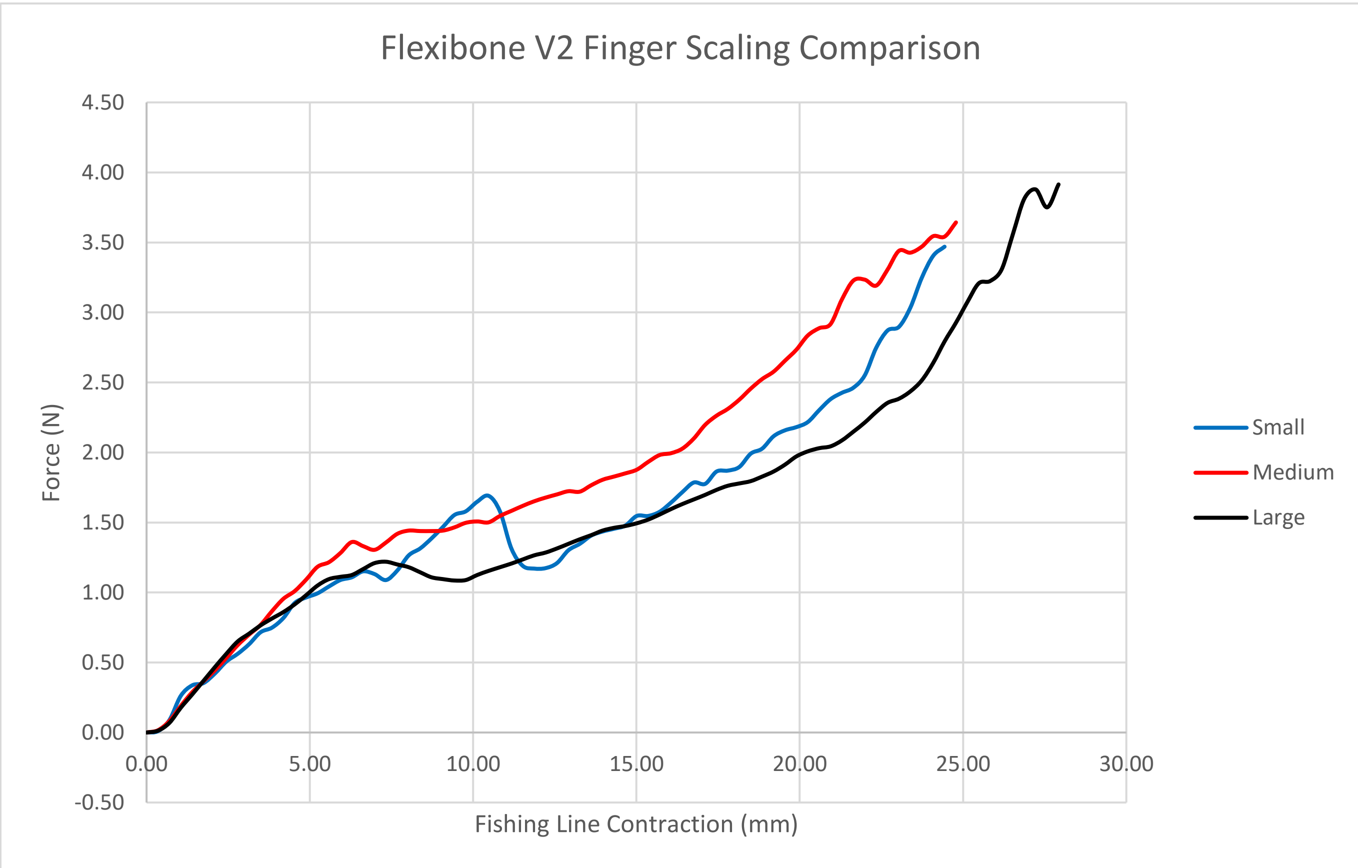


Figure 8-31: A Graph Showing the Flexibone V2's Force to Contract Over Its Contraction Cycle for Each Size of Finger.

8.1.2.5 Analysis (TE)

Breaking down the results in Figure 8-26, looking at just the medium size finger range, it can be clearly seen that there is a large disparity between the contractions force of the finger models. Starting with the Phoenix model, it required the smallest force of only 2.98N to fully contract. This is due to it being assembled with 63g low force dental bands to make contraction easy. Additionally, the elastic bands had two moment arms to provide the torque to stretch them, one from the fishing line to the joint and then another from the joint to the dental bands, further increasing the ease of contraction. The contraction of the Phoenix finger is therefore dependent on the strength of the dental band attached and it therefore shows that the pin and elastic joint is the easiest method to contract the joints.

On the contrary, the Kwawu model requires the greatest force of 14.35N to fully contract. This result firstly shows that the torsion bar joint is the hardest to contract out of the three methods. This is due to multiple reasons, the first being the cross-sectional area of the torsion bar makes up a large area of the joint. This creates a large polar moment of inertia for the joint as the thickness of the bar is cubed from Equation 8-2, therefore contributing heavily to the torque required to twist the joint, *Equation 8-1*. Secondly, the length between the intermediate constraint and the proximal constraint on the torsion bar is relatively small compared to the size of the joint. Looking again at *Equation 8-1*, this small distance will therefore require a greater torque to contract the joint. Finally, as the torsion bar is constrained on both sides by the intermediate bone, double the torque must be produced to twist both sides. This already high torque from the dimensions of the joint is therefore doubled, compared to the other designs which only have one area that needs to be bent or stretched.

Comparing the contraction forces of the Flexibone V1 and V2 design shows that the updates carried out to the V2 design have made the finger easier to contract, only requiring 3.64N compared to 8.93N for the V1 design. The first change made was the width of the Flexibone in the V2 is thinner than the V1. This therefore reduces the second moment of area for the joints, hence decreasing the torque required to contract in Equation 8-4. Another redesign for the V2 was the thickness of the Flexibone joints were decreased. This again reduces the second moment of area of the joints, but this time by a greater amount due to the thickness being cubed in Equation 8-5. These changes to the cross-sectional area drastically decreased the contraction force for the Flexibone design by 5.29N, bringing it to a comparable force of the Phoenix model.

Comparing the fishing line contraction lengths for the medium sized fingers in Figure 8-27, even though all the models have been scaled to the same size, they all require different lengths of fishing wire to fully contract them. This is due to the moment arm that the fishing line applies the torque through also acting as a radius for the wire. This creates an arc length that must be rotated through to contract the joint. As each model has a different length moment arm, they will therefore each require a different distance of line to contract the fingers.

From Figure 8-27 it shows that the Phoenix finger has the largest distance of 33.51mm and therefore the largest contraction moment arm. Comparing the two Flexibone designs the V1 design has a greater distance of 28.97mm compared to the V2's 24.78mm. This difference isn't to do with the moment arm length but instead to amount of rotation that each joint can do. As the V2 design has additional ABS on the shells to cover the joints, they also decrease the amount of rotation they can do. The impact of this is a reduction in fishing line length required to contract the joint due to a smaller angle to turn through.

Looking at the effects of scaling the models on the fishing line distance, it reiterates that the greater the moment arm the greater the amount of fishing line needed to contract. This is due to the moment arm also being scaled during the process. The chart shows that if the size increases, the fishing line distance needed to contract increases, and the inverse is shown if the scaling deceases the model. The anomaly to this relationship is the large Kwawu finger, which had a contraction length of 22.34mm. This is due to it not fully contracting before motor stall, hence requiring a shorter fishing line length.

Overall the Flexibone V2 model requires the least fishing wire to contract, with the Phoenix requiring the greatest length. This fishing line length will decrease even further for users requiring scaled down models, but adversely increase for users with larger size requirements. The Flexibone V2 will therefore allow for a smaller size pulley to be designed for a servo motor, or smaller contraction length linear actuator to be chosen, conserving on weight, size and cost of the system.

Looking again at Figure 8-26, the overall pattern of the effect of scaling on the maximum contraction force for each model can be seen. Firstly, the Phoenix model's maximum contraction force decreases from 4.97N to 2.98N to 2.29N when scaling up from the smallest to the largest size respectively. This occurs because the force to extend the dental band remains the same, with the bands having a fixed force rating of 63g. As the extension force doesn't increase but the finger size has, so has the moment arm for the tension acting on the joints. As the torque required to contract remains the same, but the moment arm has increased, the knock-on effect is the tension force required decreases. Looking at Figure 8-28 this relationship can be seen all the way through the contraction cycle on the Phoenix finger. However, during the contraction of the medium and large fingers, there is a section where the larger finger's force is higher than the mediums. From reviewing the digital footage of the tests, this overlap is due to the contraction order of the joints reversing for the large finger compared to the medium. The order for the medium is proximal followed by intermediate, whereas the large fingers order is the inverse. As the geometries of the two joints are different they are expected to have different behaviours while contracting. Therefore, the scaling of these geometries may have had a greater effect on the intermediate joint, making it easier to contract than the proximal hence changing the order.

Moving to the Kwawu's pattern in Figure 8-26, the force is seen to increase from 13.58N to 14.35N to 14.77N as the model size increases. However, when looking at Figure 8-29, the relationships seen throughout the contraction do not meet the expectations. From the video analysis it was seen that the medium size of the Kwawu finger was misassembled in the test set up. The fishing wire had not been threaded through the path in the proximal bone of the finger but instead had gone from the intermediate bone to the palm. This increased the moment arm significantly for the two joints making them easier to contract therefore producing the lower gradient line in Figure 8-29. This result is not able to be used in the comparison for scaling. As the large finger did not fully contract, it highlights that as the torsion bars dimensions increase so does the amount of torque needed to contract it. However, when comparing the region that contracted with the small finger, the gradient of the line is slightly lower. This is due to a couple of reasons, with the first being the larger moment arm from scaling upwards. This moment arm not only reduces the amount of force needed to rotate the joint, but also increases the fishing line distance needed to contract. Both impacts will reduce the gradient of the graph. However, the gradient hasn't reduced by a significant amount due to the increase in torque needed to twist the torsion bar. From *Equation 8-1*, even though L has increased, decreasing the torque needed, so has the polar moment of inertia to the power of three. The torque has increased overall, therefore increasing the gradient and force required to fully contract. The lower gradient is therefore due to the moment arm increase having a greater effect on reducing the force than the increase in torque from the torsion bars greater cross-sectional area.

Finally, looking at the overall pattern of the Flexibone designs in Figure 8-26, both require a greater contraction force as the model's scale is increased. This therefore supports that the greater the cross-sectional area of the joint the greater the torque needed to bend and hence contract it. However, looking at their full contraction cycles in Figure 8-30 and Figure 8-31, there is no clear pattern for the effect of scaling as the medium is the hardest to contract throughout, followed by the small finger, and finally the large is the easiest. One possible explanation could be due to the additional effect of friction from the fishing line through the finger. Compared to the large open gap in the other two models, the Flexibone designs only have a small hole travelling through the finger. The nature of this hole means there is more of the fingers surface area in contact with the fishing wine leading to greater friction. Therefore, the medium finger requires a greater force throughout than the small as the increase in joint cross-sectional area has a greater impact than the increase in moment arm. Furthermore, the large finger then requires less for the contraction than the medium due to the moment arm providing the greater impact but additionally, the scaling of the fishing line route has gone over the critical threshold were the fishing line only interacts with one side of the hole therefore reducing the friction significantly.

Overall, the Phoenix model responded the best to scaling, increasing as its contraction force decreased, unlike the other three models. The Kwawu model performed the worst with the largest sizing not contracting before motor stall, highlighting that the torsion bar joint method becomes increasingly stiff as the size increases. The Flexibone designs both showed the same pattern during the scaling process, with the friction from the fishing wire also contributing to the unexpected pattern. The main takeaway from the scaling test is that it is difficult to analyse specific relationships, meaning they can only be hypothesised, due to too many variables being changed during the scaling of every dimension of the model.

8.1.2.6 Conclusion (TE)

The results for the entire test showed firstly that the Phoenix model required the lowest force to fully contract and the Kwawu required the greatest. This therefore showed that the elastic and pin joint method is a better joint mechanism the torsion bar joint with their current designs and dimensions. The results of the Flexibone designs showed that it's dimensions can greatly impact the force taken to fully contract, with the V1 requiring a larger force than the V2. The Flexibones smaller joint design brought its contraction force to that comparable with the Phoenix hand, therefore highlighting the Flexibone joint design as another effective way to contract the fingers.

The scaling of the fingers did not create clear relationships for each of the models. Due to all features being scaled equally within the model, many factors changed such as; moment arms, joint cross-sections and system friction. However, it did show that firstly, the Phoenix was the best model for scaling upwards, as the force to contract decreased with size. Also, the Kwawus force increased as the size increased, leading to motor stall before reaching full contraction in the large scale, hence reiterating the designs unsuitability for the prosthetic.

Finally, the contraction distance results showed that the Flexibone V2 design required the shortest length of fishing wire, with the Phoenix needing the most. This implies that the Flexibone V2 would allow the smallest motor/pulley to be chosen for a more compact, lightweight design.

8.1.3 Grip Test (TE)

8.1.3.1 Introduction (TE)

One of the main criteria for the project is for the prototype to be adaptable to multiple users, each having different needs and uses for their prosthetic. Depending on the user, the functionality of the prosthetic can vary greatly. The tasks that could potentially be carried out will involve objects which have a range of sizes and weights. To help achieve an adaptable prosthetic it is important to choose a model of hand which can function well over a large range of object sizes and can grip to the greatest weight. Therefore, this investigation took place to advise in the choice of the hand model.

A secondary objective of this investigation is to understand what the effect of a fixed distal joint geometry, meaning no distal joint, has on the models gripping capabilities, compared to a model with three joints. In this test two models, the Phoenix and Kwawu, only have the intermediate joint and the proximal joint, with the distal bone at a fixed angle. The other two models, Flexibone V1 and Flexibone V2, have all three joints available to contract.

From the results of the force test in section 8.1.2, it was found that the Phoenix hand required to smallest amount of force to contract, with Kwawu requiring the largest, see Table 8-4 . A final objective for this test is to see how heavy an object the model can grip compared to how great a force taken to contract it.

Model	**Force for Full Contraction (N)**
Phoenix	2.29
Kwawu	14.77 (Did Not Fully Contract)
Flexibone V1	9.39
Flexibone V2	3.91

Table 8-4: Force Test Results

The aims of this investigation are therefore:

- To find the finger model which can hold the greatest range of objects to the highest weight.
- To investigate the relationship between two or three joints on a finger model and it's gripping capabilities.
- To investigate the relationship between contraction force and gripped object weight.

8.1.3.2 Materials (TE)

Part	**Number**
Test Rig (Section 8.1.1.2)	1
Grip Test Rig Attachment (Section 8.1.1.4)	1
Grip Test Objects (Section 8.1.1.4)	6
Kwawu Index Finger Large	1
Phoenix Index Finger Large	1
Flexibone V1 Index Finger Large	1
Flexibone V2 Index Finger Large	1
Asso Dyneema SK71 0.21mm Fishing Line Reel	1
Laptop Running Arduino IDE	1
Code 'Grip Test' (Appendix H)	1
Force Sensor Circuit (Section 8.1.1.2)	1
Grip Test Results Spreadsheet (Appendix I)	1
Camera	1
Scissors	1

Table 8-5: Grip Test List of Materials

8.1.3.3 Method (PB & TE)

1) Launch Arduino IDE on the laptop, connect the Arduino to the laptop and run the code ‘Grip Test’
2) Check that the force sensor is calibrated correctly by using the method described in section 8.1.1.2.
3) Do an initial test to measure the friction caused by the force sensor.
   a) Attach the force sensor with the arrow facing towards the pulley using the fishing line, see Figure 8-25.
   b) Open the serial monitor in Arduino IDE.
   c) Turn the switch on.
   d) Turn the switch off once the pulley has returned to 0^o.
   e) Copy the data from the serial monitor into the post processing spreadsheet, see Appendix I.
   f) Repeat 2 more times.
4) Remove the force sensor by untying the knots (using the needle) or cutting the string.
5) Reverse the force sensor so the arrow is facing the clamp and attach the opposite end to the pulley using the fishing line.
6) Attach the first finger to the gripping support attachment using the location screws and holes.
7) Attach the gripping support to the clamp and tighten the clamp so it has secured the palm and attachment in place.
8) Attach the finger to the arrow end of the force sensor.
9) Place first object in between the support and the finger.
10) Open the serial monitor and use the ‘a’ key to contract the finger.
11) Contract the finger until the object is gripped.
12) Take a photo of the gripped object with a top view and side view.
13) Record the force required to grip in the spreadsheet, see Appendix I.
14) Repeat 2 more times.
15) Increase the object weight by 100g and repeat steps 9 to 13.
16) Once the finger can’t grip the object anymore untie the finger from the force sensor and remove the finger from the gripper support.
17) Attach the next finger and repeat stages 7 to 15 for the three remaining models.

Use triple knots to attach the fishing line to the fingers, force sensor, pulley and objects to reduce fishing line slip.

Never loosen the bolts on the force sensor as it will change the sensors calibration factor.

8.1.3.4 Results and Photos (See Appendix I for Full Results Spreadsheet and Photos) (TE)

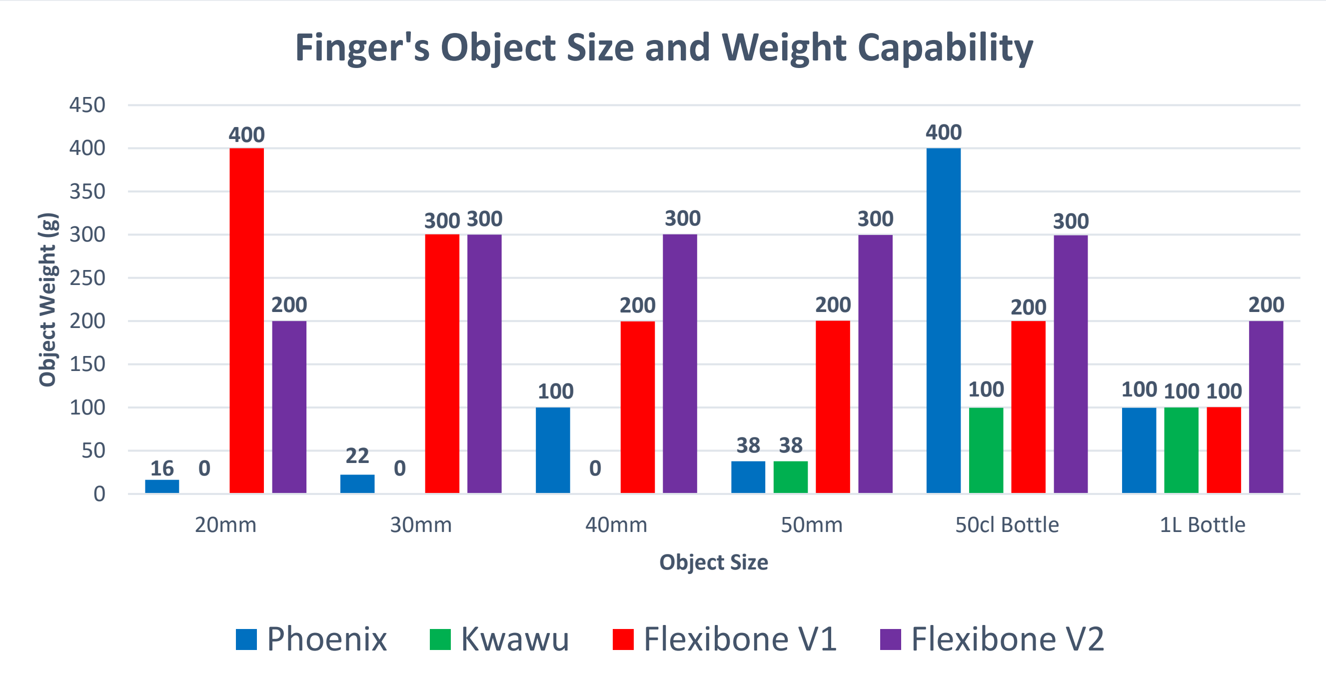


Figure 8-33: A bar chart showing the capability of each finger model to grip different size objects, and at what weight they can maintain grip.

Figure 8-32: Four images showing the gripping geometry of the four models around the 50mm diameter object in the following order; a - Phoenix finger, b - Kwawu finger, c - Flexibone V1 finger and d - Flexibone V2 finger.

Figure 8-34: An image showing the Phoenix model supporting the 50cL bottle with no contraction force applied.

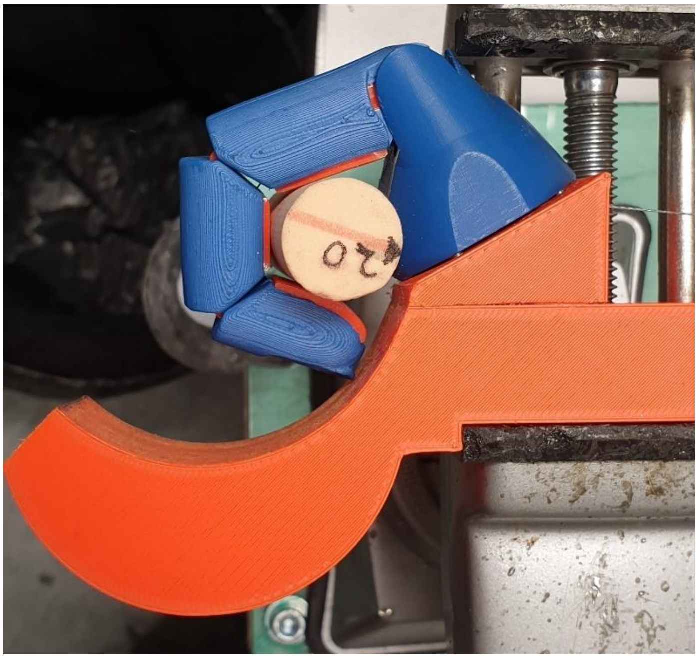


Figure 8-35: An image showing the Flexibone V1 finger curling around and gripping a 20mm diameter object.

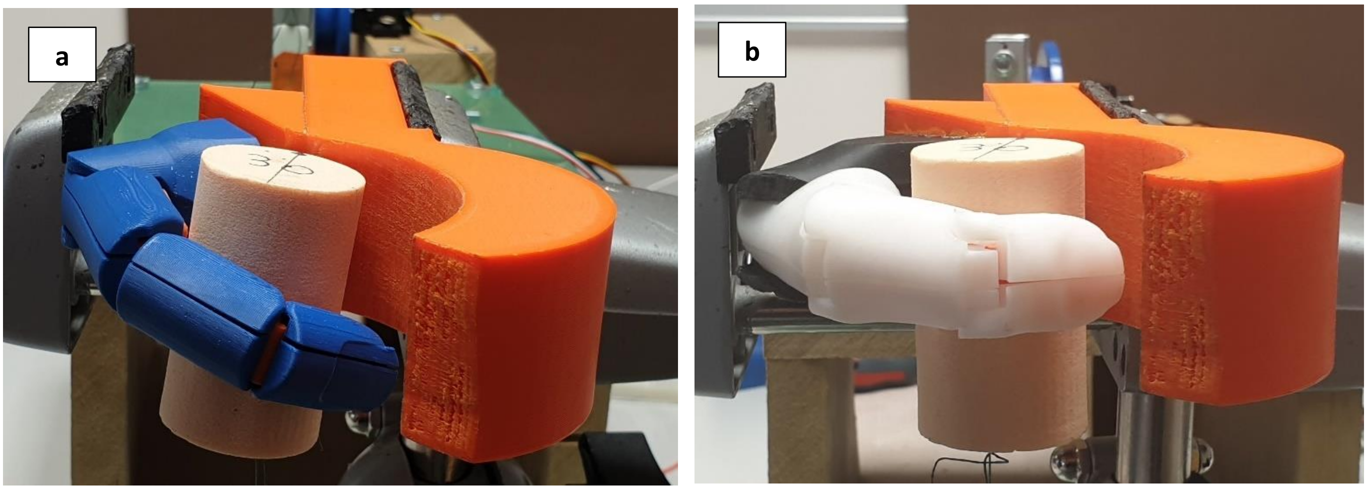


Figure 8-36: Shows the shape of the two Flexibone designs while gripping a 30mm diameter object at a weight of 200g.

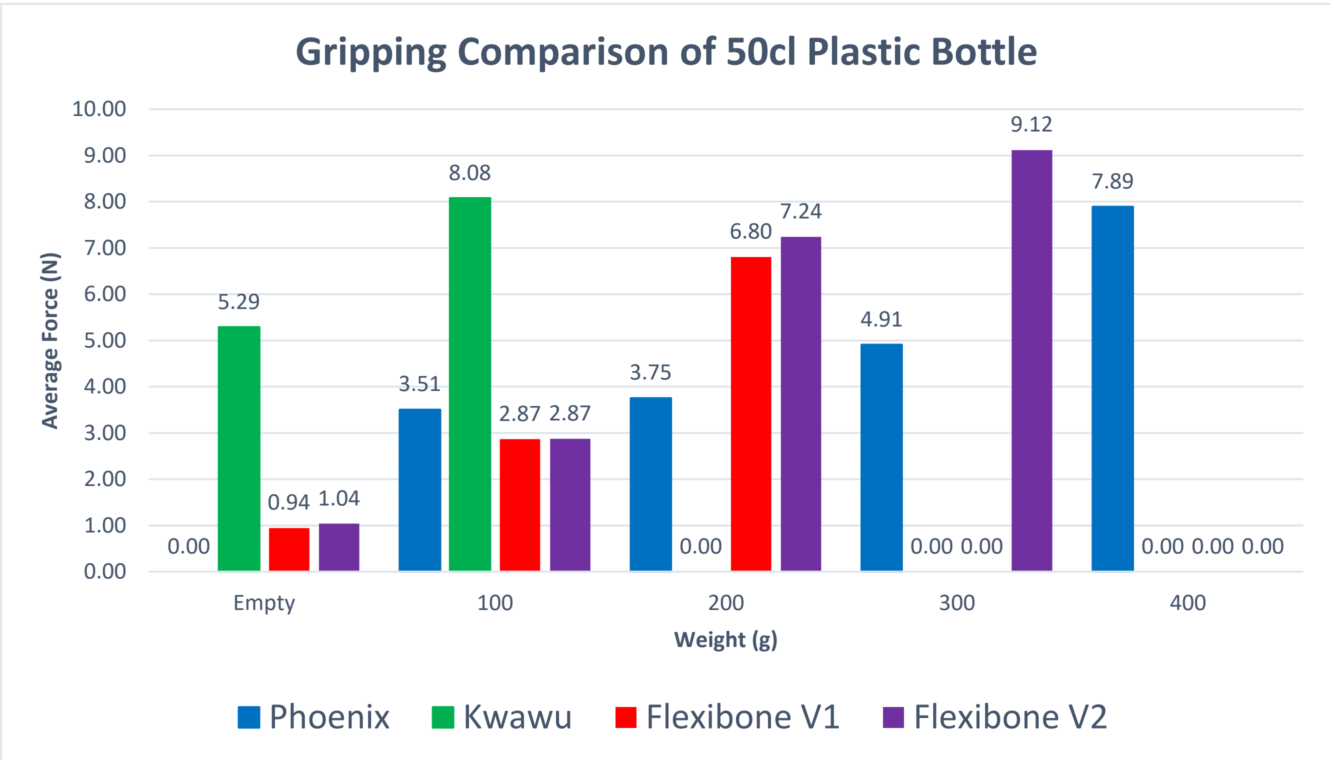


Figure 8-37: A bar graph showing how much force needs to be applied for each finger model to grip a 50cL bottle at different weights.

8.1.3.5 Analysis (TE)

From the results of the overall grip test in Figure 8-33, clear patterns can be seen about which finger models are suited for gripping which sized objects and at which weights. The bar chart shows that both the Phoenix and Kwawu models are not suitable for gripping objects below a 50mm diameter, and if they do grip it is only if the object is at a low weight. The two Flexibone hands can both grip the full range of objects, with them both consistently gripping objects up to at least 100g. The Flexibone V1 gripping weight fluctuated across the size range, with it capable of gripping greater weights at smaller objects and struggling to grip larger objects to a high weight. In comparison, the Flexibone V2 was consisted across the object size range, with it always being able to lift to 200g but more commonly 300g with larger objects.

A note to make is that the 1L bottle caused a degradation in the performances of all the fingers compared to the 50cL bottle. This is due to this object being incorporated into the test to test the extremity of the fingers gripping capability. It has a very large diameter, therefore making it too large for the gripping attachment which was designed up to the size of 50cL bottle. However, the 1L bottle shows that all the fingers are capable of lifting objects which are too large for their palm grip to a low weight.

Looking at the fingers individually and the geometries by which they grip objects in Figure 8-32, reasoning for the overall tests can be deduced. Firstly, the Phoenix finger in Figure 8-32a, shows how the finger only applies one pressure point on the objects from the distal bone. This grasp is creating three contact points with the finger and attachment, two on the attachment and one on the distal bone. This small amount of contact area results in a lower friction force being created to hold the objects. Therefore, as the diameter of the object reduces so does this contact area reducing the gripping force further. This is therefore why the Phoenix finger can grip small objects but to only very low weights, and as their size increases so does the weight it can grip it too. Additionally, an anomaly was highlighted during the test in Figure 8-34. When the Phoenix finger was being tested with the 50cL bottle, the geometry of the attachment and finger allowed the bottle to be gripped when empty with no contraction force. This was due to the grooves on the bottle sitting perfectly in this geometry to support itself. However, once weight was added to the bottle, contraction of the finger was needed for the 50cL bottle to be gripped.

Looking at the geometry of the Kwawu's grip in Figure 8-32b, it creates the same geometry as the Phoenix finger when gripping objects, one pressure point from the distal bone. However, it only creates one contact point with the attachment as the Kwawu palm is more curved than the Phoenix palm. Therefore, the Kwawu finger can similarly grip larger objects to heavier weights, but to not as high a weight as the Phoenix finger as it only has two contact points with the objects. Another difference in the Kwawu model is that it cannot grip small objects when empty unlike the Phoenix finger. This is due to the finger requiring too much force to contract and therefore not being able to rotate enough to contact small objects.

Both Flexibone designs had similar geometries when gripping the 50mm object. As can be seen in Figure 8-32 parts c and d, due to the distal joint being able contract as well, the fingers wrap around the object and press the object into the palm, intermediate and proximal bones. This means that both designs sometimes have four contact points with the object. This in turn provides a larger surface area and friction force. This allowed both Flexibone designs to lift to a higher weight for all object sizes compared to the Phoenix and Kwawu models as seen in Figure 8-33. Therefore, allowing movement in the distal joint creates a better grip geometry for prosthetic finger models. An additional benefit of contracting the distal joint is the fact that it allows the finger to curl to a smaller diameter. As seen in Figure 8-35, the Flexibone V1 finger has completely curled round the 20mm diameter object. It has therefore obtained 4 points of contact with the object, with the object having no contact with the attachment. The contraction of the distal joint therefore gives greater versatility of ways in which objects can be gripped.

When comparing the results of the Flexibone V1 and V2 fingers directly, it shows that the two designs with the same contraction method are not equal with what weight they can grip for each object size. The Flexibone V1 performs better than the V2 for the 20mm object, but for larger objects they are either equal or the Flexibone V2 can grip a greater weight. A potential reason for this is highlighted in Figure 8-36. This figure shows how as the weight of the object increases the Flexibone V1 design deforms and twists in the direction of load, whereas the Flexibone V2 stays rigid. This is due to the additional ABS which covers the joints of the V2 design providing extra support under load and prohibiting deformation. The effect of this deformation for the Flexibone V1 design is that, during the gripping of small objects, the twisting allows more of the fingers surface area to contact the object. This increases the friction force and weight it can be held to, hence the 300g weight of 20mm diameter object being gripped. However, for large objects, as the finger is already more stretched out, the deformation of the finger causes some of the fingers surface contacting the object to pull away. The knock-on effect is that the friction force therefore decreases and hence the weight that can be maintained by the grip for larger object decreases compared to the Flexibone V2 design. The incorporation of ABS covers for the joints is therefore a benefit to the Flexibone design, as a greater range of objects could be gripped to a higher weight.

The final relationship that can be drawn from the grip test is the relationship between contraction force and maximum weight gripped. Figure 8-37 shows that as the object weight increases so does the force required to grip it. This is due to greater normal force being needed at the contact areas on the object to increase friction. This in turn will prevent the slipping of the object. Therefore, if the finger requires a greater contraction force, such as the Kwawu, more force is needed to grip that object compared to the other models with lower contraction force. This will lead to the motor stalling before a great enough force can be applied to grip the object if its weight is increased. Therefore, a model with a high contraction force can't grip an object to as high weights. This relationship therefore shows that a lower contraction force for a finger provides a more versatile model for gripping objects.

8.1.3.6 Conclusion (TE)

Overall the Flexibone V2 design was the most consistent at gripping objects to high weights over the full range of sizes. The Flexibone V1 had a similar performance but due to the deformation at higher loads, could grip to as high a weight. The test also showed that having the distal bone free to move is beneficial for the design due it being able to grip smaller objects more easily, and as it allows more contact points to be made with the objects, allowing them to be gripped to higher weight. Finally, the test showed that if a finger model had a lower contraction force it allowed objects to be gripped to higher weight as the motors are providing more force to gripping the object than contracting the finger, allowing higher objects to be gripped before motor stall.

8.2 Wire Routing Friction Tests (JP)

It was necessary to determine how the routing of the wires through the palm affected the total friction in the system. Figure 8-38 shows the test-rig. The finger force test test-rig, the development of which is outlined in section 8.1.1.2, was adapted for the purposes of these experiments. The main alterations between this experimental set up and that of the finger force tests is the use of the wire routing plates and the 500g bottle of water used as a weight to tension the fishing wire (Asso Dyneema braided line sk71). 2.5mm PTFE tubing, which is commonly used in 3D printers to pass plastic filament to the extruder head, is a low friction tubing that was also used during testing.

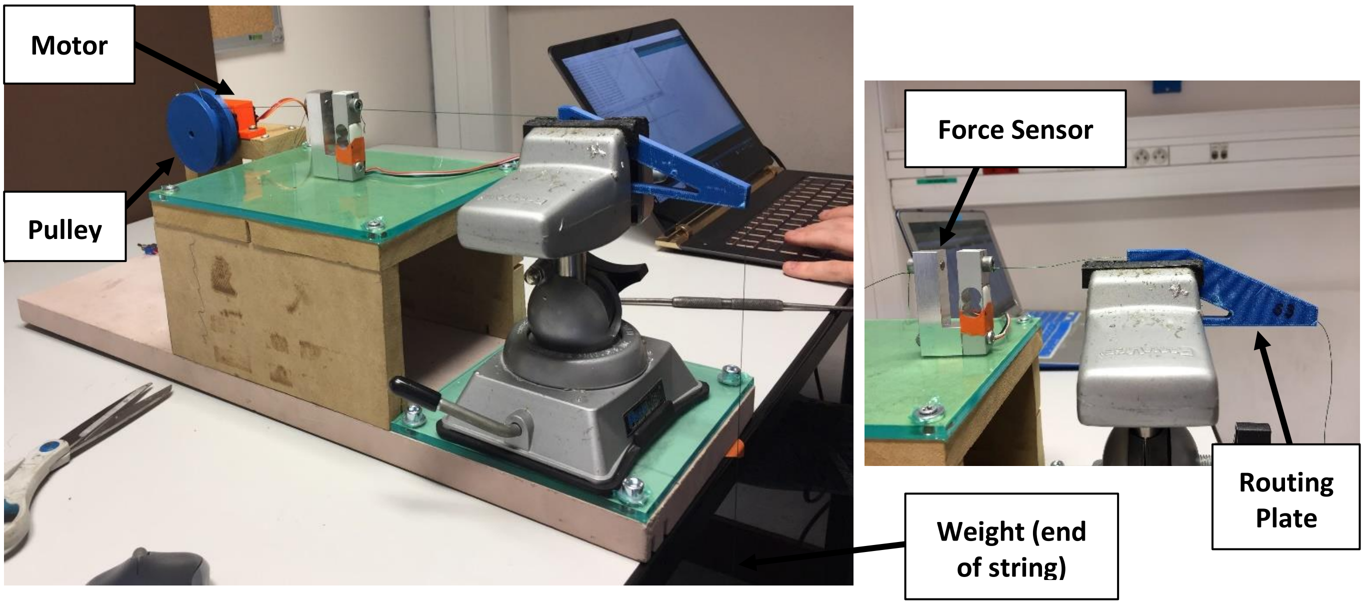


Figure 8-38: Wire Routing Friction Test Setup

Experimental aims:

1. Determine relationship between the angle of curvature and the friction observed in the system.
2. Observe how the general routing path affected the friction in the system.
3. Observe the effects of PTFE tubing on the friction in the system.

8.2.1 Premise (JP)

The premise of the experiment was to measure the average force required to pull a 500g bottle of water with the fishing wire through the wire routing plate using a servo motor. The force would be measured using a force sensor and the additional force required to pull the bottle above 0.5kg multiplied by gravity would be equal to the friction in the system, see

Equation 8-6.

$$F_P = F_{REC} - F_W - F_S$$

Equation 8-6: Friction Formula

F_P = Friction in wire routing plate

F_S = friction due to force sensor sliding across surface

F_{rec} = Force recorded by force sensor

F_W = Weight of 500g bottle of water

8.2.2 Procedure (JP)

The wire routing friction test procedure document can be found in appendix J. But a summary of the test is highlighted below:

1. Force test code uploaded to Arduino.
2. Test rig set up as seen in Figure 8-38.
3. Motor switched on.
4. Tensioned fishing wire (500g water bottle) pulled through routing plate.
5. Motor switched off after reaching 180° .
6. Results recorded.
7. Repeat 3 times for each plate + 3 times with PTFE tubing.
8. Repeat for all 6 plates.

8.2.3 Routing Plates (JP)

Each of the individual routing plates had a 3mm circular hollowed path passing from one end of the plate to the other as seen in Figure 8-39.

The angle and shape of the hollow paths within each of the routing plates differed by some degree. Figure 8-39 shows the shape of the hollow path within each of the routing plates and Table 8-6 and Figure 8-40 gives further details on each of them and the data from the experiment.

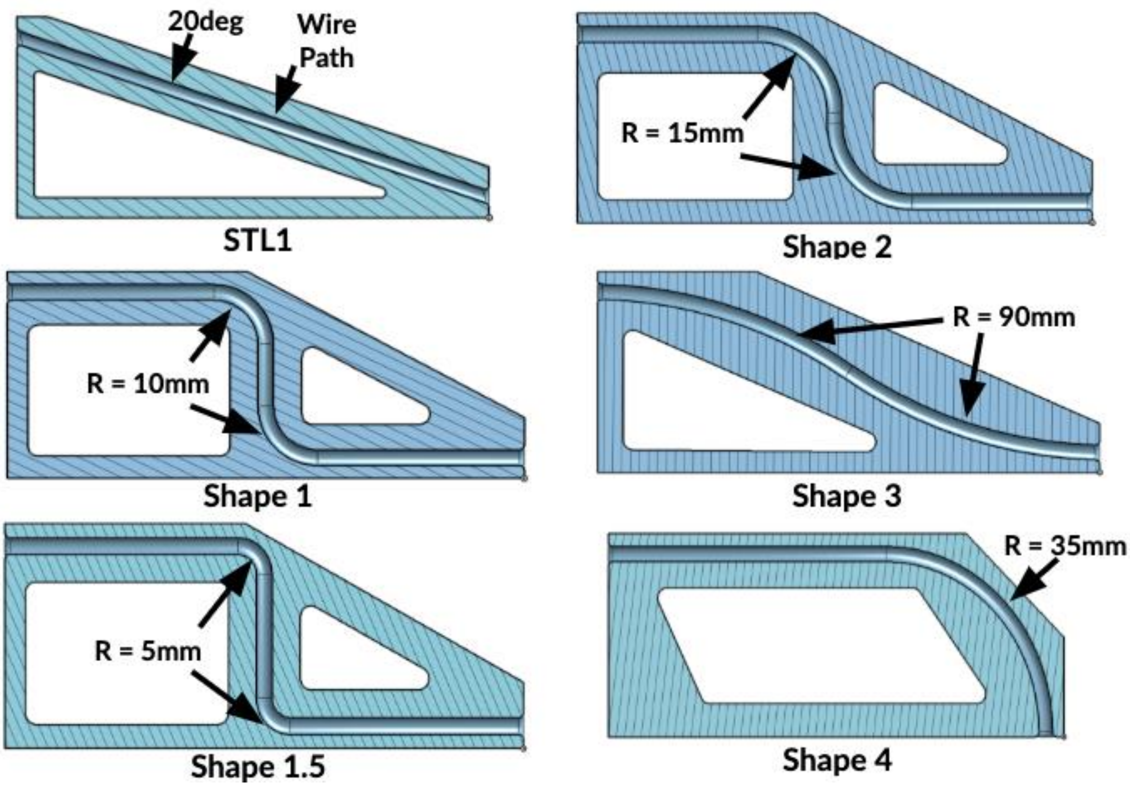


Figure 8-39: Wire Routing Friction Test Plates

8.2.4 Results (See Appendix K for Full Results) (JP)

Routing Plate	Path	Fp max (tubing) / N	Fp max (no tubing) /N	% Decrease in friction
Shape 1	2 x 10mm radius	0.934	2.33	59.9
Shape 1.5	2 x 5mm radius	1.01	2.01	49.9
Shape 2	2 x 15mm radius	0.934	1.79	47.7
Shape 3	2 x 90mm radius	0.382	0.801	52.4
Shape 4	1 x 35mm radius	0.165	0.495	66.7
STL 1	20° straight	0.207	0.594	65.1

Table 8-6: Wire Routing Friction Test Results

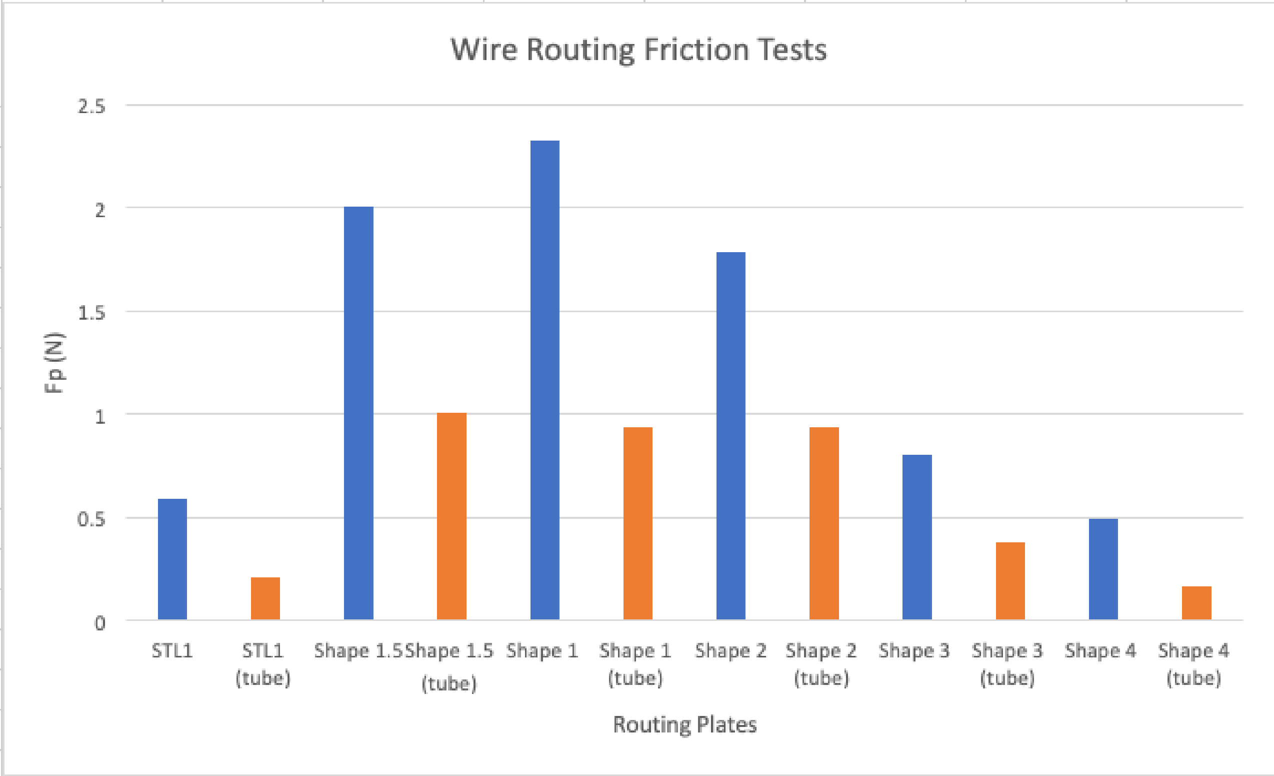


Figure 8-40: Graph of Friction vs Plate Type

8.2.5 Experimental Conclusions (JP)

The three aims of the experiment were to see if there was a correlation between the angle of curvature and the friction observed in the system, to observe how the general routing path affected the friction in the system, and to observe the effects of PTFE tubing on the friction. Unfortunately, it was not possible to develop the relationship between angle of curvature and friction in the system as the hypothesis that increasing the angle of curvature would decrease the friction was not observed in shape 1, shape 1.5 and shape 2, were the radius of curvature at two points in each plate was increased in 5mm increments from 5mm to 15mm.

This may be due to several reasons:

- The test for shape 1.5 was completed the day after the rest.
- A different printer was used for shape 1.5 so the print quality could have been slightly different leading to different friction results.
- The same fishing line was used throughout all the experiments. However, the fishing lines wears over time which could change the friction observed. (This should be considered for all the experiments).

However, a general trend observed over the routing plates, even though a relationship could not be calculated, was that reducing the angle of curvature within the routing plates reduced the friction in the system. Additionally, using PTFE tubing reduced the friction in the system by an average of 56.9% over all the plates.

It was a time intensive process to develop each routing plate, print it off and then test it. Had more time been available additional routing plates would have been printed and further testing done to investigate the relationship between angle of curvature and friction within the system.

It would have been optimal to just use one specific 3d printer to print all the wire routing plates to ensure the print quality didn't vary. However, due to time constraints this simply wasn't possible. Additionally, it would have been optimal to use a new piece of fishing wire for each test, but this also wasn't possible due to how labour intensive the process would be, and due to the limited amount of fishing wire.

8.3 Mechanical Design Development (PB)

A small amount of time during this stage of this project was spent on developing concept designs surrounding the 3D printing filament NinjaFlex to better understand its properties and potential applications. A flexible, durable and high strength plastic, NinjaFlex offers unique properties and potential applications not offered by traditional hard polymers such as ABS and PLA. According to Adafruit, a supplier of the filament, one of the recommended applications of this material is wearables such as wristbands [85], making its use highly applicable to this project.

8.3.1 Gauntlet Attachment (PB)

It was proposed that NinjaFlex could be used as a method of attaching the gauntlet to the users forearm due to its flexible properties and so testing was carried out to assess this. For an effective attachment mechanism, it should be tight fitting, easily adjustable and durable.

As a flexible material, the team wanted to determine if it was also stretchable. Although it wasn't directly, some spring designs were designed and printed to see if it could be used in this way. A spring mechanism could be used to automatically form the gauntlet to the user's arm, providing solid contact. An attachment method could, for example, be used in conjunction with the haptic motor array and wristband already designed in section 7.3. These were merely concepts and were not taken forward into the next stage of the project (see Appendix L).

8.3.2 Proprioception (PB)

Based on the findings in section 5.3.6, methods of mechanical haptic feedback were also conceptualised and prototyped (see Appendix L for photos).

- Feedback Wheel - A wheel concealed inside the gauntlet rotates based on the position of the fingers. A pin on the wheel is in constant contact with the user's forearm. As the pin rotates, it brushes across the users' arm and therefore indicates the position of the fingers in space.
- Pressure Pins - As a linear actuator moves along its path, it compresses pins that press into the users' arm. Based on the position of these pins, the user knows approximately where the fingers are in space.

9 Designability

On 19th March 2019 the design team had an interview with Hazel Boyd who works for Designability, a Bath based Charity, who design and make products to help people with a disability. Hazel has a PHD in wrist biomechanics and she is also heavily involved in user-centred design as one of Designability's User Interface Engineers.
There were several key takeaways from this interview and they are outlined below:

- Hazel highlighted that the interview with the user would be very important as it would prevent the design team from having to many diverging design options and that it could potentially narrow the scope to one design.
- If the wrist was completely constrained there would most likely be a trade-off between strength and dexterity. Limited wrist/finger movement with good strength vs good control of the fingers but no strength.
- Mass market product vs custom job for niche audience/individual user. If the user's disability is representative of a group of people, then this may provide a niche market for the prosthesis.
- Is the business going to be a solely charitable endeavour where the job is to meet individual users' requirements or is the job to mass produce something? Because if all the research and design is based on the user and then it is discovered her case is completely unique, then it simply wouldn't be feasible to sell the product to a wider market. Therefore, these decisions should be outlined early.
- Designing the perfect solution would be incredibly hard and most likely wouldn't be impossible due to the time constraints of the project. Therefore, find where the limits of sensible compromise are by asking the user, other amputees, or experts what it is that they need.
- Therefore, a lot of emphasis should be put on asking the user what they want in the design of the prosthesis, to reduce the total complexity of the design and provide some constraining boundaries to the project that make it more manageable.
- Hazel reiterated the importance of keeping the design intuitive and user friendly. She said that people can tolerate stuff that isn't simple if the instructions for use are clear.
- Hazel said that it would be best to focus on a set of core project aims during the interview and keep it semi-structured with open-ended questions as to not limit the prospective answers from the user.

10 First User Interview

The first interview with the user was conducted on the 3rd April 2019. At this stage in the project a prototype had not yet been made and testing was still being done. Hence, a range of different open-ended questions regarding her current prosthesis were asked in a semi-structured interview format to gauge what they liked and disliked about these designs, hopefully offering an insight into what could be improved upon. A semi-structured interview is as an interview style that does not have a rigorous set of questions that are strictly followed, but rather it allows new ideas and questions to be brought up during the interview based on what the interviewee says [86].

An additional challenge was added in that the user only spoke French, and the team did not. Much of the discussion was therefore between the supervisors and the user, with them translating between the two. Fortunately, much of the dialogue was also recorded by hand. There were several key take-aways from the interview:

- The user's current myoelectric prosthesis was too heavy for them, weighing 1.5kg. A device closer in weight to their current mechanical prosthesis, the Kwawu hand at 370g, would be ideal.
- The user also found the myoelectric prosthesis very difficult to control and it would often make accidental and unwanted movements.
- The myoelectric prosthesis also had a bad thumb design that had to be manually moved into place.
- Resorted to using the mechanical hand due to its simplicity.
- The Flexibone V2 finger was their favourite of the four finger designs.
- It became apparent that the user still had a portion of their thumb on their right hand that had enough dexterity to possibly be a method of control.

- The user wanted the gauntlet to be easy to put on with a simpler method of attachment that would not require the use of Velcro straps or assistance to put on.
- The bottom edge of the palm of their current prosthesis was rubbing against their hand causing discomfort.
- The user liked the idea of having a locking mechanism instead of their ratcheting mechanism to secure objects.
- The use also said that they would find the addition of haptic feedback useful, so they are always aware of the force being applied to an object.
- The user also highlighted that they care more about function than looks and that if it is necessary to change the shape or size of the hand or fingers to improve functionality then that would be okay.
- The user also liked the idea of having movement of the wrist when the fingers are locked in place. Something that isn't possible with their current mechanical prosthesis when the ratcheting mechanism is engaged.
- The user did not feel that feedback relating to finger position was necessary as visual feedback was enough.

In conclusion, the interview was a success and a large amount of useful information was gathered. It also allowed the focus of the project to be narrowed, influencing the future course of the prosthesis design.

11 Mechanical Design Evaluation (TE)

		Phoenix Hand			Kwaku Hand			Flexibone V1 Hand			Flexibone V2 Hand		
Criteria	**Weighting**	**Value**	**Weight**	**Total**	**Value**	**Weight**	**Total**	**Value**	**Weight**	**Total**	**Value**	**Weight**	**Total**
Print Time (hr:min)	2	03:54	4	8	05:24	1	2	03:36	5	10	04:29	3	6
Durability (Contraction Cycles)	4	200	1	4	Indefinite	5	20	Indefinite	5	20	Indefinite	5	20
Ease of Assembly	1	Needs Nothing Additional	5	5	Needs Glue	4	4	Needs a screwdriver and force to insert finger into palm	3	3	Needs additional string and a very large force to assemble the flexible part into the palm	2	2
Max Contraction Force (N)	5	4.97 (Size Small)	5	25	14.77 (Size Large)	1	5	9.39 (Size Large)	2	10	3.91 (Size Large)	4	20
String Distance for Max Contraction (mm)	4	34.56	2	8	31.76	4	16	32.46	3	12	29.32	5	20
Scalability Force Factor (From Size 1 to 3)	3	0.46	5	15	1.09	1	3	1.42	2	6	1.13	3	9
User Feedback	4	Dental bands break often	1	4	Current Prosthetic Design looks good but difficult to pull	3	12	Uses flexible filament, making it easier to pull and it's a 3-articulation finger	4	16	Uses flexible filament making it easier to pull, but looks more realistic with more support at each joint	5	20
Asthetics	3	Angular Unrealistic Shape	2	6	Realistic Rounded Shape	5	15	Realistic but Hinges are Visible	3	9	Realistic Rounded Shape	5	15

Gripped Object Size	5	20mm, 30mm, 40mm, 50mm, 50cl, 1L	5	25	50mm, 50cl, 1L	1	5	20mm, 30mm, 40mm, 50mm, 50cl, 1L	5	25	20mm, 30mm, 40mm, 50mm, 50cl, 1L	5	25
Grip Mass per Size (g)	5	16.4, 22.4, 100.2, 37.8, 400.1, 99.8	2	10	37.8, 99.8, 100	1	5	500, 300.5, 199.7, 200.3, 200.2, 100.4	4	20	200.2, 300, 300.4, 299.9, 299.5, 200.1	5	25
Additional Part	2	Rubber Dental Bands	2	4	Ninja Flex, Glue	3	6	Ninja Flex	4	8	Ninja Flex	4	8
Number of Finger Articulations	3	2	1	3	2	1	3	3	5	15	3	5	15
Weight (g)	2	23.9	4	8	33	2	4	20.7	5	10	24	4	8
Cost (€)	4	0.77	5	20	1.32	1	4	0.97	3	12	0.99	3	12
				145			104			176			205

Table 11-1: Evaluation of the Four Hand Model Designs

11.1 Comparison (TE)

- **Print Time**
  - Flexibone V1 – The quickest time, due to small parts for the ABS and little supports needed. Flexibone part is also simple to print.
  - Phoenix – Second quickest, only needs one printer as all made from ABS so it can all be printed at same time. However, parts are larger and taller increasing print time.
  - Flexibone V2 – Third Quickest, requires more supports than the Flexibone V1 due to the new hinge design, increasing print time. Also, slightly more complex geometry for the Flexibone part.
  - Kwawu Hand – Slowest, has large ABS parts that need to be printed, additionally has multiple parts to be printed out of ninja flex increasing print time.
- **Durability**
  - Flexibone V1, V2, Kwawu – High durability, all hinges are made of ninja flex, which is also used for the restoring force of the fingers. This material is extremely durable, stretchy and impact resistance.
  - Phoenix - Low durability, hinges receive their restoring force from elastic dental bands, however they break after a few hundred cycles, and feedback from users say they must be replaced often during use. Additionally, the hinge bolts are made of ABS, which could snap more easily if a finger receives an impact.
- **Ease of Assembly**
  - Phoenix – Quickest to assemble, only additional part is the dental bands which can be applied easily.
  - Kwawu – Not difficult to assemble, but each segment of the finger needs to be glued together, slowing down the process and requiring glue.
  - Flexibone V1 – Difficult to assemble, fingers are easy to assemble and can be made permanent with glue, however not necessary. However, assembling the finger into the palm is difficult requiring a lot of force and a usually another utensil such a screw driver.
  - Flexibone V2 – Most Difficult, same as the Flexi V1 however it can't be inserted into the palm with the help of a screwdriver due to the covers on the side of the proximal joint. Therefore, a fiddley method involving fishing line must be adopted. This requires even more force and is a waste of fishing line.
- **User Feedback (From First Interview)**
  - Flexibone V2 – The best, looks like the Kwaku hand but a lot less force to contract, they also like the use of flexible filament throughout giving three articulation points compared to their current prosthetic. Was better than the flexi V1 due to aesthetics and the additionally support for sideways loads on the finger due to the covered hinge sections.
  - Flexibone V1 – Good, easier to pull and more natural movement due to three articulation points in the finger.
  - Kwawu – Okay, Current model for her prosthetic, aesthetically pleasing for them, however it requires a lot of force to contract the fingers.
  - Phoenix – Worst, even though it is the E-nable hand, they hated the rubber bands and doesn't want a design involving them as is stops the hand from working so frequently.
- **Aesthetics**
  - Kwawu, Flexibone V2 – Most appealing to them as they are both based off the same hand model and look the most realistic.
  - Flexibone V1 - Rounded finish, however hinges are on show which makes it look more robotic than natural.
  - Phoenix – Angular design and not very finger like.

- **Additional Parts**
    - Flexibone V1, V2 - Is all ABS and then also uses Ninjaflex for the hinges, therefore that material will need to be ordered additionally.
    - Kwawu – Also requires Ninjaflex but must be assembled with glue to work.
    - Phoenix – Doesn't need Ninjaflex, but does require dental bands for the joints, which might be difficult to procure.
- **Number of Finger Articulations**
    - Flexibone V1, V2 – Most natural, has three joints and therefore have a more natural movements and can fit better to object geometries.
    - Kwawu, Phoenix – Only has two joints, therefore have a very large upper finger section making it look less realistic with a less natural movement.
- **Weight (Not Important as they are all so light)**
    - Flexibone V1 – Lightest, due to minimal size of ABS parts and light Ninjaflex centre.
    - Phoenix – Second Lightest, due to minimal design and no Ninjaflex.
    - Flexibone V2 - Almost the same as Phoenix, however slightly heavier due to the additional abs for the finger joint covers over the Flexibone V1.
    - Kwawu – Heaviest due to its large design and all ABS.
- **Cost**
    - Phoenix – Cheapest, not including the purchase of dental bands, but uses no expensive NinjaFlex.
    - Flexibone V1 – Second cheapest due to less weight of material being used that the other designs but uses ninja flex.
    - Flexibone V2 - Only 2 cents more expensive than the Flexibone V1 due to the additional ABS material in the design but reduction on Ninjaflex.
    - Kwawu – Includes Ninjaflex and a lot more ABS than the other design, therefore is the most expensive.

11.2 Conclusion (TE)

The finger model that was deemed to be the most suitable from the testing and criteria applied to them, was the Flexibone V2. From the overall comparison in Table 11-1, the Flexibone V2 received a score of 205, with the user's current prosthetic, the Kwawu receiving the lowest score of 104. It was therefore decided that the Flexibone V2 hand would be taken forward as the mechanical model for the development of the prosthetic.

12 Stage Gate 3 Conclusions

Brought Forward	Dropped	Newly Developed
• Force Feedback • Allow movement in the wrist • Use PTFE tubing • Flexibone V2 finger was the best	• Myoelectric, pressure, and flex sensors inaccurate for control • Mechanical haptic feedback for proprioception	• Easier method of attachment • Locking mechanism • Joystick control method • Wire routing through palm and axis of rotation • Remaining Flexibone V2 fingers • Tensioner pulley mechanism • Comfortable palm base • Internal liner • Internal cavity in palm for residual limb
What else was Learned?		
• User's current Myoelectric prosthesis was too heavy, difficult to control, and had a bad thumb design. • User just used mechanical hand due to its simplicity. • User cares more about function than aesthetics.		

Table 12-1: Conclusions of the Tasks that will be Brought Forward, Dropped and Will be Developed from Stage Gate 3

13 Prototype Development

13.1 Electrical

Because of the decisions made at the end of stage gate 3, the team focused development on specific areas of the design with the goal of developing a full prototype. In terms of the electrical design, this meant choosing a control method, an actuation method, and continuing to develop force feedback. This would then need to be combined into one circuit.

13.1.1 Control (PB)

From the first interview with the User, it was discovered that she still had precise control of her residual carpometacarpal (CMC) thumb joint, comparable to that of non-amputee in terms of range of motion. The CMC joint is the most mobile joint in the hand, capable of abduction, adduction, flexion and extension.

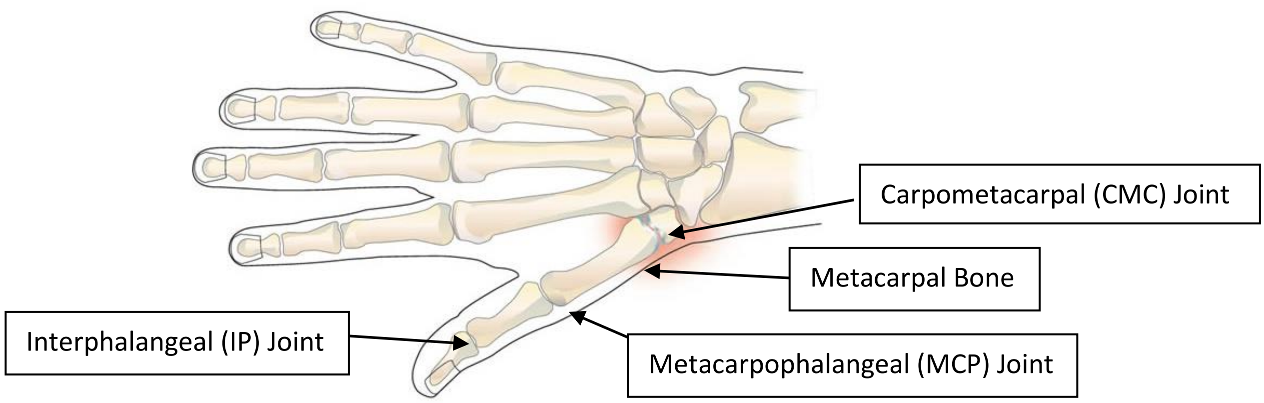
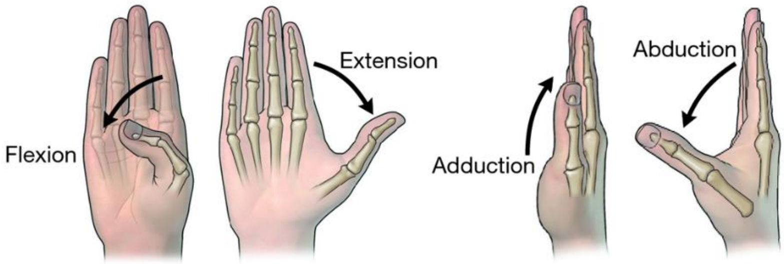


Figure 13-1: diagram of thumb joints [87]

The user has a residual thumb up to the MCP joint. The abduction and adduction of the thumb occur only at the CMC joint, and therefore should not be impaired. Flexion and extension of the thumb occur at all three joints, however much of it occurs at the CMC joint. Range of motion for the CMC joint is 53 degrees of flexion/extension, 42 degrees of abduction/adduction, and 17 degrees of rotation [87].



Source: Mark Dutton: *Dutton's Orthopaedic Examination, Evaluation, and Intervention*, 4th Edition: www.accessphysiotherapy.com
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Figure 13-2: movements occurring at the CMC joint

It therefore presented a promising option for control. A joystick was proposed as a controller as it provides two-axis control and is used in many common applications such as video games, typically using the thumb. Joysticks are intuitive and a proven and accurate means of control for a range of applications. The joystick could be directly attached to this residual joint and linking the controller closely with the central nervous system in this way also reduces cognitive overload (section 5.3).

Joystick

A two-axis joystick contains two potentiometers, one corresponding to the position in the X axis, and the other in the Y axis. As the joystick moves, the voltage in both axes changes and can be read to an Arduino's analogue pins, providing precise positional feedback that can be used to control the position of a servo motor.

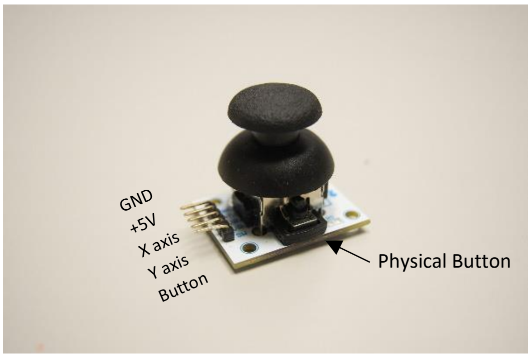


Figure 13-3: Left: Joystick with 5 pins. The button produces a 1 when whole joystick is pressed, and 0 otherwise.

Dimensions. Test rig and controlling a servo motor. Variable speed and ON/OFF.

It was proposed that each direction in an axis could be used to provide a function, therefore totalling four functions. A circuit with the joystick, Arduino and servo motor was developed along with code that controlled the position of the servo depending on the value read from the joystick.

- Code 1: Using only the X axis value the team were able to rotate the servo both clockwise and anticlockwise and vary the speed depending on how far it is pushed.

- Code 2: Using the built-in switch that is activated when the joystick is pressed down, code was also developed so that every time it is pressed it toggles the controller/servos on and off. This is an important aspect of the controller as it can be used to avoid unwanted and accidental movements – something that was highlighted by the user as an issue with her current myoelectric prosthesis.

3D Scan

A 3D scan of the user's residual limb existed in Onshape prior to the start of the project and was used for analysis.

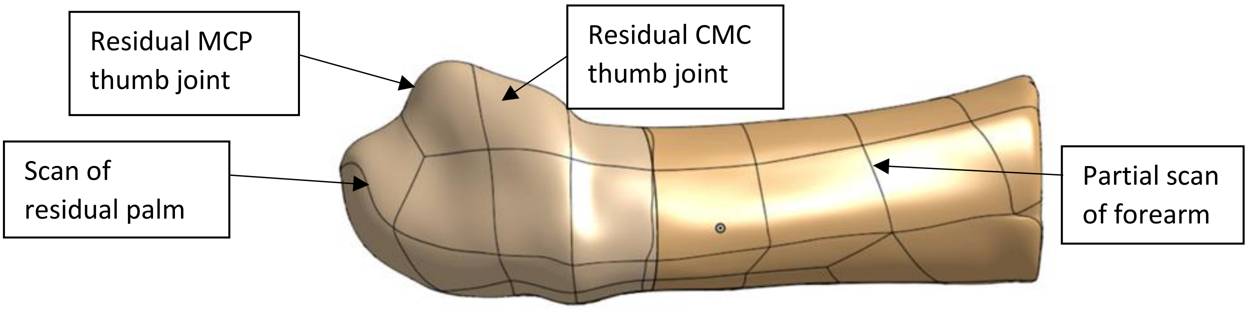


Figure 13-4: 3D scan of the user's residual right palm and forearm

To assess the viability of the joystick, the scan needed to be analysed to determine if there was enough space inside the Kwawu palm. Measurements were taken using sectional views of an assembly of the 3D scan and palm model. Upon analysing the previous design method for the palm, the inside of the pre-existing Kwawu palm was modelled by creating a 6mm offset shell of the users existing palm. This created a well-fitting mould with enough space for comfortable padding. This gap in conjunction with cutting into thick wall areas could be used to house the joystick.

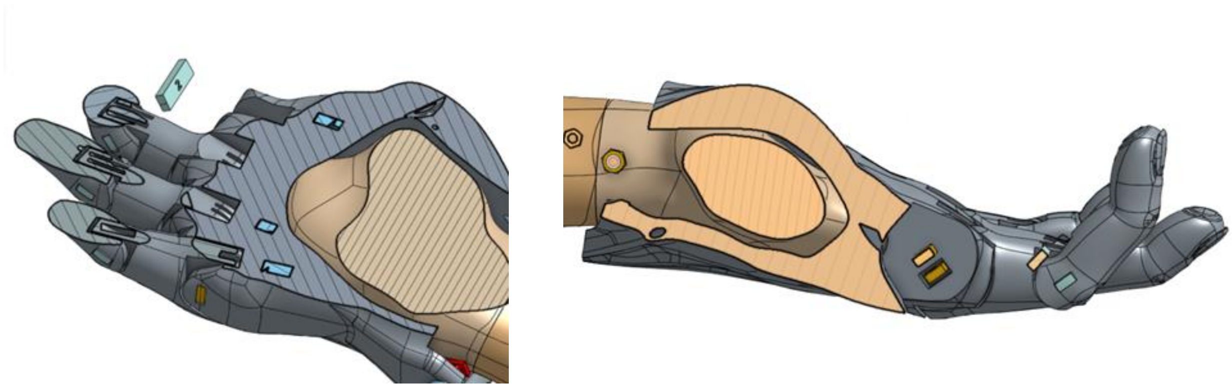


Figure 13-5: Sectional views of inside the Kwawu palm

As a result, two potential locations were identified, as shown below:

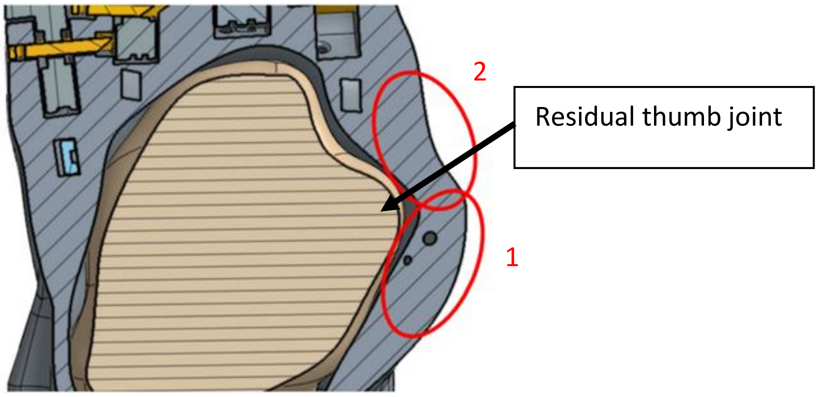


Figure 13-6: potential areas for joystick placement

Testing

For the joystick to be used effectively, a new attachment needed to be designed to fit around the user's residual thumb joint. A securely fitting attachment would be crucial for responsive and reliable control. As a result, the rubber attachment was removed, and a new attachment designed that would also allow the designers to test the accuracy of system. This was based on approximate dimensions of the designers thumb joint.

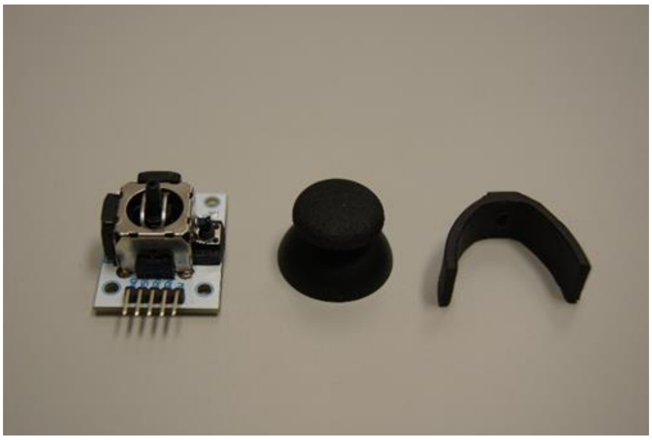


Figure 13-7: Joystick, old attachment and new attachment V1

As access to the user was limited, a crude test rig was set-up that allowed the designer to test the joystick control by only using the metacarpophalangeal (MCP) joint. This was to try and mimic the functionality of the user. This is shown in Figure 13-8.

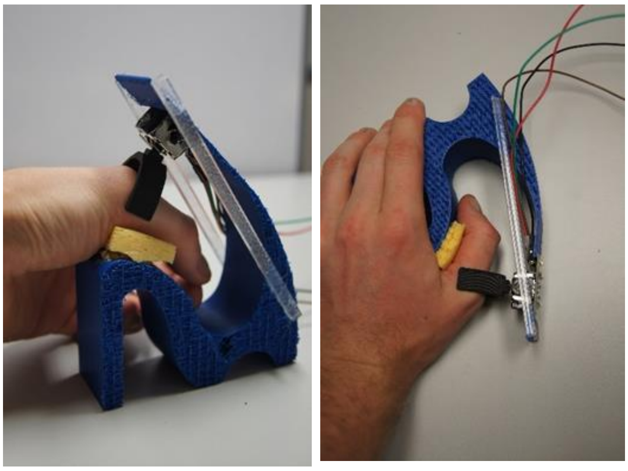


Figure 13-8: 3D printed test rig with joystick and new attachment

A quick test revealed that it was far more responsive and accurate than the pressure, flex and myoelectric sensors. It was not deemed necessary to perform a detailed test against these sensors, as it was clearly a much more accurate solution in this case, should it be feasible. This was because it was so closely linked to a joint that is designed for precision tasks. As a result, the joystick concept was taken forward for prototyping.

<u>Prototype 1</u>

Due to the large 24mm height of the joystick, it was discovered that even with a reduction in wall thickness, an extrusion would still be needed on the outside of the palm to appropriately house it. As a result, location 1 was determined to be more suitable as there was a greater wall thickness and it had less chance of interfering with grasped objects, being further from the fingers. The existing palm was therefore modified to fit the joystick sourced by the team and a section printed.

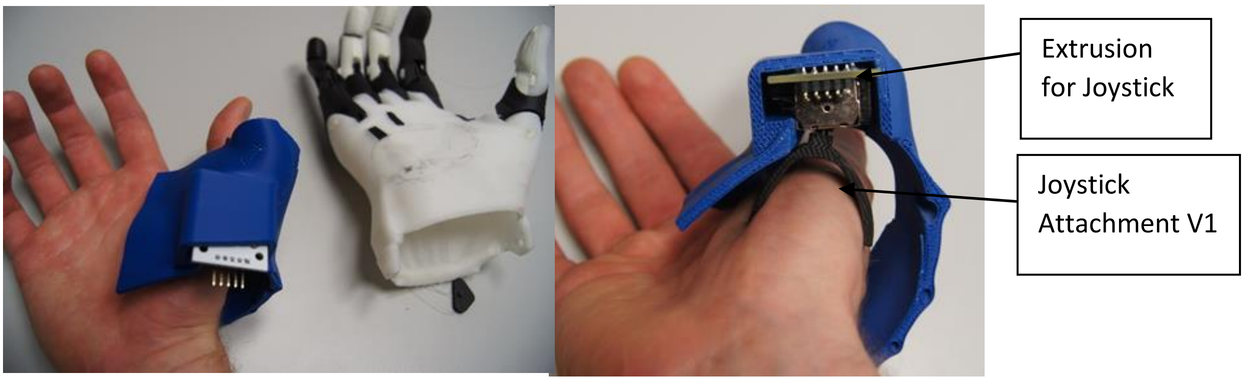


Figure 13-9: *left: printed section next to Kwawu model, right: joystick attachment*

This was difficult to test effectively without the user and by using only a small section of printed palm, however it was clear that in this arrangement only two or three functions would be possible – one direction for opening, one for closing, and the potential to press against the switch to turn on or off the controller/motors.

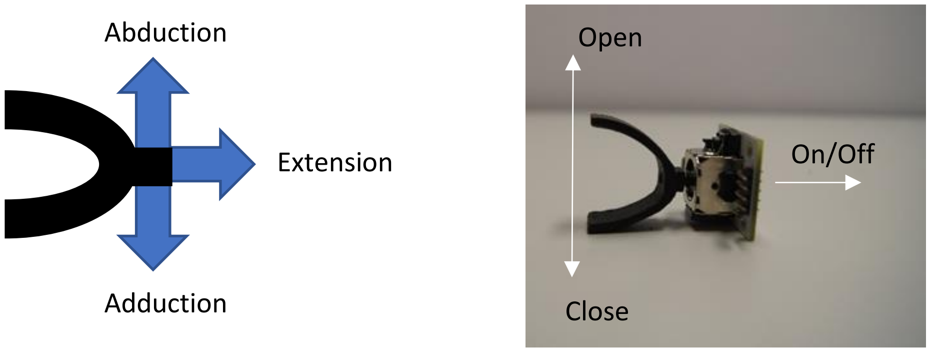


Figure 13-10: joystick configuration.

Pressing the switch in this manner, however, required an uncomfortable amount of force and was difficult to detect, meaning it may need to be combined with another manner of feedback such as vibration to indicate the system state effectively. The large protrusion in the palm would also negatively impact the overall aesthetics of the device.

Prototype 2

A smaller joystick was sourced that removed the need for the extrusion in Figure 13-10 and could also fit in location 2. Placement here allows 360 degrees of movement due to being directly on the end of the MCP joint, meaning at least 4 functions should be possible.

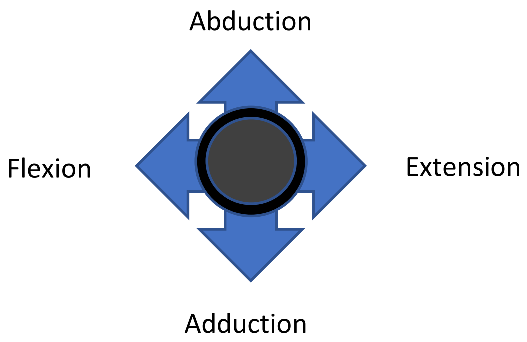


Figure 13-11: configuration of joystick in relation to CMC joint movement.

Prototyping therefore began to focus on this area of the palm.

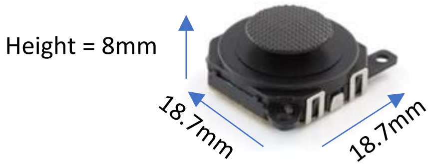


Figure 13-12: compact PSP 2-axis analogue thumb joystick by Adafruit

The joystick can move by a maximum of 2.5mm in the X-Y planes. Some quick calculations were done to check that the CMC joint could provide this full movement. Assuming the residual palm is 6mm from the joystick (due to the offset used to create the inside of the palm), the angle of movement is 22.6°.

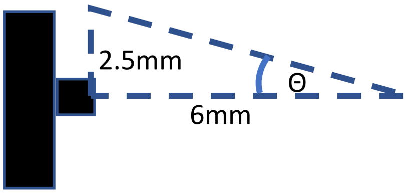


Figure 13-13: Joystick Angle

This angle is far lower than what is possible by the CMC joint in all directions, and therefore the user should be able to have full range of motion.

Again, the Kwawu model was analysed along with the 3D scan to determine an appropriate location. Consequently, a location was chosen that completely concealed the joystick from the outside while allowing space on the inside for an attachment.

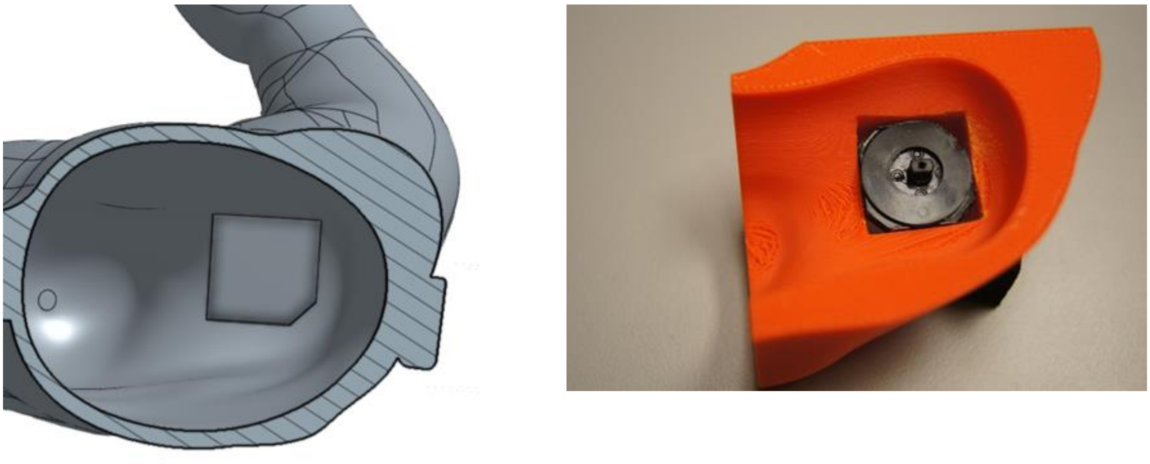


Figure 13-14: chosen joystick location inside the Kwawu palm. Left: Onshape model, Right: printed section with joystick inserted.

Joystick Design

Due to the geometry inside the palm being identical to that of the User, it made sense to make a joystick attachment that also exactly matched this geometry – not only for comfort, but also to maximise the space it could move through before being impeded. It was therefore created using a similar method, using an offset of the 3D scanned thumb joint.

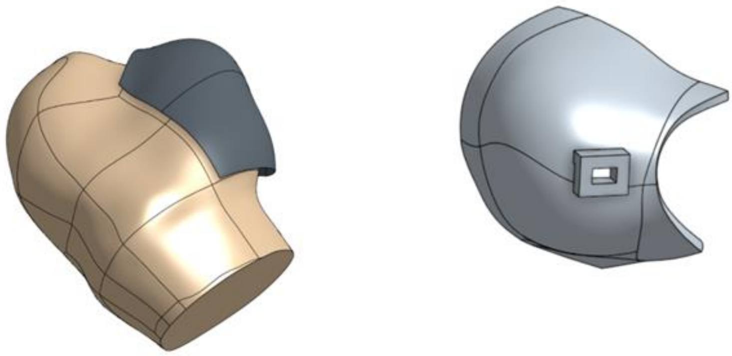


Figure 13-15: Joystick attachment using an offset of the 3D scanned palm

The offset was set as 1mm, so as not to be uncomfortably tight, but tight enough to be responsive to small movements. This was then thickened by 1.5mm to produce a rigid shell. An extrusion was finally added that allowed it to be fitted onto the joystick.

In theory, with 6mm of space inside the palm, this should have allowed enough movement for the joystick to move through its full range of motion, however when printed and tested it did not. Several reasons were found to account for this:

- The 2-axis joystick was designed to allow approximately 20 degrees of rotation, so when off centre the attachment sometimes became physically impeded by the palm. This rotation may improve comfort, with the CMC joint capable of a similar angle of rotation but was difficult to determine without the user.
- Some discrepancies in the joystick placement meant that the attachment did not sit exactly in the corresponding palm geometry, limiting movement.

These issues could be resolved by constraining the joystick from rotating and adjusting the placement of the joystick. Further testing revealed, however, that the self-centring mechanism used weak springs and did not always return the attachment to the neutral position. This could result in unwanted movements and therefore also needed to be addressed.

As a proposed solution, sponge was added to the outside of the attachment that could compress against the inside of the palm enough to allow motion but would provide a small returning force in addition to that of the springs.

Figure 13-16: joystick, attachment and sponge

To allow enough space for this and to address the other issues discovered from the prototype, the inside of the palm surrounding the attachment was thinned by 2.5mm – any more than this and the total wall thickness would have become less than 1mm in some areas (see section 13.2.3).

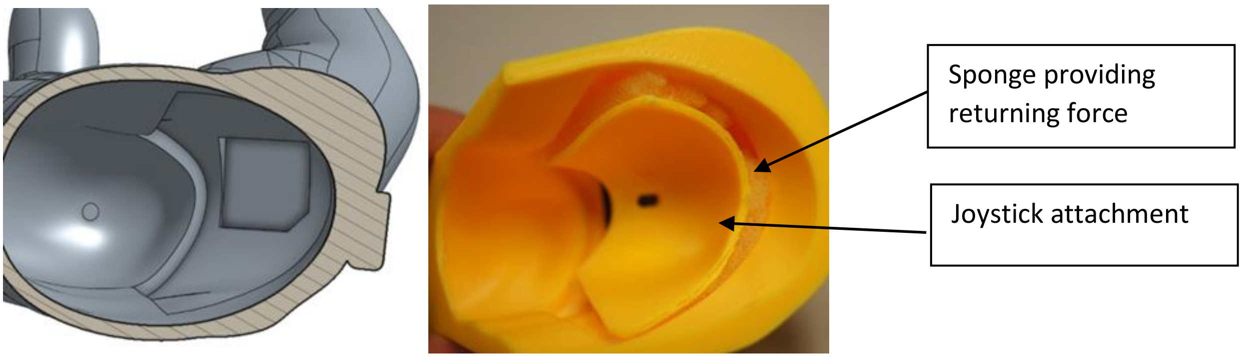


Figure 13-17: 2.5mm thin inside the palm

This successfully resolved the issues highlighted, with the sponge providing enough returning force to centre the joystick when not in use.

At this stage, the joystick worked as hoped by the team, but it could not be deemed an effective method of control until it could be tested on the User. It was also unclear as to what would be the optimal configuration for opening/closing the fingers and would need to be determined through testing with the User.

13.1.2 Force Feedback (PB)

As a direct result of the positive feedback from the user in the first interview regarding force feedback, development continued this aspect of the design. As previously highlighted, for this to be successful two problems needed to be overcome:

- A conductive material was needed that would not fatigue under the large and repetitive flexion of the finger joints.
- A pressure sensor would need to be found or designed that could fit inside the fingertip.

The index finger for the Flexibone Hand V2 was already designed, and therefore was chosen for a pressure sensor as it could be immediately analysed and modified. Due to NinjaFlex's flexible nature, it was proposed that the pressure sensor could be placed inside, entirely concealed, and still be effective. Measurements were taken from the index finger to find a sensor that would fit. A compact pressure sensor supplied by Interlink Electronics was found that fit these required dimensions. Shown below in Figure 13-18:

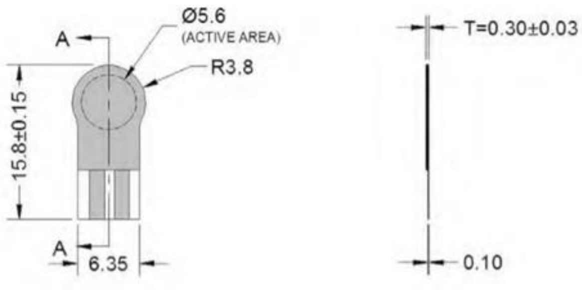


Figure 13-18: Model 400 round short tail force sensitive resistor dimensions (mm).

The team therefore began modifying the fingertip in Onshape to house the sensor, as shown below:

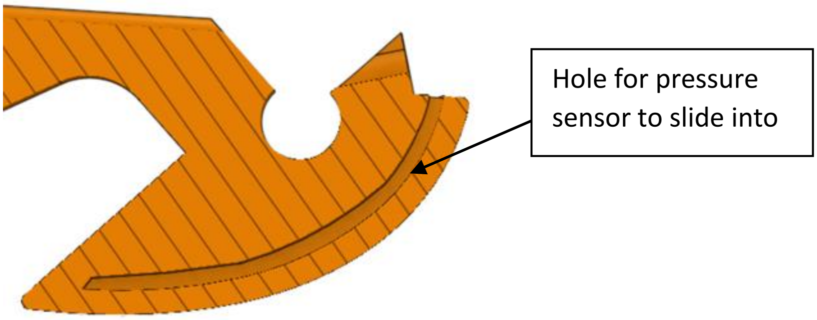


Figure 13-19: modified fingertip

Conductive Fabric

As an alternative to standard wire, conductive fabric was proposed due to its flexible properties. To first test its conductive properties in comparison to wire, a 100mm length of wire was used in series with standard wire and a pressure sensor. The reading was read on the Arduino with a known pressure. The value remained constant. The 100mm wire was then replaced with 100mm of conductive fabric, with the pressure kept the same. The value matched that of the wire and remained constant. It was therefore deemed to be a potential solution.

The fabric was cut into 2.5mm strips and routed along the back of the NinjaFlex bone, as shown below, and fixed down with the adhesive side:

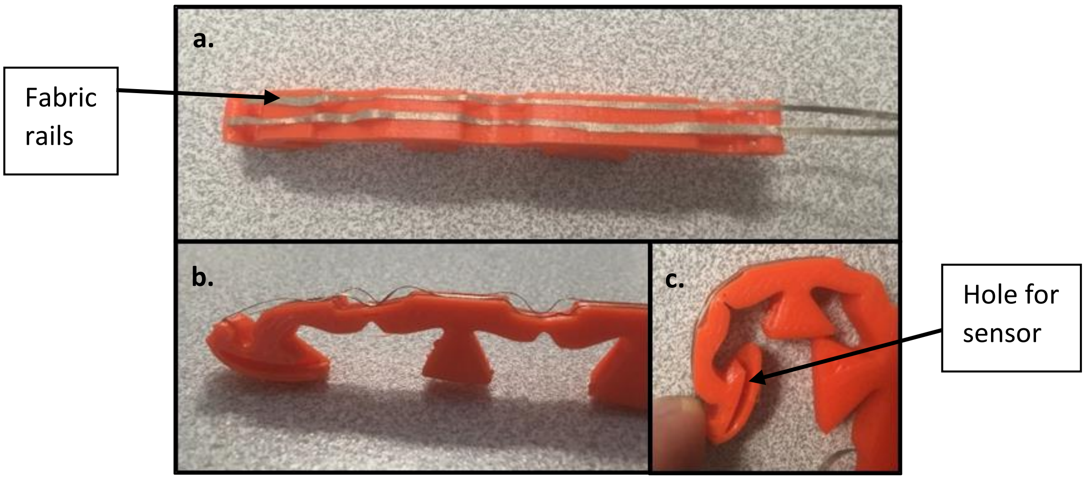


Figure 13-20: Flexibone with Conductive Fabric Running Down the Back

The fabric was then observed during contraction of the bone. It was found to function well, deforming at the joints and adding no extra tension to the system.

The bone was modified with two rails for the power and ground tracks to the sensor. These grooves would prevent the two fabric strips from short circuiting. Laying them below the surface would also prevent the fabric from getting damaged during assembly.

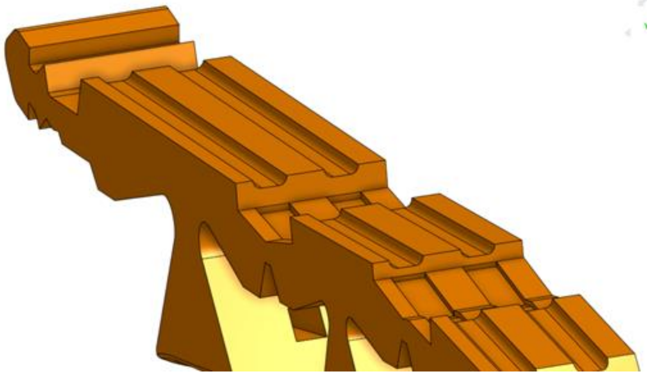


Figure 13-21: ground and power rails

The NinjaFlex bone, conductive fabric and ABS parts of the finger were then assembled together.

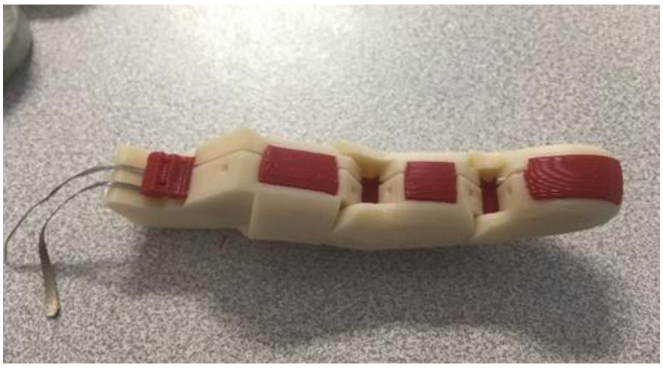


Figure 13-22: conductive fabric successfully routed through finger

It was found, however, that there was insufficient room at the joints for the conductive fabric to flex, due to the ABS being too restrictive. This was therefore edited to allow enough movement.

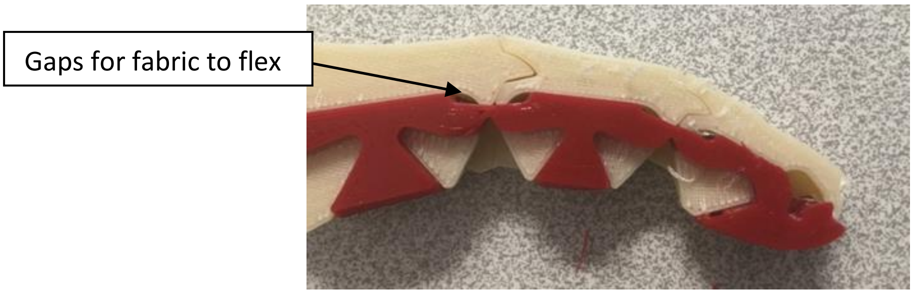


Figure 13-23: modified ABS

The next step was to find a method of attaching the conductive fabric to the sensor. The fabric itself was part Nylon, and so could not be soldered to the metal pins of the sensor. The team sourced mechanical connectors that were able to securely clamp the material in place and form a solid connection, shown in Figure 13-24.

Figure 13-24: Amphenol FCI Clincher Connector (2 Position, Male), Sparkfun Electronics

The first prototype is shown below in Figure 13-25:

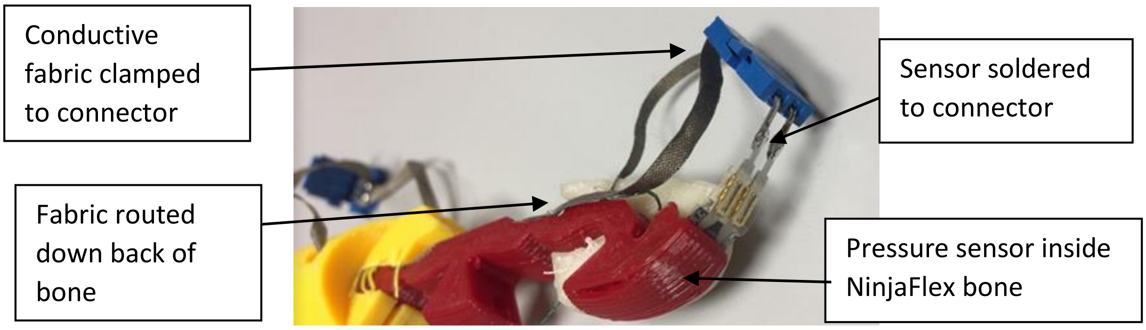


Figure 13-25: Fingertip pressure sensor, prototype 1

Conductive thread was proposed as an alternative, however upon testing it was found that the thread frayed significantly and was therefore highly prone to short circuits. This could be potentially resolved by coating the thread in a non-conductive coating such as paint. As the fabric worked, however, it was not investigated due to time constraints.

Findings:

- The pressure sensor was highly sensitive. It was found through rapid prototyping of the NinjaFlex fingerbone, that for high sensitivity the sensor should be pre-compressed using a tight-fit. Without this, a small initial force is required before the sensor provides readings. Any air gap between the sensor and the NinjaFlex would also mean that this area would need to be compressed before any readings were given.
- The sensor only detected force when the area directly above the active sensor area was compressed
- The connectors formed a solid connection but were too large to fit inside the finger. The pins of the pressure sensor would also need to be trimmed down.
- The pressure sensor suffered from weakness in the connection between the pins and the sensor itself. As a result, the sensors had to be handled delicately during testing. Additional reinforcement could be added to prevent this, i.e. from glue.

Second Prototype

After analysing the first prototype, modifications were made to resolve the highlighted issues:

- The connector in the first prototype was dismantled to obtain only the metal connectors. These alone were significantly smaller than the full connector and could fit inside the finger.

Figure 13-26: metal connectors connected to conductive fabric

Grooves were also added the top of the fingertip to make room for the connectors. They then sat flush with the top of the fingerbone and did not impede the ABS parts.

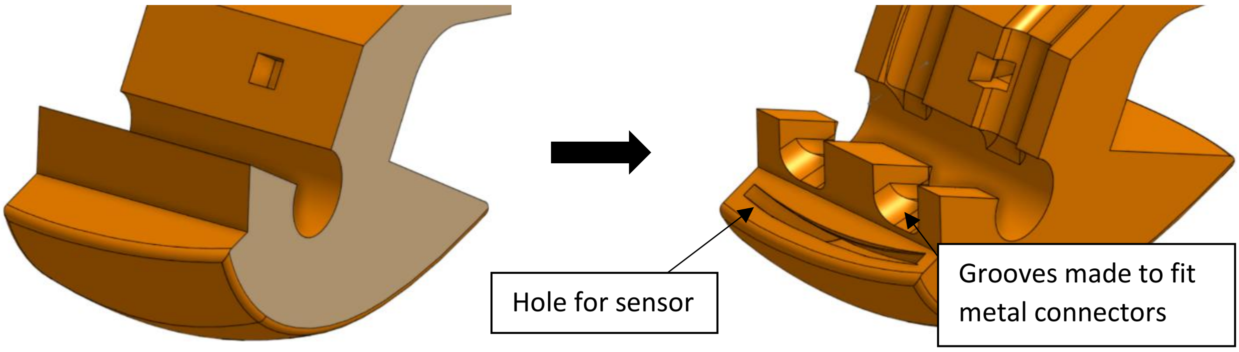


Figure 13-27: Left: original Flexibone, right: modifications made to fingertip

Puck Design

To increase the area over which force could be detected on the fingertip, a puck design was proposed to focus force anywhere on the fingertip to the active sensor area of the sensor. The puck is a small cylinder inside the finger that has a diameter slightly smaller than the active sensor area of the pressure sensor. This puck then sits directly in the centre of the sensor area. The first iteration of this design is shown below:

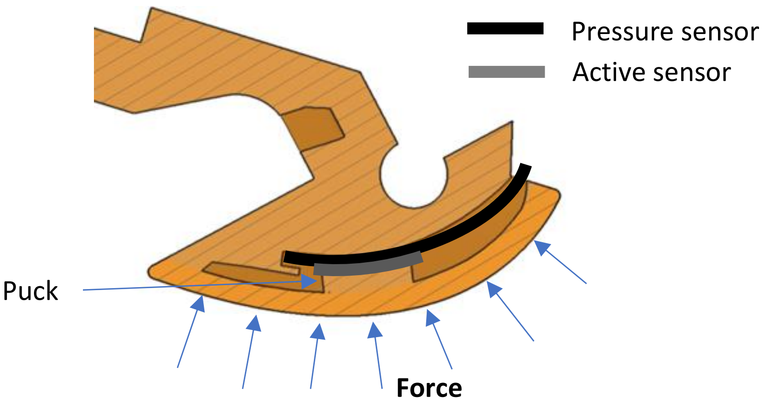


Figure 13-28: V1 puck design

This required many iterations due to tight tolerancing, but the design was successful. The fingertip was now able to detect force over most of the fingertip area.

The pins of the pressure sensor were cut to allow the sensor to be fully concealed within the fingertip. It was then discovered that closer to the sensor area it could only be soldered on one side. This required rotating the sensor 180°. This did not affect the functionality of the sensor, but the inside of the fingertip had to be altered and the puck inverted to accommodate this.

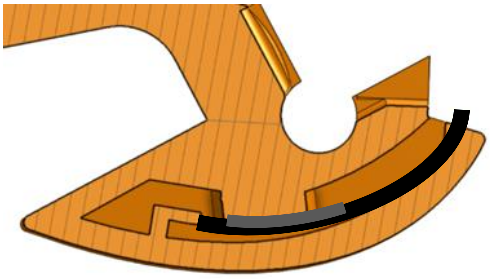


Figure 13-29: V2 puck design, with the puck and lip inverted

13.1.3 Actuator Choice (PB)

Positional rotational servo motors were chosen for the final design. In this section, a comparison of different motor types will be given, and finally the reasons why positional rotational servos were chosen for this project. Four options were considered due to their high precision, high force and compact design: positional and continuous servo motors, linear actuators, and linear servo actuators.

Servo motors are electric motors that push and rotate, typically used in tasks where a specific position needs to be defined. When a servo motor is given a PWM command, it moves to the specified position and holds it there with a resistive force. A servo motor can be rotational or linear to control angular or linear positions. They are used with controllers to give closed loop control and feedback, are highly accurate, and used for precision tasks.

Linear actuators are widely used to provide a linear movement in a wide range of applications. The direction of the movement can be regulated by using a switch that reverses the motor wiring. They typically come with gearing that alters speed and force, with the force decreasing as speed increases.

Type	Description	Example implementation
Positional Rotational Servo	Rotates within a 180° range. They have a built-in mechanical stop to prevent the motor moving beyond its preset limits.	Toys, robot arms
Continuous Rotational Servo	Can rotate in either direction continuously, without limits. Rather than position, control is set as speed and direction of rotation.	Radio controlled cars, airplanes or helicopters
Linear Actuator	Normally consists of a linear actuator motor, a cylinder housing a tube and a lead screw attached to a nut which moves back and forth along the cylinder, creating the motion. Similar profile to the linear servo.	Robot arms, disk drives
Linear Servo	Like a positional rotational servo, but with a rack and pinion to convert rotational to linear motion. It is also like a positional rotational servo in that it has set limits.	Robotics, retractable landing gear for planes and helicopters

Table 13-1: Different Motor Options

Below is a comparison between four commonly used linear actuators and servo motors, they were chosen because they are quite representative of the broader market. They demonstrate the advantages and disadvantages of each type (see Appendix M for further detail).

Name	**Type**	**Max Speed**	**Max Force /Torque**	**Holding Force**	**Max Dimensions (mm)**	**Mass**	**Input Voltage (V)**	**Price (euro)**
Actuonix L12-R Micro Linear Servo (50mm)	Linear Servo	25mm/s	22N at 25mm/s, 42N at 13mm/s & 80N at 6.5mm/s	200N	111x18x15.1	40g	5.0 - 7.5	70
Actuonix L12-R Micro Linear Servo (30mm)	Linear Servo	25mm/s	22N at 25mm/s, 42N at 13mm/s & 80N at 6.5mm/s	200N	91x18x15.1	34g	5.0 - 7.5	70
Hitec HS-85BB Servo Motor	Positional rotational Servo	0.14s/60°	3.5kg/cm	N/A	29x13x30	21.9g	4.8 - 6	17.79
HS-5585MH Servo	Positional rotational Servo	0.14s/60°	17kg/cm	N/A	40x20x38	59.5g	6 - 7.4	57.84

Table 13-2: Motor comparison [Actuonix & Robotshop]

Positional rotational servo motors were chosen for the following reasons:

- Positional rotational servos can complete their full range of motion in 0.42s, almost three times as fast as a 30mm linear actuator. At its fastest speed it also provides a low force. To provide its peak force, the linear actuator must slow down from 18.5mm/s to 6.5mm/s. With a contraction length of approximately 30mm, this would take 4-5 seconds, which is highly unresponsive for the user.

  Grasp speed should be fast enough for smooth operation of the prosthesis. In a human hand, finger flexion was found to be between 170 and 200 degrees per second [88]. Commercial hands are typically slower, at 60-103 degrees per second. This correlates to a hand closing time of between 1 - 1.5 seconds [89].

- Linear actuators have a high maximum force; however, servo motors torque capabilities generally increase with cost and/or size. Servos are also easily upgradeable should the torque be too low to contract the fingers effectively.

- Positional rotational servos are generally cheaper, and as the team had a target material cost of lower than €200, linear actuators would be too expensive, with two costing €140 - 70% of the budget.

- Linear actuators are longer than servo motors, but the width and height is comparable. The long length is not necessarily an issue, however other components may need to be built in series with the actuator such as a whippletree and tensioner box which would use a lot of space on the gauntlet. These mechanisms could be built into a pulley for a servo motor, which could be a more efficient use of space.

A positional rotational servo would need the pulley to transmit the torque, and this would need to be dimensioned to allow the full contraction of the finger. At this stage in the project, the team did not know what the maximum contraction length would be. Having chosen the Flexibone Hand V2 design, the team knew the contraction of the index finger, which was 27.9mm. Due to this, it was uncertain what size actuator was needed without any force calculations or contraction lengths. As a result, a servo motor was deemed to be a better solution as the contraction length could be easily altered by 3D printing a new size of pulley.

The Hitec HS-85BB servo motor detailed in Table 13-2 was chosen for the first prototype. It presented a moderate torque, low weight and size, and had a low price point – all of which were ideal for this project. Two servos were to be used, with one attached to the index finger and thumb, and the other to the remaining three fingers. This was to increase the overall torque provided to the system, and to increase the number of possible grip patterns - i.e. turning off the 3-finger servo would allow thumb and index pinching. A precision grip, when an object is held between only the tip of the index finger and the thumb, and a power grip, when the fingers oppose the palm, are the most used grips in daily household activities, used approximately 70% of the time, at an even split [90,91]. Therefore, having the ability to switch between these grips could increase the functionality of the device greatly.

13.1.4 Circuit (PB)

A combined circuit of all developed electronic components was drawn using EagleCad. This was then used to prototype the circuit.

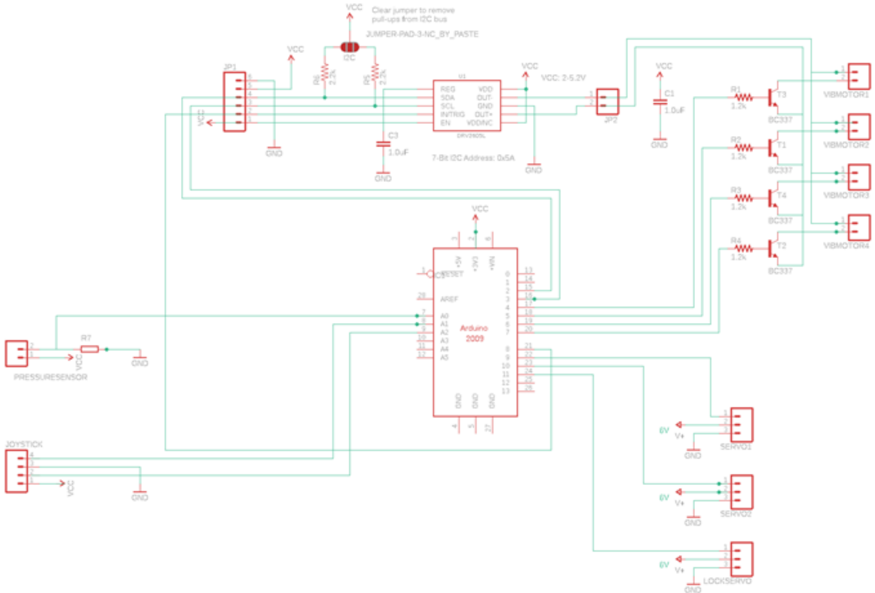


Figure 13-30: Schematic

An Arduino Uno was used throughout the initial phases of the project for its ease of use, but for the combined circuit and full prototypes an Arduino Micro was used as it was more compact and provided the same functionality with the required number of pins for the design.

A first prototype was designed using a compact 50mm x 32mm prototyping board to limit the overall size of the circuit. Unfortunately, the small size of the board meant that short circuits were hard to detect, and as a result it did not work, even after rigorous diagnostics. As the team were running out of time before the second interview, it was deemed better to simply rebuild the circuit using larger prototyping board and jumper wires.

The new circuit used a much larger board with a larger pitch between holes. This meant that short circuits were far easier to detect. Headers were used to easily plug/unplug components, including the Arduino, haptic driver and all jumper wires to the joystick and pressure sensor. The servo motors could also be easily unplugged. Both iterations of the circuit are shown in Figure 13-31.

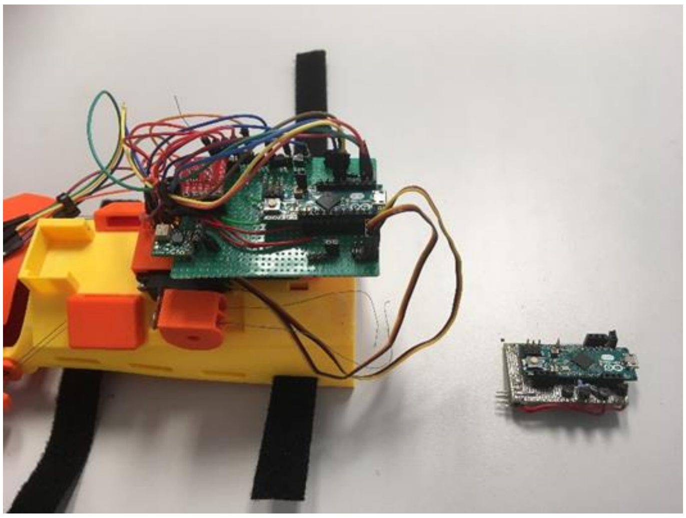


Figure 13-31: Left: redesigned large circuit used in first prototype. Right: Faulty, compact circuit.

13.1.5 Code (PB)

In the same manner as the circuit, all relevant code was compiled into one master code, with the goal of making it is as simple and readable as possible. Using the code, it is possible to customise the functionality of the joystick. The proposed configuration is shown below:

Figure 13-32: chosen joystick configuration for the first prototype

The chosen configuration was to have abduction close the fingers, and adduction open. It made the most sense to have open and close in opposing directions to be intuitive, and as it was uncertain if flexion would be easy for the user, these two directions were chosen. Furthermore, moving the residual thumb joint towards the inside of the palm (and therefore the object) to close the fingers seemed the most intuitive, and hence this configuration was used in the first prototype.

In terms of the thumb flexion being used to toggle between grip patterns, the team were uncertain if the user would be able to use this effectively, as they may move their residual thumb out of the joystick attachment. There would either need to be a very tight fit for the joystick to move with the residual thumb, or a way for them to grip the joystick in this direction. As the joystick had not been trialled and proven as a means of control yet, it was not included in the first prototype.

In terms of thumb extension and turning the control on and off, it seemed highly feasible. With the locking mechanism in mind, a section of code was originally added that allowed the servo motors to be turned off once the mechanism was triggered.

```
// Thumb extension in joystick X-axis toggles servo control and locking mechanism ON and OFF
if (joyX > 700) {
  delay(500); // delay for debouncing and to avoid accidental double clicks
  togSwitch = togSwitch * -1;

  if (togSwitch == 1) { // if ON, re-attach servos and unlock
    servoL.attach(12);
    servoR.attach(11);
    lockServo.write(unlocked); // locking mechanism servo move to unlocked position
  }

  else if (togSwitch == -1) { // if OFF, detach servos to save power and avoid accidental movement
    lockServo.write(locked); // locking mechanism servo move to locked position
    delay(250); // delay for mechanism to move before detaching
    servoL.detach();
    servoR.detach();
  }
}
```

Figure 13-33: locking mechanism Arduino code

As this locking mechanism was removed from the overall design (see section 13.2.7), it was altered to only turn off the controller and leave the servos on. This simplified the code to the following:

```
if (joyX > 650) {
  delay(500); // delay of 0.5s for debouncing and to avoid accidental double clicks
  togSwitch = togSwitch * -1;
}
```

Figure 13-34: Simplified Code

The servo control then only initiated if the value of the integer 'togSwitch' was +1. The small delay after the switch is triggered provides debouncing, which ensures that multiple clicks are not registered simultaneously and therefore the device does not end up in an undesired state.

The pressure sensor haptic feedback code was finally added to the control code to complete the compiled code. This required little modification beyond copying it in as its operation is entirely separate, despite operating inside the same main loop.

13.1.6 Motorised Pulley System (SS)

Currently our client, the user, uses a gauntlet that has Velcro straps to secure her forearm to the prosthesis. This often requires assistance to put on and takes time to strap up. We wanted to develop a simpler method of attaching the gauntlet to the forearm that our client could perform unaided. Different concept designs were developed and finally decreased down into two versions (one mechanical and one electronical) and done prototype to show and test on the user. In both prototypes a pulley system and wires were used to secure the gauntlet in her forearm. In this section, the electrically assisted prototype is going to be explained. mechanical solution and other concepts are going to be further explained in section 13.2.9.

The main aim for the electrically assisted motorized solution was to control the movement of the pulley which was attached to a motor to wind and unwind the wires routed underneath the forearm by using a switch.

The prototype with electronically assisted motorized solution and current prosthesis and can be seen in Figure 13-35.

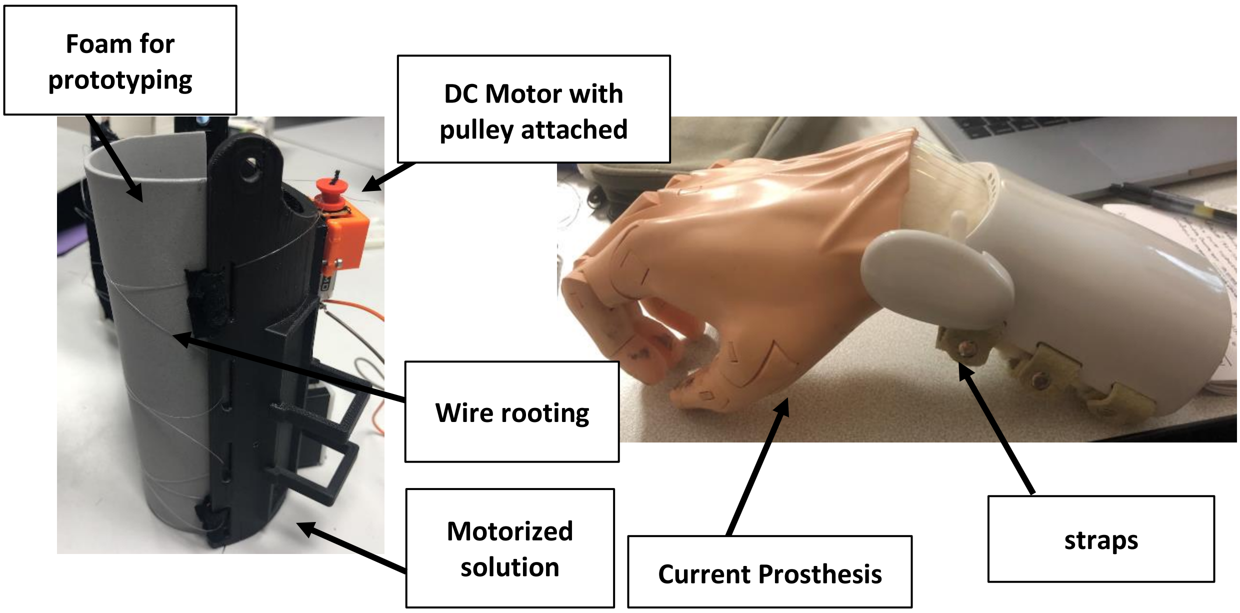


Figure 13-35: shows the current prosthesis and the motorized solution that was being made

For this solution electrical solution, certain components were needed;

- Motor
- Switch
- Motor Driver
- Pulley

13.1.6.1 Component Selection and Design (SS)

Motor

To wind and unwind the wires to tighten and loosen the prosthesis into the forearm, motor was decided to be used. In the selection phase different aspects were considered. Every motor has its advantages and drawbacks. For this gauntlet support application certain requirements were highlighted as;

- To be as small as possible/size
- To have high torque to secure the gauntlet to the forearm.
- Easily secured on the gauntlet with the other electronic parts.
- Work with either 6v or 5v battery
- Budget is considered

Motor performance was broken into three key parameters for selection process.

1. Torque
2. Size
3. Speed

Speed and torque perform as an output which were fundamental parameters to power this application and further influenced the size of the motor. A speed and the torque were the initial selecting constraints for this application.

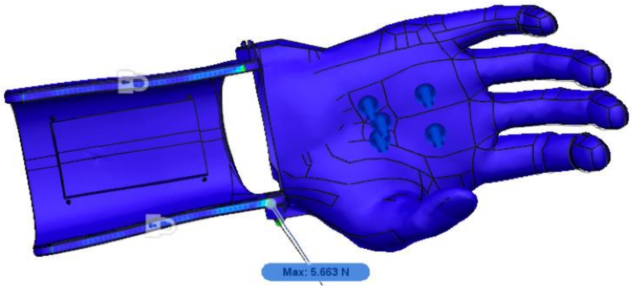


Figure 13-36 shows the reaction force when the 30N load is being applied by FEA analysis

To find the minimum force that the motor should stand, the static load test was made for the user's prosthesis assembly. The reaction force was found as 5.663N when a 30N static force was applied. The weight and environmental impacts were considered so the motor constraints are chosen to be at least to stand 1.5kg. The most likely to happen environmental impact is the wires to get hang up in somewhere.

While the motors were being researched, the motor housing and its integration to the gauntlet were considered to meet the specifications. To utilise the application, the motor was wanted to be less in weight as the allowable weight associated with the prosthesis was aimed to be 500grams.

The DC motor was chosen based on having a high torque and speed characteristic which enables the motor to deal with high resistive torques. Most importantly, DC motors can absorb the sudden rises in the load which is a crucial aspect in the prosthetists' application as it is going to be put on the forearm, and therefore, sudden movements and hits are needed to be overcome besides of wires beings hang up in places. Furthermore, the small versions of the same torque capability can be found in DC motors compared to servo or stepper motors with higher efficiency [92].

Besides the key parameters, as this solution was made for a user and she is going to put it in her forearm, the noise is an important factor to consider while specifying the motor. After looking at the key parameters in the selection process, different motors were being run and tried to select the one with less noise. However, the noise is a subjective factor, so it can be hard to work out the noise limitations are needed for the application for the user [93].

Figure 13-37 shows the JSumo geared DC motor that was being used in this application

The new DC motor of the JSumo core DC motor CORE400 was selected as it has the most power compared to its size. With a shaft diameter of 3mm and total length of 47mm, it delivers a stall torque of 3.9 kg-cm and continuous torque of 1.2kg-cm. It weights 21grams. Also, it has a nominal voltage of 6V and 400 rpm [92]. It is a geared DC motor; the gears increase the torque output while reducing the speed. The data sheet of the motor can be found in Appendix N. Comparison of different motors that were considered for this application can be found in Appendix O.

Switch

To put an on-off-on switch for the motor, the integration of a toggle switch was used. This would allow the user to tighten, loosen and stop the winding of the wire in synch with the motor movement. For this reason, MTS-103 6A 125VAC 3A 250VAC toggle switch, which is illustrated below, will serve the needs [94]. Head of the toggle switch was chosen to be long to help the user easily push it but short enough that it won't stick out from prosthesis body too much.

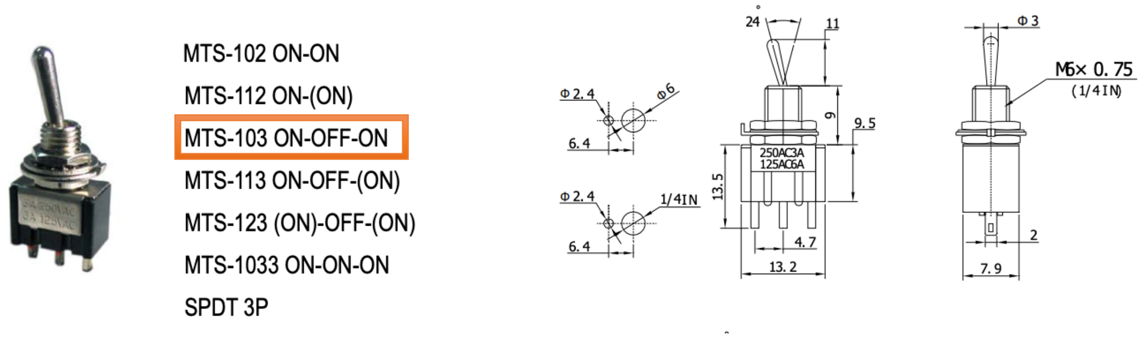


Figure 13-38 shows the selected toggle switch inside the orange rectangle and the dimensions of the toggle switch

Motor Driver

Figure 13-39 shows the motor drives L293D

Motor driver was needed to avoid damaging the members of the circuit while running the motor. To run the DC motor, high current was needed, and this will burn the circuit which works in low current [95]. Different motor drivers were available in the market including L298N, L293E and L293D. Comparison of different motor drivers can be found in Appendix P. The size is the main decision point for this component. L293D was selected for this application as it has dimensions of 20x7.1 mm.

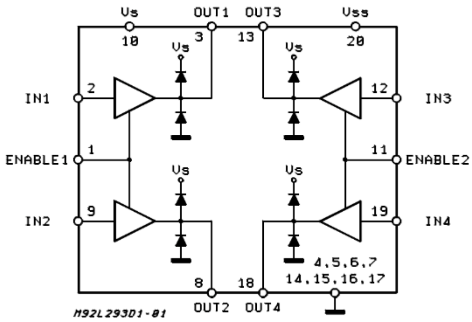


Figure 13-40 shows the block diagram of L293D

By changing polarity of the input voltage, the DC motor's direction can be controlled. For this purpose, an h-bridge is a simple circuit to control a DC motor to go forwards and backwards [16]. Each L293D chip contains two h-bridges which can drive up to two DC motors in both directions. The block diagram of the motor driver is shown in Figure 13-40. It is designed to provide bidirectional drive currents of up to 600-mA at voltages from 4.5 V to 36 V. Both devices are designed to drive inductive loads such as relays, solenoids, DC and bipolar stepping motors, as well as other high-current/high-voltage loads in positive-supply applications [18].

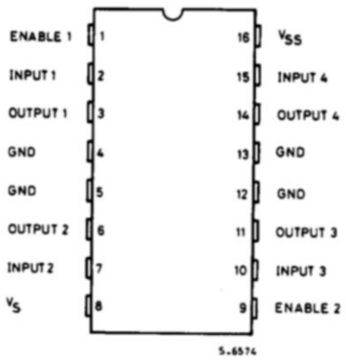


Figure 13-41: shows the pins of the L293D

In Figure 13-41 , the pins of L293 is shown. It has two power input pins. V_{ss} drives the internal logic circuitry which is generally 5V. V_s is the pin which h-bridge gets its power to drive the motors in between 4,5V to 36V. Output pins are to connect the motors whereas input pins are to control the direction of the motors. Enable pins are the speed control pins or turning on and off the motor [96]. The truth table, which is shown in Table 13-3, is used to understand the logic and run the motor.

Input	Enable (*)	Output
H	H	H
L	H	L
H	L	Z
L	L	Z

Table 13-3: shows the truth table

Pulley

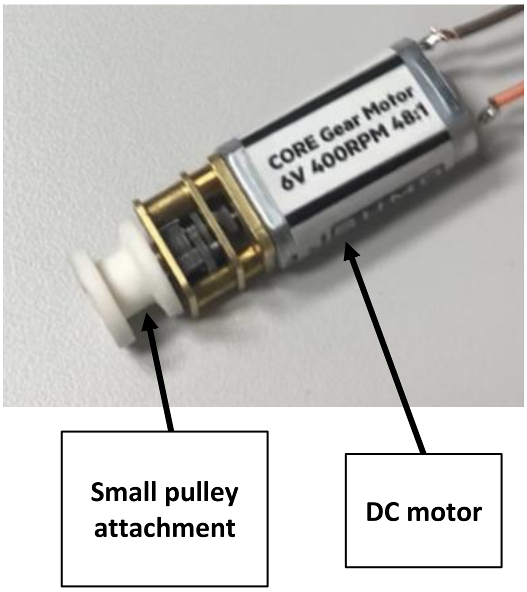


Figure 13-42 shows the pulley attachment to the DC motor

Pulley was aimed to be used to have a place to wind around when the wires are being tighten. As there was not much space on the forearm when the other electronic components were considered, the pulley was designed as small as possible to reduce the space it occupies on the gauntlet. For this reason, the wire rooting was made for the gauntlet which secures the gauntlet to the forearm and by using the 3D printed copy of the user's hand, how much wire was needed on the prosthesis for the user to pass her hand to put on the prosthesis and how much the wire is needed when the prosthesis is secured on the forearm is measured. While measuring the user's 3D printed scan of her hand was used. According to the length of the coil the volume needed on the pulley was calculated and the pully was designed according to it.

Circuit

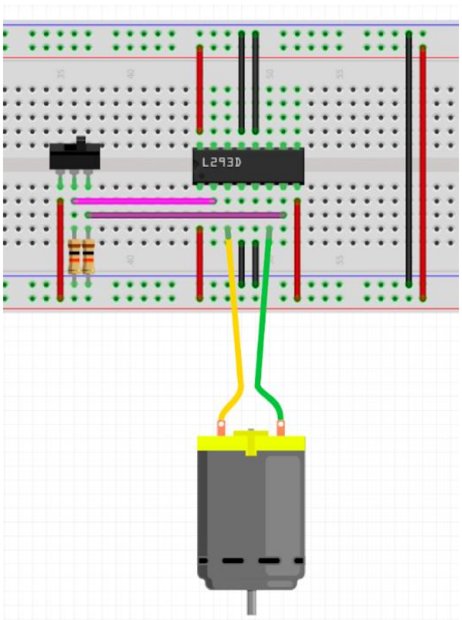


Figure 13-43 shows the circuit for the motorized solution

The toggle switch was connected to the input pins of the L293d whereas motor was connected to the output pins. In between the switch and the ground, the pull-down resistors were used to avoid floating the voltage. If there aren't any pull-down resistors, there will be a short circuit in between input voltage and ground [97]. Pull-down resistors are often being used with the micro-controller but in this case, they are used to prevent fluctuation in voltage which can be quite high and damage the circuit [98].

$$R_{max} = \frac{V_{max} - 0}{I} = \frac{6 - 0}{600 \times 10^{-3}} = 10k\Omega$$

Equation 13-1

10k ohm resistors were used. Resistors pull down the current going through the circuit and 10k ohm resistor consumes 0.33 mA. The resistance provides the required reduction in current [99].

Working principle:

To enable the motor to turn clockwise direction to tighten the wires, the toggle switch is needed to be moved right. To stop the motor, the switch needed to be turned off by moving the switch in the middle. Finally, to enable the motor to turn anti-clockwise to loosen the wires, the toggle switch is needed to be moved left.

13.2 Mechanical

13.2.1 Finger Design (JP)

After the finger force tests outlined in section 8.1.2 were completed it was determined that the Flexibone v2 finger, designed by Philippe Marin and the Gre-Nable community, would be the design that would be carried forward to the next stage and used for the prosthesis. The only parts modelled of the Flexibone v2 design were the index finger and thumb. The middle, ring and little fingers still had to be designed. However, the steps and operations used to create the index finger were easily replicable and could be copied to create the remaining fingers. It should also be noted that the 3D hand model used to create the Flexibone v2 fingers was the model obtained from the Kwawu hand. The same hand that the user currently uses as their primary mechanical prosthesis.

Figure 13-44 shows a brief outline of the design process used to model each finger. The 3D scan of the Kwawu model was used as the base of the design. The Flexibone was modelled first before the whole finger was modelled around it. Once the finger was separated from the Kwawu model is was divided into the three separate bones of the finger, the proximal, interim and distal bones. Finally, a path was extruded through the finger for the fishing wire.

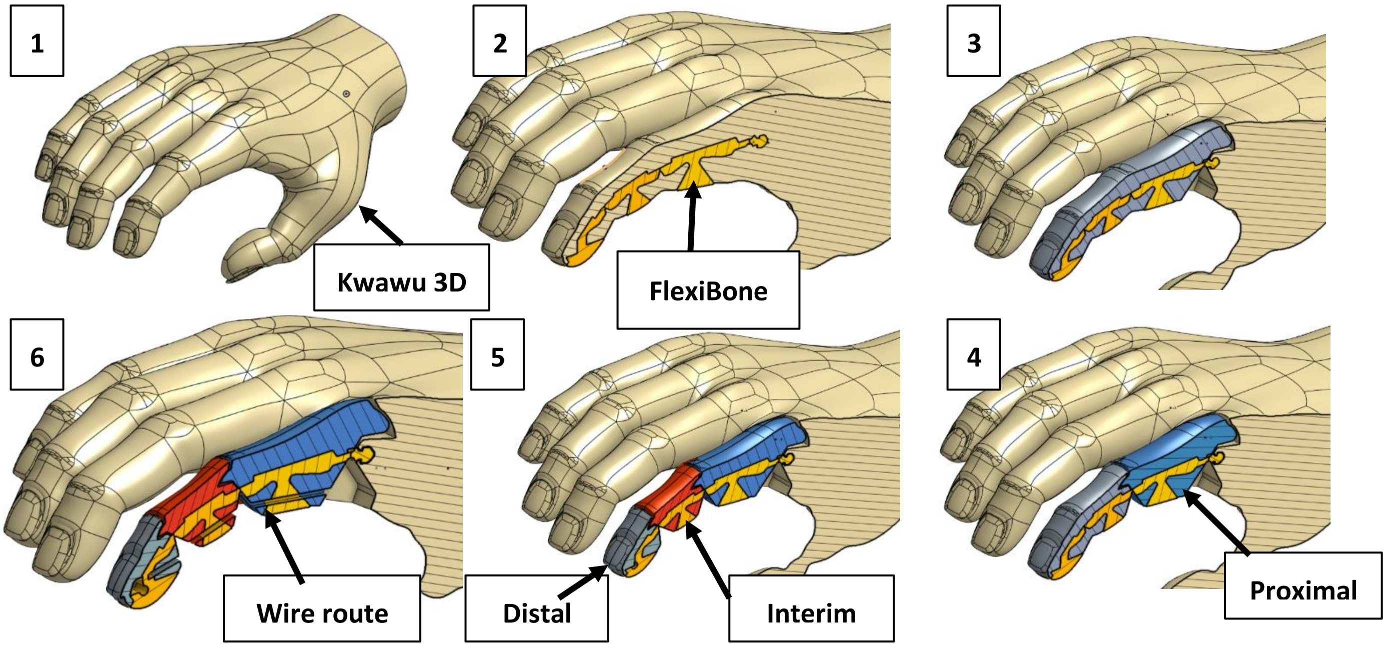


Figure 13-44: Finger Design Process

The internal Flexibone's were always printed as in Figure 13-45 Printing the bone straight but housing it within the casing at an angle provides a restoring force that returns the fingers to their neutral position after contraction.

Figure 13-45: Internal Flexibone

The blue part of Figure 13-46 represents the Proximal bone, the red part the Interim bone and the grey part the Distal bone. Each of these parts were 3D printed using ABS plastic as it is a suitably hard and durable material. The internal Fflexibone was printed using Ninjaflex material due to its flexibility. The intersections between the three bones represent the finger joints. Here the Flexibone is considerably thinner allowing for easier rotation, as well as there being a cut out of the casing to allow for rotation. At the top of the joint there is a small claw-like extrusion. This is in place to ensure the top of the joint is concealed during rotation.

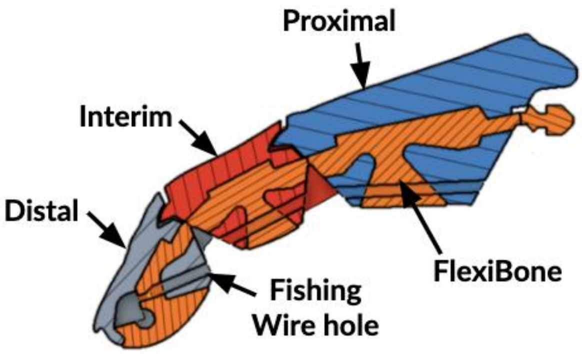


Figure 13-46: Section view of Index Finger

To connect the finger to the palm a hook was modelled into the finger bone, Figure 13-47. This is a very tight fit, so the finger cannot fall out of the hook hole in the palm. Figure 13-48 shows the hook puller holes. To get the Flexibone hook into the palm hook hole fishing wire is passed through the puller holes and the bone hook is then pulled through with a lot of force until it is secured in the palm hook hole.

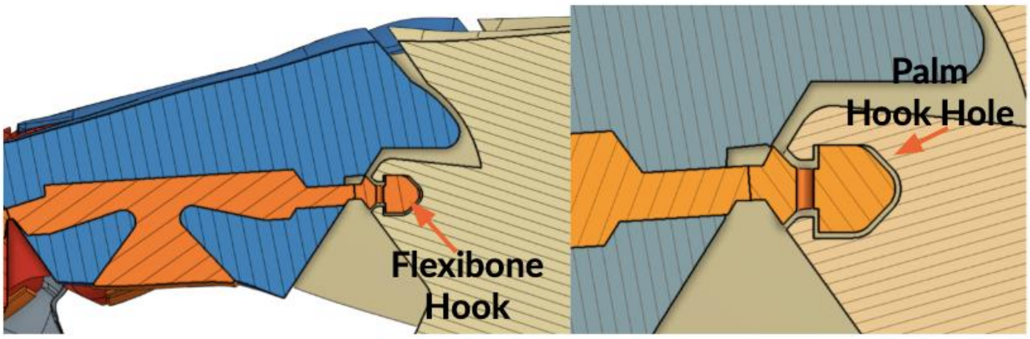


Figure 13-47: Flexibone Hook

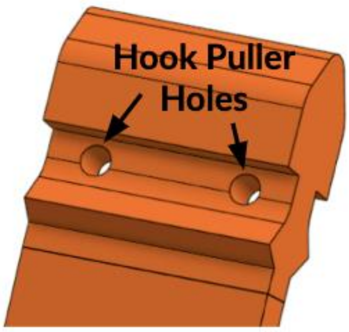


Figure 13-48: Flexibone Hook Puller Holes

13.2.2 Wrist Joint (TE)

Current open source mechanical prosthetics use the movement and force of the user's wrist to actuate the fingers. This is achieved by having the fishing wire tendons exiting the palm from the back of the hand to then connect to the gauntlet. The fishing lines are therefore a distance away from the rotation axis in the wrist joint. When the user moves their wrist, the palm rotates through an angle around the gauntlet. This increases the path length of the fishing wire tendons route to the finger. As there is an exact length of fishing wire for each finger, this change in path length causes a tension force on the fishing line hence contracting the fingers. A diagram of the mechanical actuation is shown below in Figure 13-49 and Figure 13-50 .

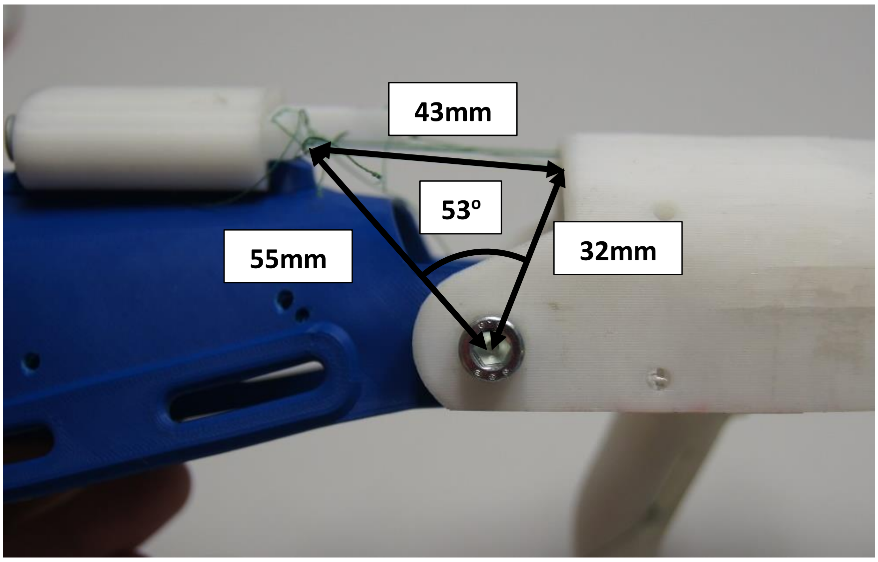


Figure 13-49: Phoenix Hand in Natural Position

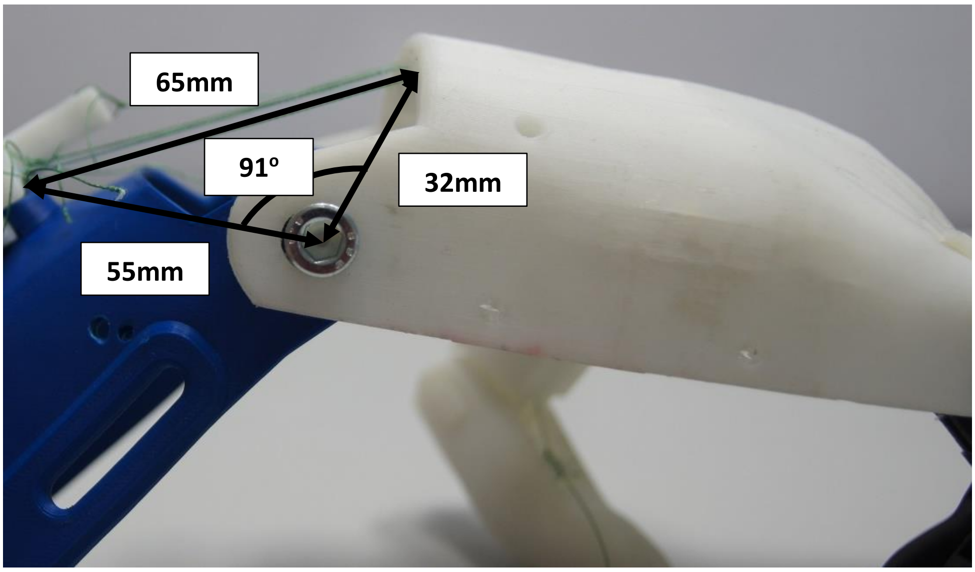


Figure 13-50: Phoenix Hand in Contracted Position

The product being developed does not use mechanical actuation to contract the fingers but instead uses the electronic method of servo motors with pulleys. Therefore, for accurate control of the fingers no change in tension is wanted when the wrist is moved. The initial idea was to constrain the user's wrist so that the fishing lines path could not be changed. However, this was heavily advised against, with the user explicitly saying that wrist movement was important during the first interview.

The solution therefore was to change the routing of the fishing wire to go through the wrist joint. This would mean that the fishing wire would go directly through the axis of rotation, therefore not creating an additional path length in the fishing wire when the wrist is bent. It would also allow the user to not have their hand in an awkward position when they had grasped the object but instead freely be able to move their wrist without effecting the objects grasp.

Version 1

To design the new wrist there were key design considerations implemented, which were:

- The fishing line routing must go through the wrist joint.
- The dimensions of the wrist joint should be as compact as possible.
- The joints must have room for PTFE tubing. This was due to the results of the friction test in section 8.2 showing that the use of the tubing halves the friction in the system.
- Individual tubing for each fishing line tendon must be used to ensure the lines don't get tangled, there is no additional friction generated through contact of the fishing wire with one another, and tensions produced within each line don't affect each other.
- The left side will have two routes for the index finger and thumb, while the right side will have three routes for the middle, ring and little fingers.

The initial version of the wrist joint can be seen in Figure 13-51. It was based off the wrist joint of the Kwawu model, with the thickness of the joint becoming 10.5mm on each side with a split in the middle to allow the wire to pass through. The routes had a diameter of 2.5mm to allow the 2mm PTFE tubing to fit inside. They were positioned vertically in the joint to keep the width as thin as possible.

Figure 13-51: Vertically Aligned Holes Wrist Joint

During the design it was decided that the pin to assemble the palm to the gauntlet would also be changed so that the routes would go through these as well, while making them stronger as the current split method snaps easily. The new pin would be solid including holes with the same dimensions and spacing as the wrist for the wire routes. The pins will then have a pin cap to secure the palm and gauntlet assembly together. The old split pin and new pin and cap can be seen below in Figure 13-52.

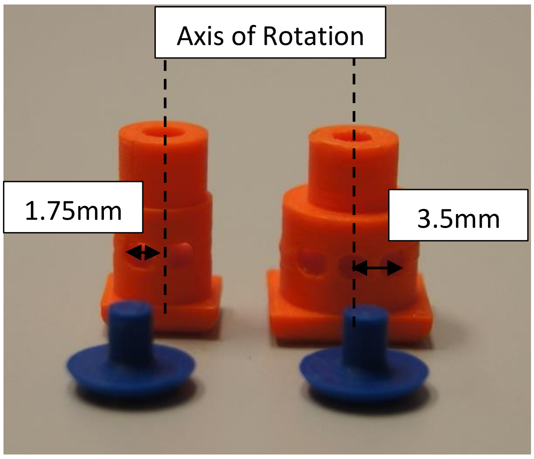


Figure 13-52: Left – Phoenix Hand Wrist Joint Pin, Right – Designed Wrist Joint Pin and Cap

Once assembled the new wrist joint was tested to see the effects of the new routing on the tension in the fishing line. This was achieved by assembling the wrist to an existing gauntlet with the new pins. Fishing line was then threaded through the routes and attached to the gauntlet, constraining one end. The gauntlet was then clamped so it was fixed in position and the other end of the fishing line was constrained to a fixed object, leaving the wrist free to move.

When the wrist was rotated there was a large amount of resistance from the fishing line as it was fully constrained. The fishing line was forcing the wrist to return to its original position, indicating that it was changing the tension within the line when rotating. The cause of this change in tension was due to 4 of the holes not lying directly on the axis of rotation as shown above. Even though the displacement was only 3.5mm and 1.75mm on each side of the wrist, it still had a noticeable effect on the tension reducing the total control of the finger actuation system.

Version 2

After evaluating the problems with the first version, key design changes were altered to the wrist joint. Firstly, the spacing and size of the routes remained the same for the PTFE tubing, however they were positioned horizontally and not vertically to all lie along the axis of rotation. The width of the wrist therefore had to increase on both sides of the palm to 17.5mm and 14mm as shown in the image below in Figure 13-53.

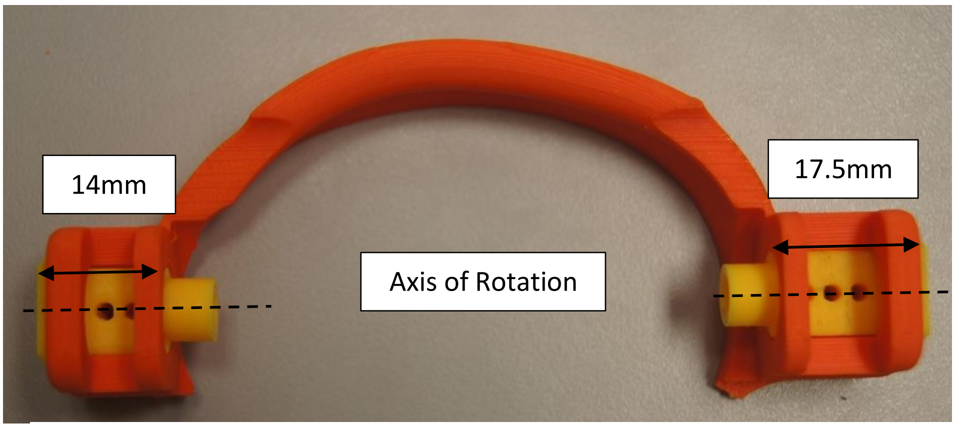


Figure 13-53: Updated Horizontally Aligned Holes in Wrist Joint

An additional change was made to the pins to ensure that point of rotation for the fishing line lay directly on the axis of rotation. In the previous version the pin diameter was offsetting the rotation point by the radius of the pin. The pin was therefore split in half removing 5.5mm from the side where the fishing line leaves the wrist joint to the gauntlet. The updated pins are shown below in Figure 13-54.

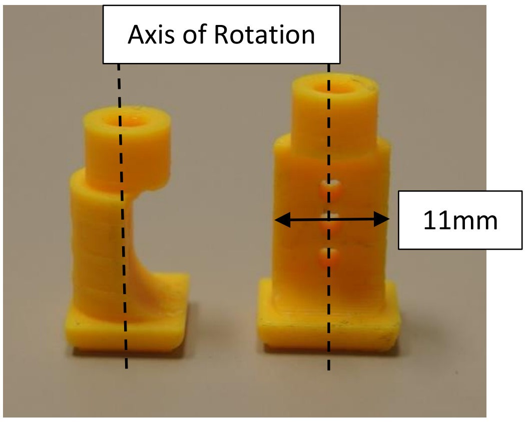


Figure 13-54: Halved Wrist Joint Pin

The tests on the wrist joint were carried out again on the updated version both with and without PTFE tubing going through the joint. The changes had achieved the desired result, the wrist could freely move in both cases with no change in the fishing wire tension. The wrist would also remain at the angle moved to as there was no tension resisting its motion.

Final Version

When implementing the design into the prototype for the palm a route was needed for the wires from the electronics in the palm to get to the Arduino on the gauntlet through the wrist. A third hole was therefore added to the left side of the wrist with a diameter of 4mm to allow wires for the joystick and pressure sensor to travel through. The thickness of the left side therefore had to increase to 19.5mm to accommodate for the new route. The final wrist design is shown below in Figure 13-55

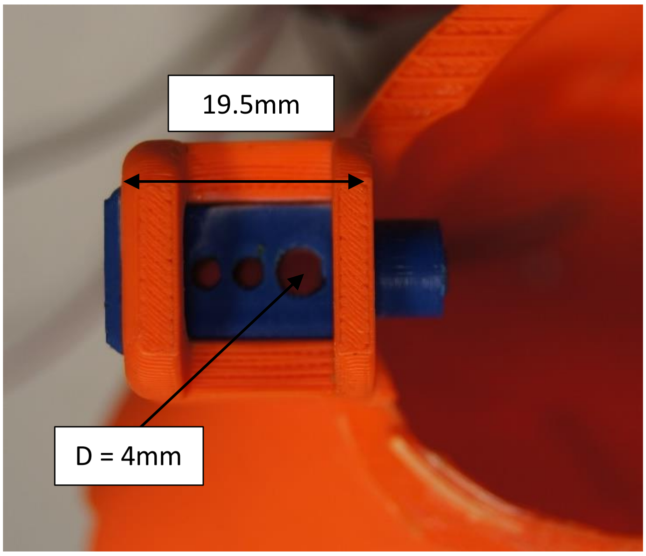


Figure 13-55: Wrist Joint with Added Wire Route

13.2.3 Fishing Line Routing Through Palm (TE)

The fishing line tendons from each of the fingers need a path to the actuation system located on the gauntlet. Classic mechanical devices have the routes going along the back of the palm to reach the gauntlet. However, due to the new routing through the wrist, explained in section 13.2.2, paths from the fingers to the wrist joint through the palm needed to be designed.

There were three key design considerations implemented for the routing through the palm:

1. The geometry of the path should contain as shallow angles as possible to reduce friction in the system, as shown by the friction test results in section 8.2.
2. Diameter of the route must be 2.5mm to allow the use of PTFE tubing because of the friction test.
3. Must be constrained within the thickness of the palm, therefore not to impede with the user's hand and to not have external veins as the 2018 model does as seen in section 2.

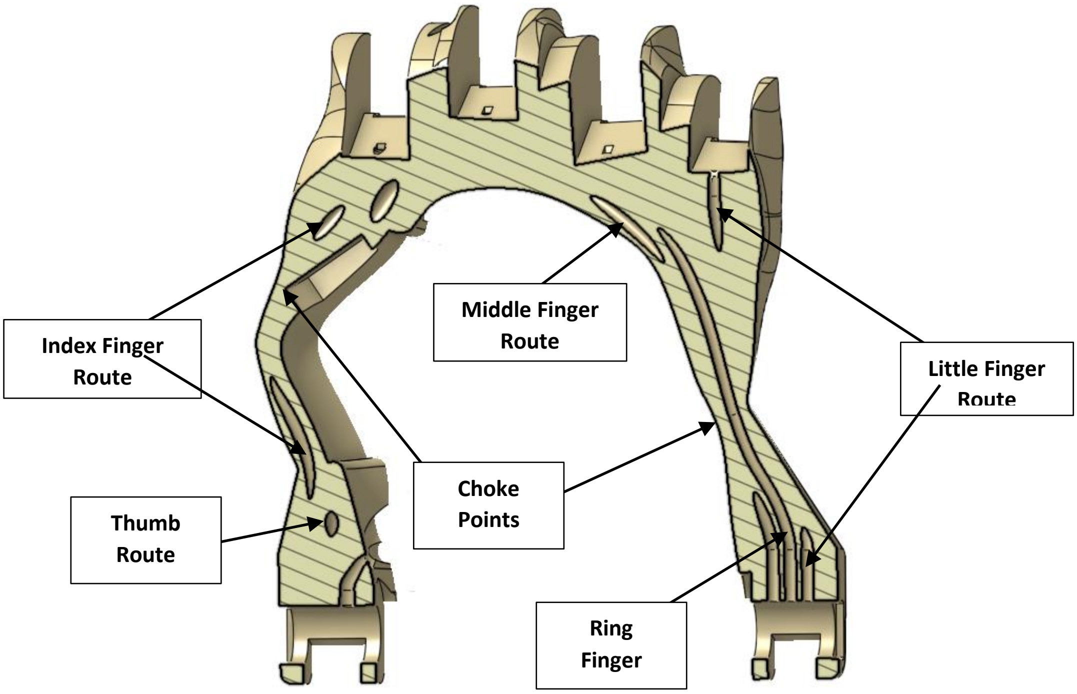


Figure 13-56: Section view of Palm Highlighting the New Fishing Wire Routes

Consideration number 3 was the driving factor when designing the routing. The palm model had areas where the thickness could not contain the 2.5mm routing, therefore dictating where it had to go. The key areas which created choke points that constrained the routes; where the joystick cut out as mentioned in section 13.1.1 and where the wrist joint merged into the palm. Three routes had to go through the right side for the middle ring and little finger from the wrist, and two routes along the left to the index finger and thumb, as seen in Figure 13-57.

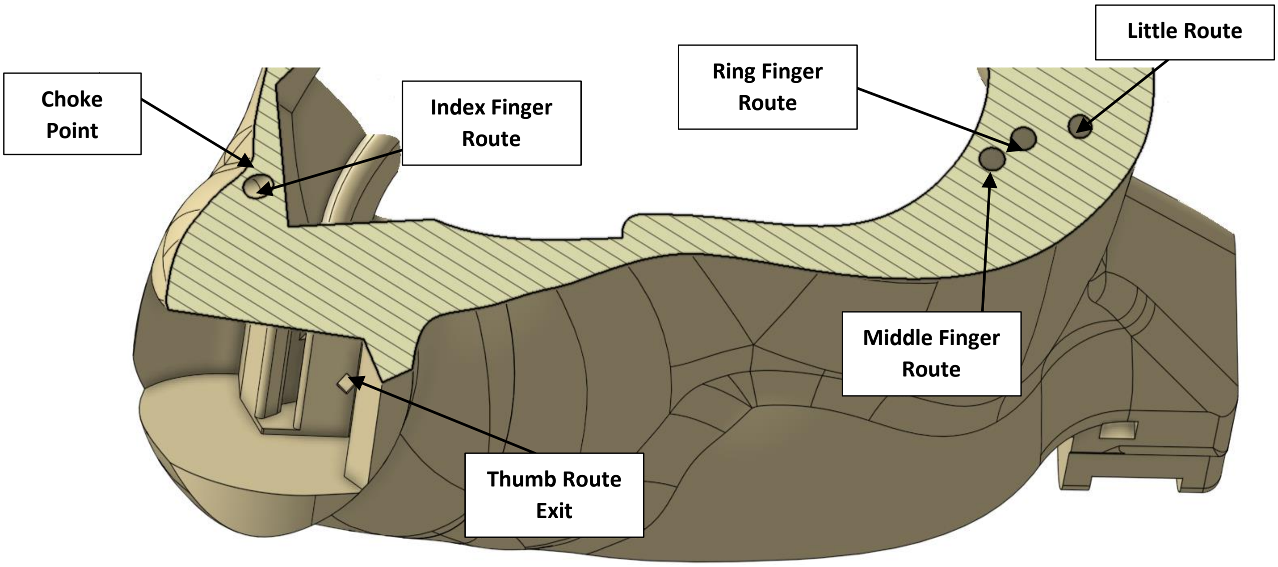


Figure 13-57: Top Cross-Section View of the Palm with New Wire Routes

13.2.4 Ninjaflex Palm Edge (TE & SS)

Version 1 (SS)

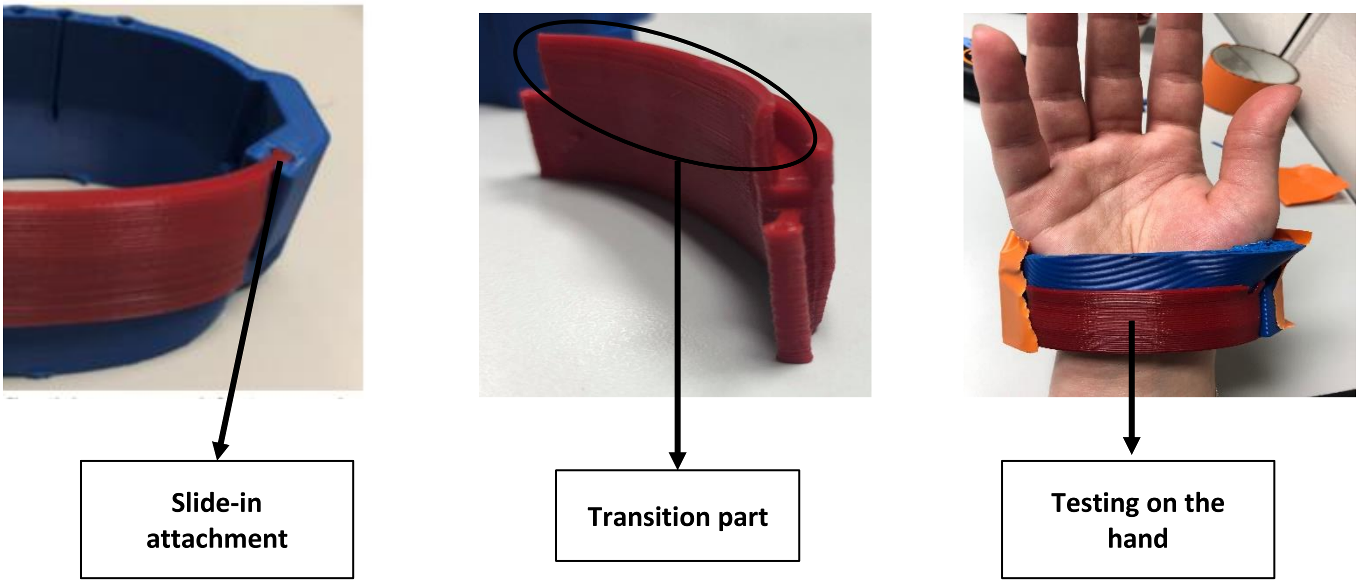


Figure 13-58: shows the flexible palm addition

In the first interview with the user, they mentioned that while moving their hand the lower part edge of the prosthetic palm was digging in and hurting her hand during wrist movements. A replacement of the lower part with a flexible part was therefore proposed.

The attachment was made by sliding the flexible part into the prosthetic palm. The flexible part's design was made by using the last year's palm design. Further, the palm's bottom part was cut down and flexible part was decided to be put. There was a transition point in between the ABS material and the flexible. To have a smooth transition, the flexible part is also extruded inside the palm.

Part of the current prosthesis' palm was printed with the addition of the slide-in part to further try and test on the hand. The flexible part was put on try.

The end part of the flexible part was decided to be decreased in thickness. In this way the wrist and forearm movement were improved. The transition part was left thick so that the edges of the palm wouldn't hurt the user.

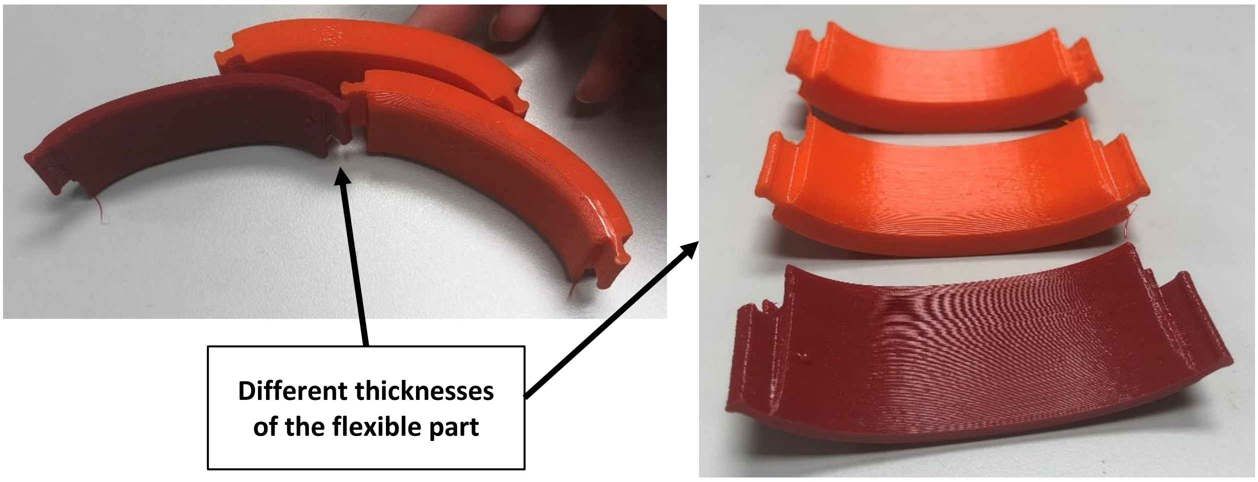


Figure 13-59 shows different versions concepts of the flexible palm addition

The flexible part for the palm wanted to be tried on for testing purposes. The 3D printed palm part was cut to put around the arm more properly. Then the remaining part is put around the hand and taped tightly. By moving the wrist, it is observed how it feels. Printed parts were compared, and it was clearly seen that decreasing the thickness improves the comfort in the movement of the wrist and it was seen that the ABS part no longer hurts the hand and it was comfortable.

<u>Ninjaflex Palm Edge Final Version (TE)</u>

Analysis of the first prototype was carried out to see how the new palm edge would affect the rest of the palm model. There were potential issues raised on the way that it was modelled, and the modifications that were made to the palm to allow the design to work. These were:

a) The location of the wrist joint was moved further away from the palm. As the palm's length had been extended the idea was to constrain the full length on the flexible part. Additional support was needed on the ABS and, therefore moving the wrist joint created this support. However, moving the wrist joint meant that the axis of rotation was being moved away from the palm as well. The axis of rotation of the prosthetic's wrist and the user's wrist would no longer line up. This change could impede the user's use of the prosthetic and make it uncomfortable.
b) The attachment method of the Ninjaflex palm was to use Ninjaflex hooks to slide into a slot in the palm of the same geometry to create a tight fit. However, to make a hook large enough to print there was not enough thickness in the palm model to fit the slot for the hook. The opening to the palm was therefore thickened to allow the assembly of the palm. The thickening of the palm however could cause a potential problem for the user. The opening to the palm had decreased in size meaning it would have been tighter or maybe not possible for the user to insert their palm into the prosthetic.

Because of the problems highlighted a new design was developed. The main design aim was not to change the location of the axis of rotation of the wrist or the geometry of the palm opening to avoid any problems for the user. The Ninjafelx palm edge was designed by cutting the palm edge up by 5mm and creating a new part that had the exact same geometry as the removed edge, therefore sitting flush with the rest of the palm. The Ninjaflex palm was then extended by an extra 5mm at an angle of 10^{o} and was not attached the ABS palm to allow it to bend freely with the movement of the user's wrist. See Figure 13-60 for the final printed part.

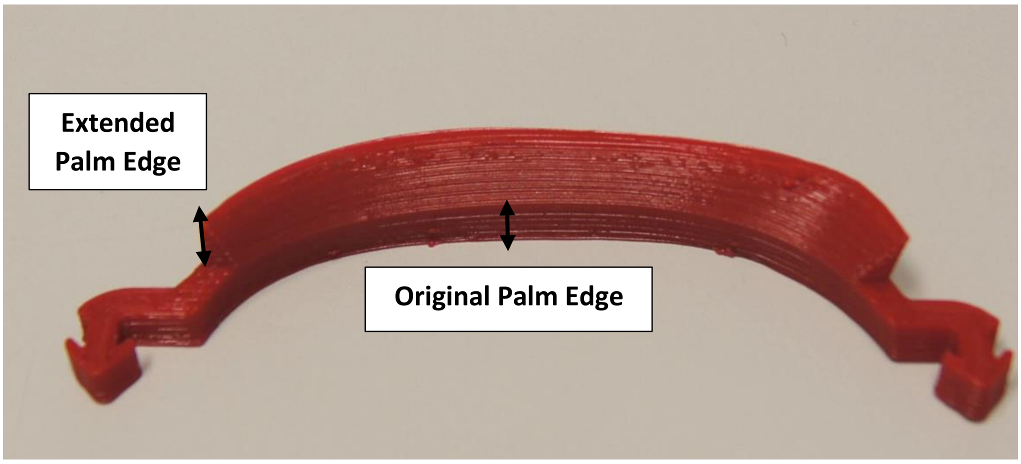


Figure 13-60: Final Ninjaflex Palm Design

To attach and locate the Ninjaflex palm to the ABS palm a secure fit method with location edges along the palm edge were used. The secure fit method was achieved by using flexible arrow heads to be inserted into a hole in the wrist joint as seen below. Due to the arrow head being flexible, it's edges would compress inwards when being inserted into the gap. However, once inside, the arrow edges would uncurl into the larger space therefore stopping the flexible palm from being removed. This method was chosen due to there being additional space in the wrist joint. This method therefore meant no alterations had to be made to the opening of the palm allowing easy entry for the user's palm. Location ridges were placed along the edge of the ABS to insert into the Ninjaflex palm therefore lining up the two palm edges to be flush, as seen below in Figure 13-61. These two palm edges can then be glued in place to maintain firm contact and position.

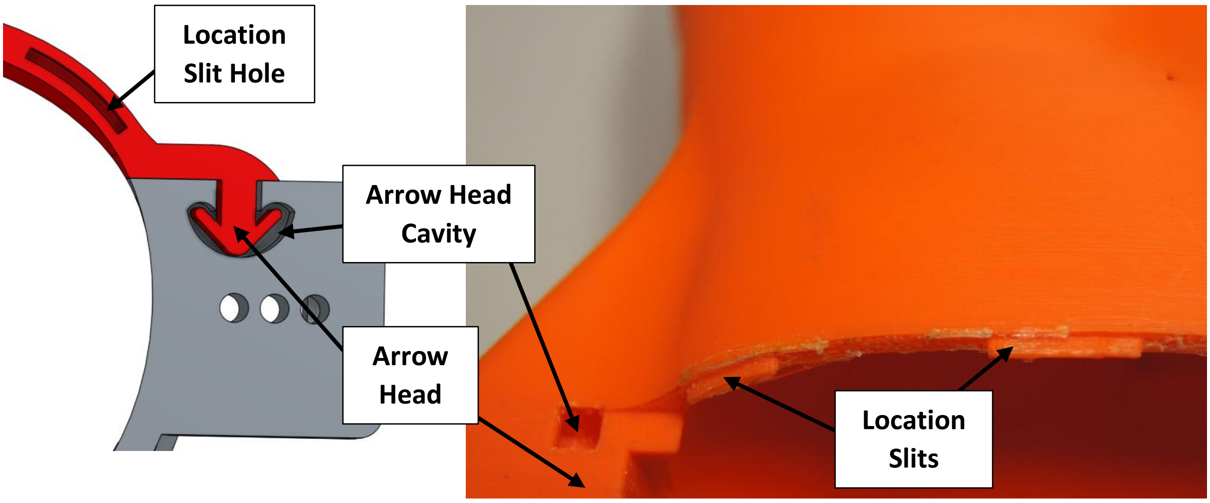


Figure 13-61: Ninjaflex Palm Edge Location Slits and Assembly Holes

13.2.5 Palm Liner (JP)

It was necessary to make an internal liner for the palm that would provide support and comfort for the user's residual palm. The material must be/have:

- Comfortable
- Easily modified
- Attachable to Velcro
- Less than 6mm thick
- Wicking properties to disperse sweat

The material chosen was Tissu3D, Figure 13-62. This material satisfies the above criteria and it was also readily available to the design team. It was also previously used to make a similar liner for the user that they use regularly with their current mechanical prosthesis. So, it has been confirmed to work well.

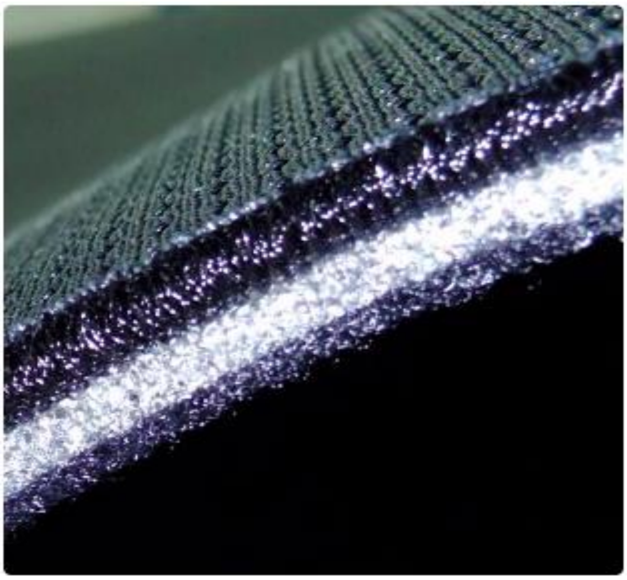


Figure 13-62: Tissu3D [100]

A commercial prosthesis liner could have been purchased. However, these liners are often designed to fit a large range of people and therefore it was not optimal to purchase one of these liners because it may not be a suitable fit. It could possibly restrict blood flow to the user's residual palm if it was too tight and, they are generally expensive to purchase. Hence, it is more practical to design and make the liner oneself, as it would then be tailored exactly to the dimensions of the user's residual limb.

The liner was made by taking a section of the Tissu3D fabric and cutting it to the shape of a 3D printed model of the user's residual palm. Hence, it was possible to tailor the liner to the exact dimensions required, see Figure 13-63. The material was simple cut into shape using scissors and sewn together using a needle and thread. A cut out was also made for joystick.

Figure 13-63: Palm Liner

The external material is fluffy and can therefore be attached to Velcro pads and the internal material has good wicking properties and can therefore wick away sweat.

The idea was for the liner to be attached to the inside of the gauntlet by thin sticky-back Velcro pads which line the inside. These sticky-back Velcro pads will hook onto the fluffy external material of the liner holding it in place. This means that the liner can be easily removed if it is necessary to check any of the electronics inside the palm. It also makes it easily removable for washing.

13.2.6 Pulley Design (PB)

As servo motors had been chosen as the actuators, a pulley was required to transfer the torque. The servo motor rotates through 180 degrees, and consequently half of the circumference would need to equal the maximum length of the fishing wire to fully contract the finger(s), where $Circumference = 2\pi * radius$. The contraction length of the index finger was 27.9mm (section 8.1.2) and therefore a pulley diameter of at least 17.8mm was required for full contraction.

The chosen diameter was 23mm to provide some tolerance but to be kept close to the minimum dimensions to limit overall size of the device. Using the torque output from the Hitec HS-85BB Servo Motor chosen in section 13.1.3, at 3.5kg/cm, the total force can be calculated using Equation 13-2.

$$Torque = Force\ x\ Radius$$

Equation 13-2: Torque

With a radius of 11.5mm, the total force supplied by the servo motor and pulley is 3.04kg, or 29.9N. With two servo motors, the total force is therefore 59.8N. From section 8.1.2, this should be more than enough to contract all fingers.

<u>Tensioner</u>

A tensioner is a mechanical system used to manually adjust the position of individual or multiple fingers. It is a system included in all e-Nable designs and therefore was an important consideration for this project. The system allows the starting tension of the fishing wire to be adjusted by either tightening or loosening a machine screw [101]. Square pins fit into square slots, and the screw is then threaded through a hole at the end of the slots and threaded into the pins.

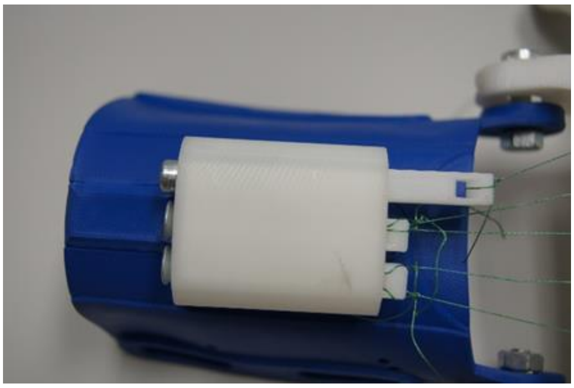


Figure 13-64: Phoenix Hand – Enable Community Foundation with five tensioner boxes.

A similar tensioner box was combined with the pulley design to include this mechanism, although the length of the box was restricted by the diameter of the pulley. The length of tensioning available in the phoenix hand is approximately 25mm. The ratio of fishing line contraction lengths between the Flexibone index to Phoenix index is 27.9mm:34.56mm, or approximately 0.8:1. Therefore, for a similar tensioning ability, the tensioner in the Flexibone V2 would need to be 20mm. Due to the small size of the pulley, this was not possible, and instead only 8mm of contraction was given. As the e-Nable hands are purely mechanical, a direct comparison cannot be drawn. There is also little information on the benefit of this in an electronic prosthesis, however the team found that 8mm was enough to adapt the grip slightly, depending on the user's preference of finger positions. It was also meant as a proof of concept, that it could be combined effectively within a pulley mechanism.

The resulting design can be seen below:

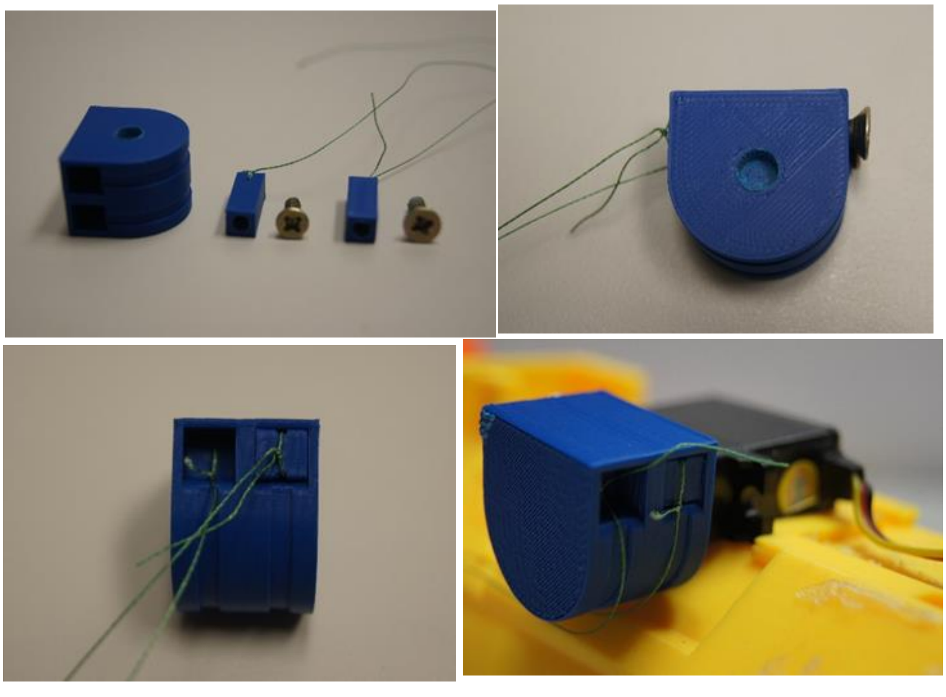


Figure 13-65: Tensioner Pulley Design

Two screws screw into two tensioning boxes inside the pulley. When the screws are twisted clockwise, the box moves further into the slot, pulling the fishing wire tighter. If they are twisted anti-clockwise, it moves out of the slot, creating slack in the fishing line.

To limit the width of the pulleys, only four tensioner boxes were used instead of five and therefore two fingers shared the same tensioner. It was determined that the middle and ring finger would be most appropriate to leave the little finger separate. This was due to its abilities to behave as a support finger, and therefore can be tensioned to flex ahead of other fingers and provide support to the bottom of an object during grasp, for example when holding a bottle.

13.2.7 Locking Mechanism (TE & JP)

Reasons for Locking Mechanism

Currently the user uses a mechanical prosthesis that has a ratcheting mechanism to lock the fingers in place around an object. This is not ideal because the residual palm and wrist must be kept in an uncomfortable position while the hand is locked.

This project is centred around the design being an electronically controlled prosthesis and hence the locking mechanism must be designed in conjunction with the motors that will be actuating the fingers. Having a locking mechanism for this design is beneficial because when the locking mechanism is initiated the motors actuating the fingers can be switched off and this will save considerably on battery life.

There were two options when creating the locking mechanism:

1. A manual locking mechanism that had to be physically moved by the user.
2. An electronically controlled locking mechanism that is linked to whatever control method has been adopted for the design.

Manual Locking Mechanism (JP)

The only real benefit for a manual locking mechanism over an electronic one is that the design will not require any motor actuation. This would almost certainly reduce the devices weight, power consumption and cost. However, it is more difficult to control in conjunction with the motors actuating the fingers.

Concept Designs (JP)

Four concept designs were developed testing different 3D printable methods of locking the wires in place.

Concept 1 (JP)

In this concept (Figure 13-66) the fishing wires pass through the circular holes in the box. To lock the fishing wires in place the key gets pushed down and is itself locked in place. To release the fishing wires the 'key arm' gets dislodged from the groove in which it sits in the box by pushing it through the small rectangular slits in the side of the box.

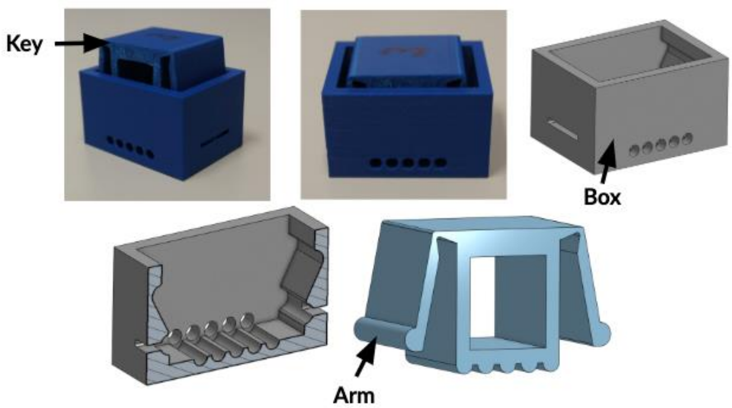


Figure 13-66: Locking Mechanism Concept 1

Concept 2 (JP)

In this concept (Figure 13-67), like concept 1, the fishing wires pass through the circular holes in the box. To lock the fishing wires in place the key gets pushed down and is itself locked in place. To release the fishing wires the 'key arm' gets dislodged from the groove in which it sits in the box by pushing it through the small rectangular slits in the side of the box.

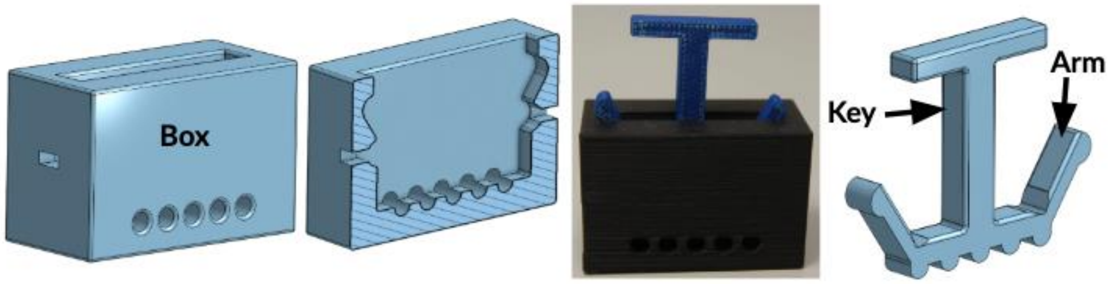


Figure 13-67: Locking Mechanism Concept 2

Concept 3 (JP)

In this concept (Figure 13-68) the fishing wires pass through both the holes in the box and the key (while it's in the box). To lock the fishing wires in place the key gets pushed sideways and is itself locked in place. The holes of the box and in the key are sufficiently misaligned to cause the wires to jam between them, consequently locking the wires in place. To release the fishing wires the 'key arm' gets dislodged from the groove in which it sits in the box by pushing it through the small rectangular slits in the top of the box.

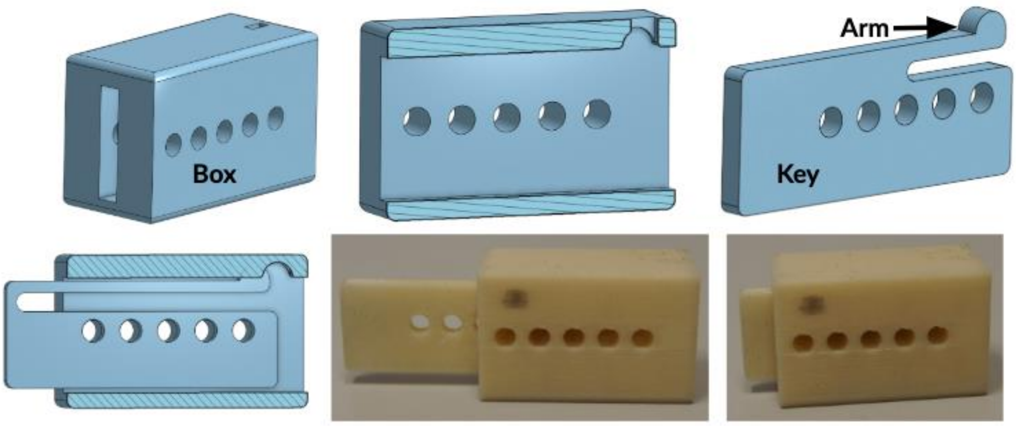


Figure 13-68: Locking Mechanism Concept 3

Concept 4 (JP)

In this concept (Figure 13-69) the fishing wires pass through the circular holes at the bottom of the box. The key is secured into the box by pushing the pins down into the two slots at the sides of the box. The arms are free to rotate in the box unless they are also aligned with the two slots. In which case, they will lock in place and the circular grooves at the bottom of the key align directly with the semi-circular grooves at the bottom of the box through which the wires pass, thus locking the wires in place. To release the wires the two key arms are pinched out of the slots and the wires will be free to move again.

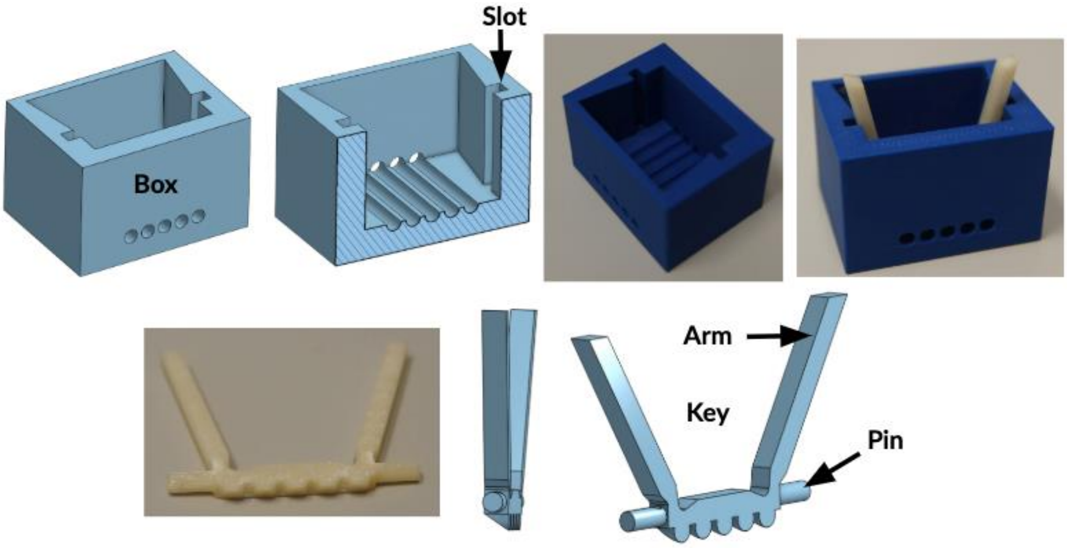


Figure 13-69: Locking Mechanism Concept 4

<u>Issues with design</u>

One of the main issues with the design of the locking mechanism is to try and prevent the wires from becoming frayed and worn after repeated locking. To do this is may be necessary to incorporate in some rubberised padding around the holes of the concepts to prevent abrasion that would cause the wires to wear over time.

<u>Concept Choice (TE)</u>

Once concepts had been developed for the locking mechanism they had to be evaluated on; how they could be implemented into the prosthetic, how they could be activated and how easy they would be to use.

Firstly, it was decided that the locking mechanism should be electronically activated. As the input control method being developed for the user was a joystick controller, see section 13.1.1, one of the degrees of movement could be used to turn the prosthetic on and off. If the locking mechanism was electronically controlled, it could be implemented with this function. Therefore, when the prosthetic is turned off the locking mechanism would activate to maintain the grasp of the object without the motors requiring any power.

Secondly, due to the new wrist design mentioned in section 13.2.2, the mechanism would have to be split in two to facilitate the wire paths entering the gauntlet from both the left and right side, therefore having separate routes for locking.

The simplest way to incorporate the two design choices was to use one servo motor controlled by the Arduino to actuate 2 keys into the lock boxes on either side of the gauntlet. The idea would only use one servo motor to keep the system simple with less chance of electronic fault and to conserve on space and cost on the gauntlet.

The concept that would be easiest to adapt to this layout and activation method was concept 3. This is due to the orientation of the lock boxes with the keys sliding in from the side. This would give the mechanism a compact design adding little height to the gauntlet compared to the other concepts which are all activated from the top. Additionally, the fact that the holes of the key could go past the holes of the box meant that a greater friction and crimping of the fishing line could be achieved.

Version 1 (TE)

The design of the locking mechanism consisted of 2 lock boxes, one located on the left of the gauntlet containing two holes for the wire routes of the thumb and index finger, the other on the right with three holes for the middle, ring and little finger wire routes. Each lock box has a key inserted from the side with the same number of holes as the box. In the bottom of each box are two springs which restore the keys to their original unlocked position, see figure Figure 13-70.

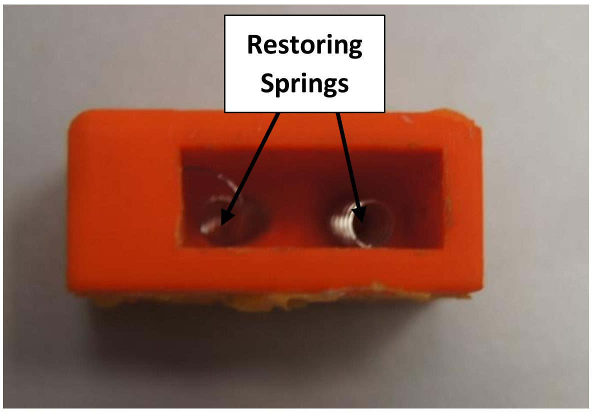


Figure 13-70: Lock Box Restoring Springs

The motor MG90s Tower Pro micro servo was chosen due to its compact size and low weight. The servo motor will insert the keys into the lock boxes via an attached propeller which provides the force to the edge of the keys. To lock the fishing wires the motor rotates 15° clockwise, causing the keys to move 2mm into the box, compressing the springs and misaligning the holes. As the holes have a diameter of 1.5mm, the 2mm movement ensures the fishing wire is trapped with the inclusion of dimensional errors. When in the locked position the propeller and motor will be horizontal, therefore the spring force is acting directly through the axis of the motor, providing no rotational force. The motor can therefore be turned off while maintaining the locking force on the keys, see Figure 13-71 below.

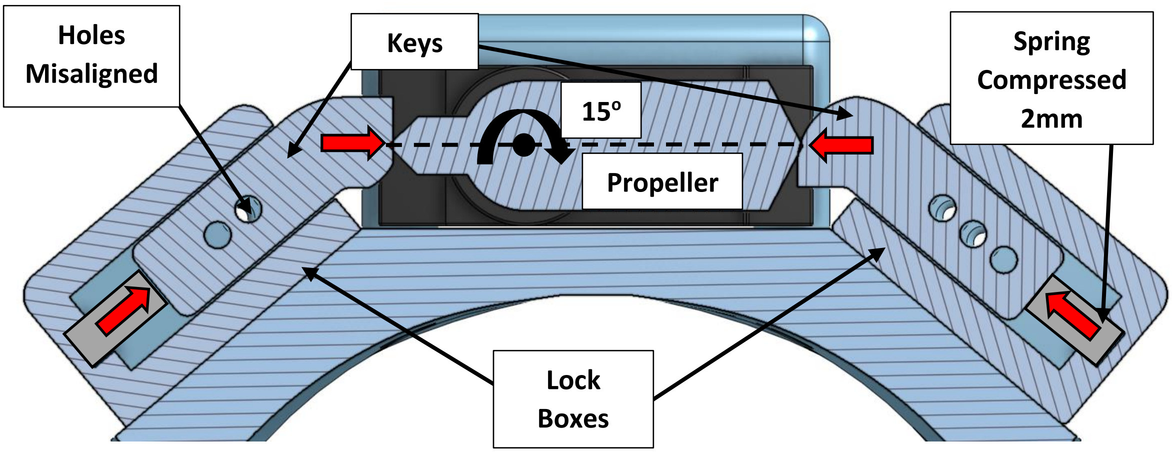


Figure 13-71: Locking Mechanism Locking the Fishing Line

To unlock the fishing wire the motor rotates the propeller 15° anticlockwise allowing the springs to decompress and restore the position of the keys. This realigns the holes allowing for free movement of the fishing wire, see Figure 13-72 below.

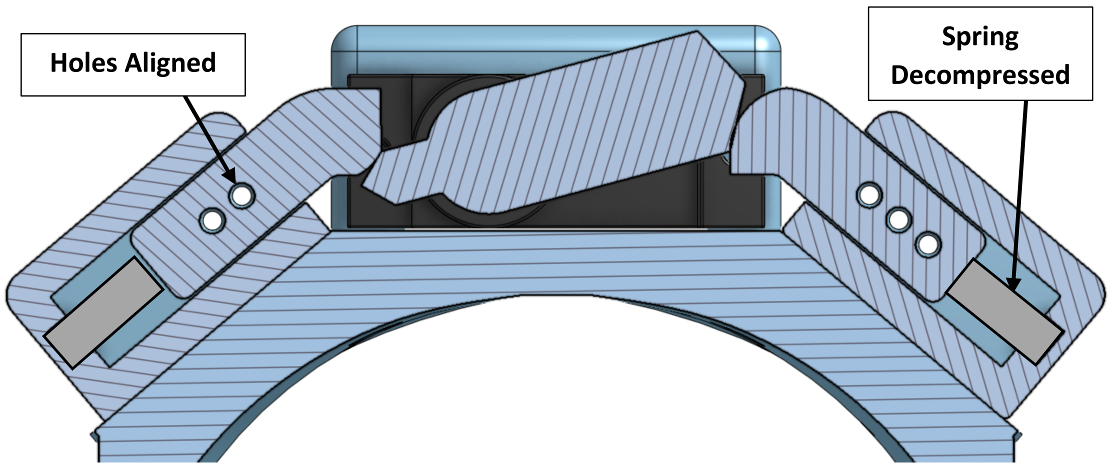


Figure 13-72: Locking Mechanism Unlocked

The first version of the locking mechanism was to show a proof of concept. A rudimentary test was carried out by passing fishing wire though the holes, locking the mechanism and seeing if the fishing wire would still pass through. It showed that it clamped the fishing wire, stopping it from moving. However, due to time limitations in the project it was decided to reduce the size of the mechanism to its minimum before conducting full force tests to understand how much tension in the fishing lines could be held before the wire slipped through the mechanism.

Version 2 (TE)

The main design aims of the locking mechanism redesign were:

a) To minimise the size of the system, as the first version protruded from the gauntlet 13.5mm, making the lock boxes outer edges lie beyond the edge of the gauntlet, see Figure 13-72.
b) Increase the force that the mechanism produced to ensure the system can clamp and hold a large tension force from the fishing wire.
c) Move the holes away from the centre of the gauntlet to minimise the friction for the fishing line by reducing the angle its path travels through.

When minimising the size of the locking mechanism, only the height was to be reduced. The length was to remain the same to provide the same area for the friction force to clamp the fishing line. The height was reduced by following the minimal distance between features and tolerance, being 1mm and 0.4mm specified in section 6.1.3. The height of the lock boxes was therefore reduced to 9.8mm from the surface of the gauntlet.

To increase the force provided by the mechanism, the distance that the keys move inside the box was increased to 3mm from 2mm. This would make the holes of the keys misalign with lock boxes further. This increase would clamp the wires more, causing the wires to bend around the key to create a high friction geometry, see Figure 13-73. This would therefore enable the mechanism to lock higher fishing line tensions.

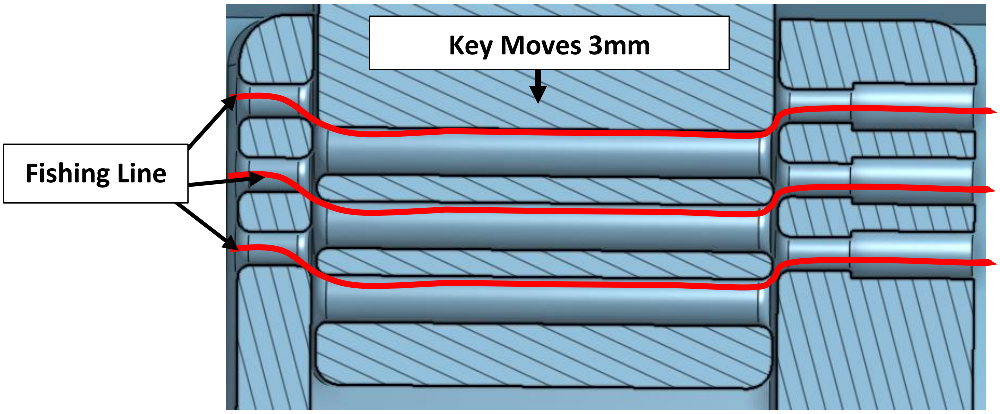


Figure 13-73: Fishing Wire Being Trapped

To move the holes away from the centre of the gauntlet, it was decided to have the springs in pre-compression to allow the keys to sit further inside the boxes in their unlocked position. The position of the holes on the boxes could therefore be moved towards the outside edges. An image of the locking mechanism version 2 is shown below in Figure 13-74.

Figure 13-74: Final Version of Locking Mechanism

<u>Problems with Mechanism (TE)</u>

Before conducting a thorough test on the second version of the mechanism, the rudimentary test was carried out again. However, this time the fishing wire was tied in tension to make the scenario more realistic.

The test showed that the mechanism would no longer clamp the fishing wire, with it starting to slip after a low force was applied to it. This was due to the motor not fully rotating the 15°. The reason for this was because of these changes to the design:

a) Pre-compressing the restoring springs.
b) Having the keys move 3mm instead of 2mm.
c) Having the fishing wire in tension.

These three changes meant that the there was too much force acting against the keys from the tension of the wire and springs. The motor therefore did not have enough torque to lock the keys in place. Additionally, minimising the size of the mechanism resulted in the propeller misaligning with the keys. This size reduction increased the accuracy the system had to have to work. The mechanism was therefore no longer reliable at performing its task.

After establishing the problems with the locking mechanism, it was decided that due to time constraints it would take too much development to get the system function properly and reliably. Additionally, it was still unknown if it would be able to maintain the force needed for locking high tension fishing lines. Therefore, it was decided to remove the locking mechanism from the gauntlet as it was not a necessity for the creating a working prosthetic. On the positive side it created additional space to plan out the positions of the battery, servo motor actuators and circuitry.

13.2.8 Gauntlet (PB)

<u>Layout</u>

The gauntlet is one of the key aspects of the design – it is where all primary electronics and actuators had to be housed. For this to be successful, all aspects of the design had to be carefully considered. Due to the nature of rapid prototyping, it also had to be easily modifiable throughout the design process as ideas developed and changed.

An initial gauntlet was designed based on last year's model, this was to save time and allow immediate prototyping. It was stripped of all components to leave a shell, and the exterior was flattened into a hexagonal shape to allow components to be easily screwed on for rapid testing and prototyping. Holes were kept in the sides that allowed the gauntlet to be secured to the arm using Velcro straps – a method of attachment used by the User in her Kwawu prosthesis. The method of attachment to the palm using a pin joint was also kept the same.

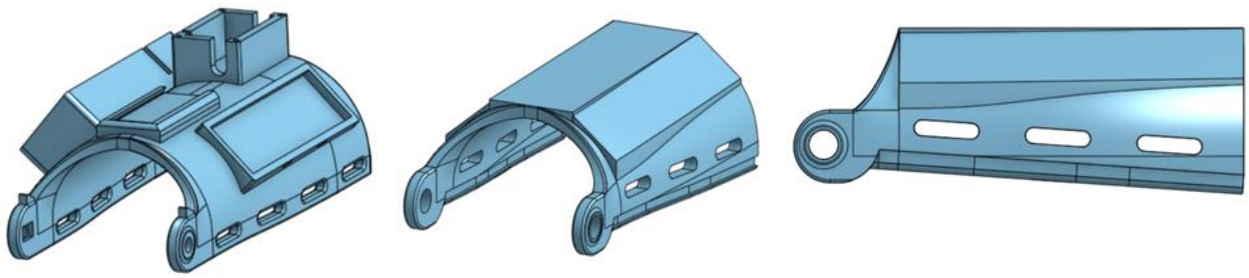


Figure 13-75: First design of gauntlet (V1)

This prototype was used initially to trial the locking mechanism (section 13.2.7), as shown:

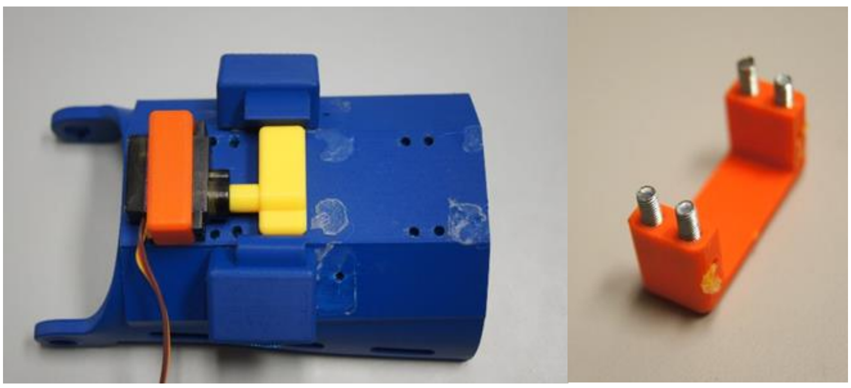


Figure 13-76: prototyping of locking mechanism

The position of the locking mechanism would therefore influence the positions of all other components. Once its position was determined, the rest of the design was carefully considered to dimension the gauntlet. The other key components for consideration were:

- Two servo motors and pulleys
- Haptic array
- Circuit and Arduino
- Wire routing, both fishing wire and electrical

As it was uncertain whether the locking mechanism was a viable solution, and a gauntlet needed to be designed, the rest of the gauntlet had to be designed in such a way that meant everything could be moved forwards should the team need to remove the locking mechanism. The gauntlet was extruded to have a full length of 177mm. This was to maximise space for components to be attached. Due to the print bed having a limit of 180mm, this was just short of the maximum length possible.

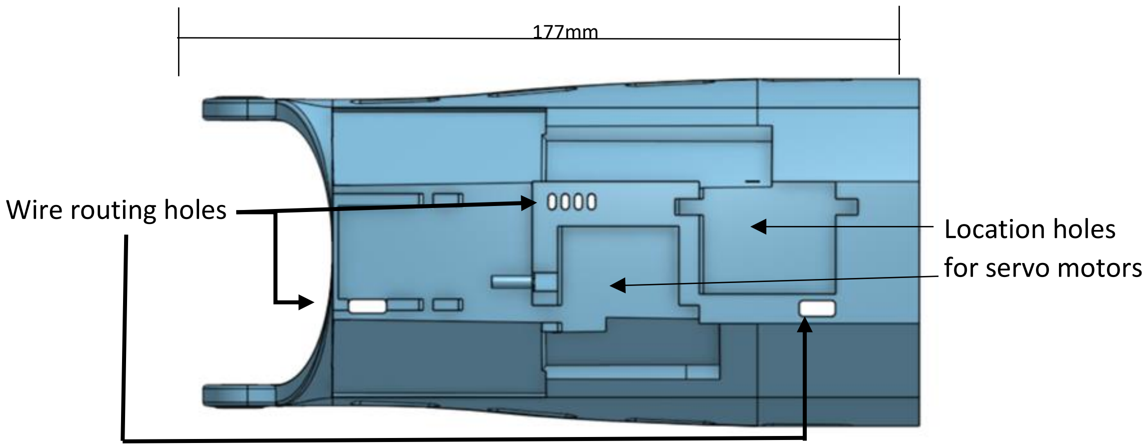


Figure 13-77: Gauntlet design V2

Every effort was also made to constrain the overall footprint of the gauntlet, keeping it as compact as possible. As a result, the two servo motors were placed adjacently behind the locking mechanism. This kept both the height and the width of the gauntlet to a minimum. Depressions were also created to reduce height and to locate the motors. Holes were made to allow for routing of the wires from both the servo motors and haptic motors beneath. These wires would be routed to the main circuitry, housed above the servo motors.

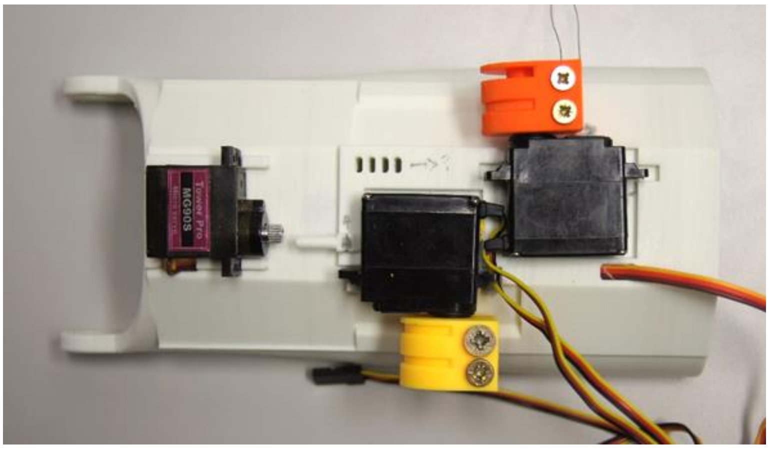


Figure 13-78: gauntlet V2 with servo motors attached

Haptic Array

Depressions were created on the underside of the gauntlet for the vibration motors and their corresponding wire routings. The motors were equispaced at 40mm to optimise differentiability of vibrations (section 5.3.9). The wires were routed to not be in contact with the user and therefore not negatively impact comfort of the gauntlet.

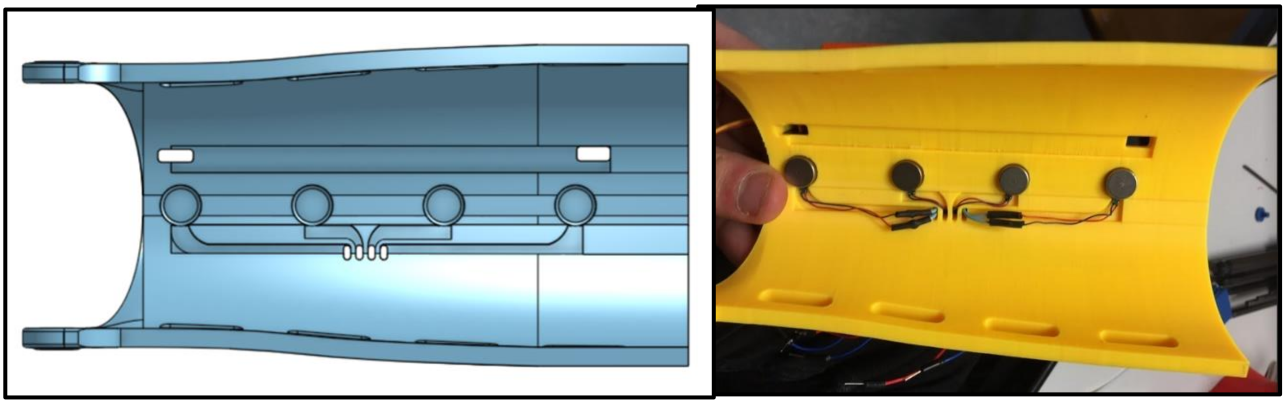


Figure 13-79: Haptic motor array built into the gauntlet

The design was further iterated to add the locking mechanism, and a basic housing was designed to better constrain the servo motors and house the circuit.

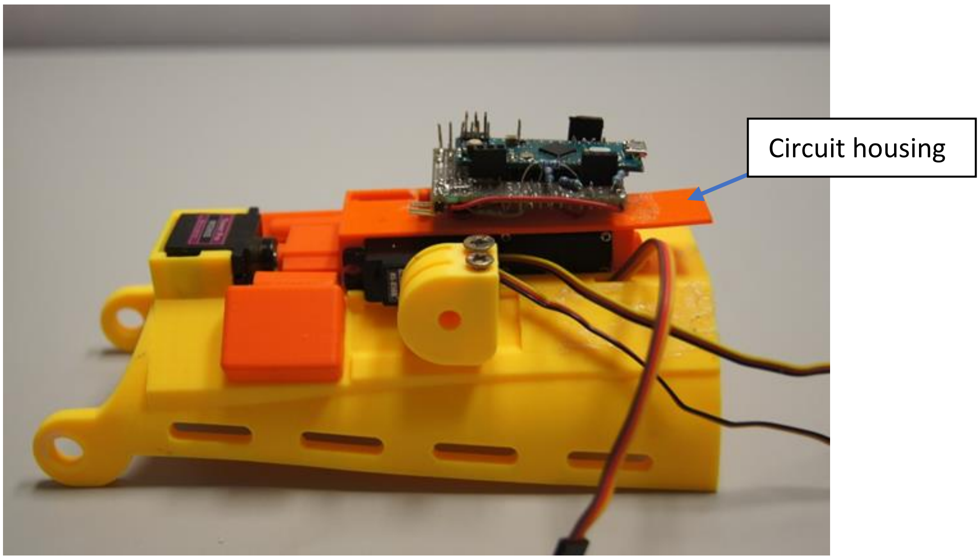


Figure 13-80: Gauntlet with Small Circuit on

Unfortunately, this circuit did not function correctly and was rebuilt at a larger scale. This did not require any redesigning of the gauntlet and was merely glued onto the casing.

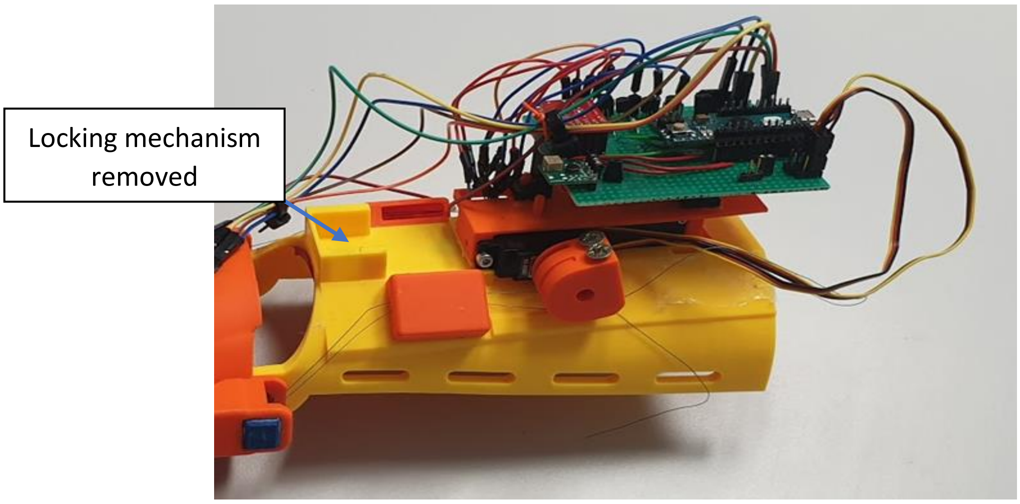


Figure 13-81: Gauntlet on the first prototype, presented at the second interview.

13.2.9 Gauntlet Attachment Mechanism (SS)

The mechanical solution idea was taken from snowboard boot's tightening mechanism and a snowboard boot style twistable locking mechanism that tightens a set of wires under the forearm decided to be used. Different applications were researched, and pawl type of mechanism was decided to be used. In this way, the pawl type of mechanism will allow the mechanism to move in only one direction.

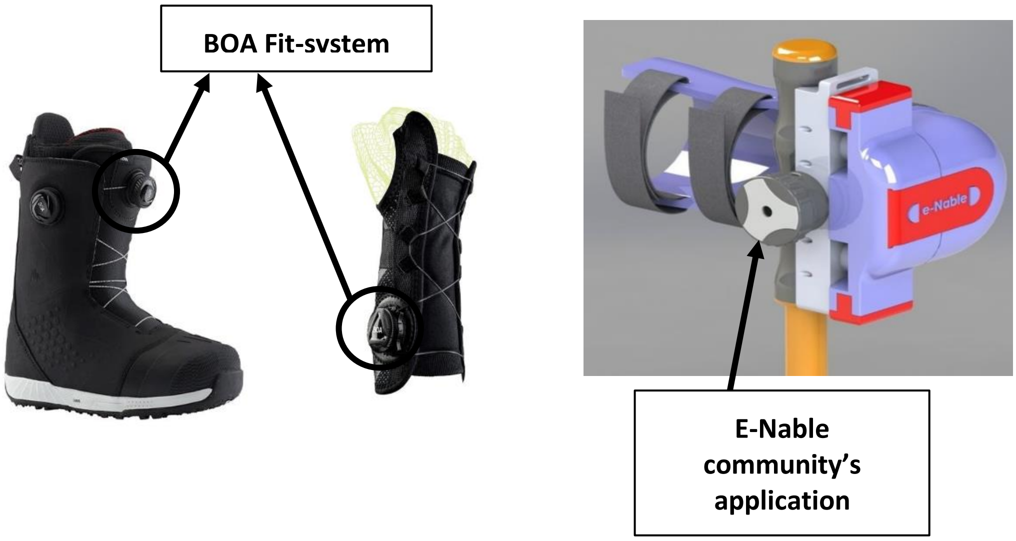


Figure 13-82: shows different applications of locking mechanism [102] [103]

BOA was found as the biggest supplier of these kind of locking mechanisms and their applications not only in snowboarding boots but also in brace applications which are shown in Figure 13-82. The working principle of the product was being researched and application of the mechanism to the prosthesis was being designed. Similar applications were also researched on e-Nable community's Facebook page.

Parts of the mechanism and application to the prosthesis

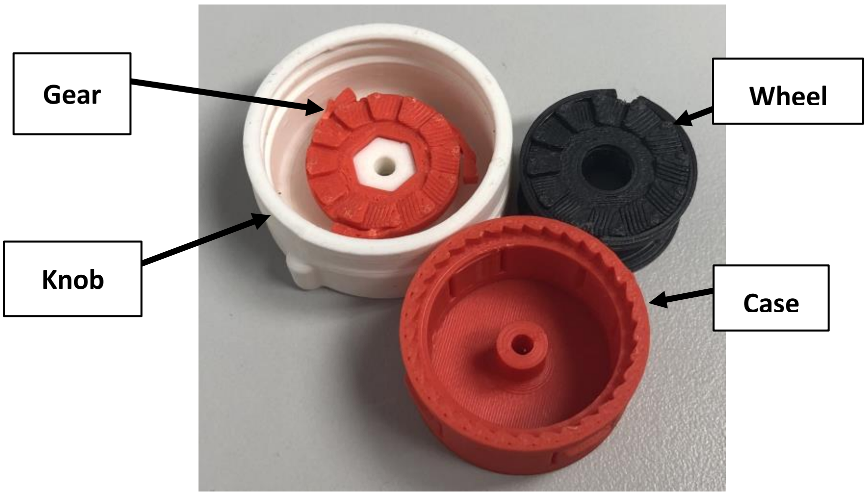


Figure 13-83 shows parts of the twistable locking mechanism

The mechanism consists of four different parts. Knob is the top part of the mechanism which is being turned by the user to tighten the wires. Gear is attaches to the knob and it includes the three part of the ratchet wheel which engages with the pawl for locking purposes. Wheel is the place the wires are coil around. On top of the wheel another gear was included which engages with the gear with ratchet wheel on it. The case covers the wheel so that the wires will only wire around the wheel. Also, it includes pawl on the top which engages with the gear part.

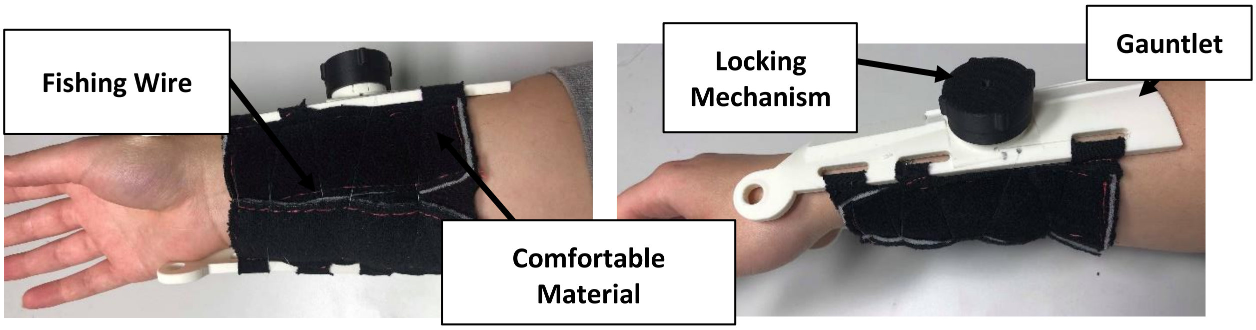


Figure 13-84 shows the application of the mechanism to the gauntlet to fix the prosthesis to the forearm

In the application to the prosthesis, the wire was selected as 0.25 mm in diameter Teklon Hi-Tech Line. While choosing the wire, the diameter and the strength of it were the key parameters. The wire was pulled till it breaks and the force that it breaks is recorded. It was seen that the wire can stand up to 18.3N of force which was high compared to its diameter. The force was measured by using a load cell sensor.

To loosen the wires, the user needs to hold the gauntlet and push her arm downwards and the release can easily occur. Different routings were tried, and it was seen that double helix (cross hatched method) rooting was a better option to have a uniform tightening and distribution of the load.

On top of the fabric part, to decrease the contact between the wires and the forearm, Tissus3D decided to be used. The measurements are made, and the fabric part is designed. When the wire is loosened the two parts of the foam are separated and they are hold together with a cotton fabric. When the wires are tightened the foam, parts get together and wraps the forearm.

Working principle of the mechanism

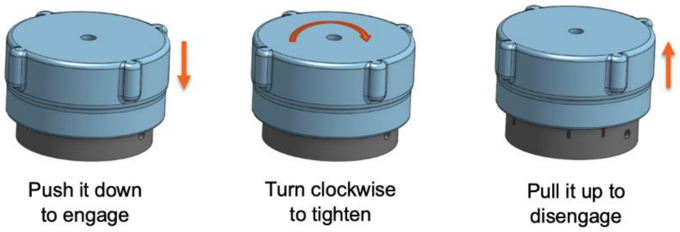


Figure 13-85 shows the working principle of the twistable locking mechanism

To the mechanism to start working, the knob on the top needs to be pushed to engage the gears. By simply turning in the clockwise direction, the wheel inside it will start to turn. This enables the mechanism to tighten the wires. As it has a pawl mechanism inside the wheel cannot turn backwards. To disengage from the gears and from the pawl mechanism, one should need to pull the knob up. In this way, by pulling the wires on the sides, the wheel will start turning backwards and loosen the wires without putting so much effort.

As the user still has a portion of her thumb, it was possible for her to twist the knob to tighten the wires to secure the gauntlet to her forearm. Pulling the knob releases the tension in the wires as it disengages the gears and allows the user to remove their forearm from the prosthesis easily. This mechanism enables the user to have a comfortable and fast tightening. The pawl on the sides of the case are made as small in distance as possible to enable the user to have a fine tuning. M3x20 screw can be used to fully secure the knob and avoid getting out when it was being pulled to disengage.

Different versions:

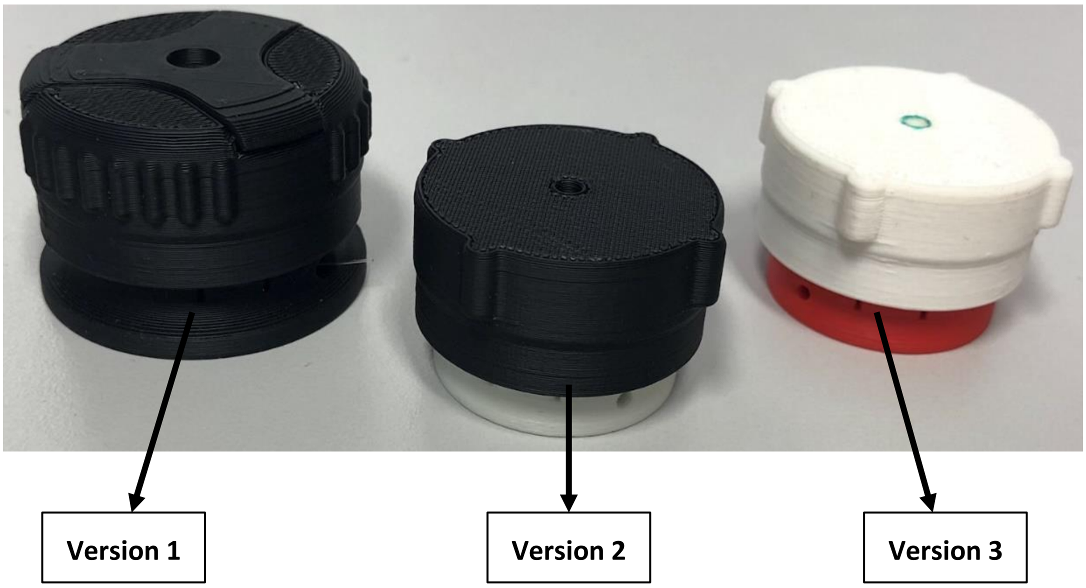


Figure 13-86 shows different versions of the twistable locking mechanism

By looking at the E-Nable community's pages, a similar model for the snowboard boot tightening mechanism was found. A ratchet clamping mechanism was designed by the Younes Zitoni's who is a member of the E-Nable France community. He designed the mechanism for a prosthesis project which focuses on children who doesn't have fingers and wants to ski. The mechanism was used to secure the ski pole to the prosthesis [104]. This version was 3D printed, and the working principle was analysed. Further, different versions were being design by taking Younes Zitoni's design as a base. Difference between the versions were the size and the ratchet wheel parts.

13.2.9.1 Load Cell Test

The mechanism helps the user to hold the prosthesis on the forearm and support the user when she is holding something like a water bottle. The amount of load that the mechanism can held wanted to be examine so the force test was applied. For this test wire, load cell sensor and the different versions of the twistable locking mechanism was used. The wire was tied around the column to have a fix the wire and the other end of the wire was tied through mechanism's right side. Another wire was tied through the mechanism's left side and the other end of the wire was tied to the load cell. From the additional L-shape part another wire was secured to apply force.

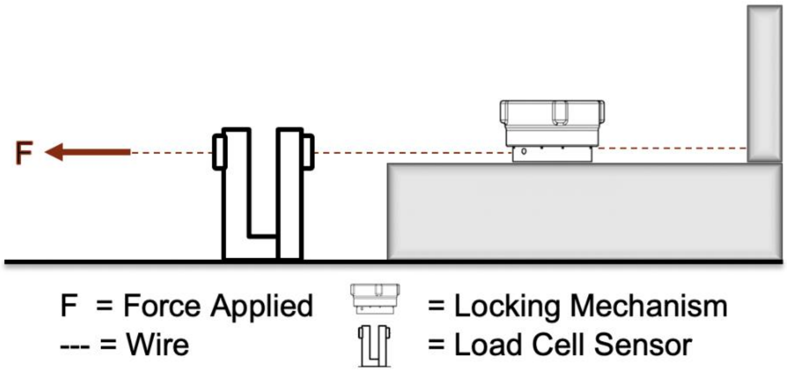


Figure 13-87 shows the diagram of force test set-up

Test aims

1. Determine the mechanism's release point
2. Determine how the mechanism reacts in extreme load conditions

Test procedure

1. Upload the force test code to Arduino
2. Set-up the test as seen in Figure 13-87
3. Turn on the switch and apply force by gradually increasing
4. Apply the force till the mechanism releases the wires or till the force reaches to 1.5kg
5. Turn the switch off
6. Repeat steps 4, 5, and 6 for each versions of the mechanism 3 times
7. Copy the recorded data and paste to the excel spreadsheet

Results

The force was applied manually in a straight-line manner and increased gradually to examine when the mechanism was being released. The test was stopped when the mechanism released which was a failure or the force reached to 1.5kg which is a pass. This test was held three times for every version to get an accurate result. The data sheet can be found in Appendix Q.

	Durability to 1.5kg	**Fail load**
Mechanism V1	Pass	-
Mechanism V2	Fail	6.994N
Mechanism V3	Pass	-

Table 13-4: shows the test results

Conclusions

For this application most, important parameters were the force endurance and the size. After the test is held, it was seen that Version 2 did not endured the force and the mechanism was released when the force reached at 6.994N. In between Version 1 and 3, the sizes are compared as they passed the test. The smaller one is chosen as it occupies a less space on the gauntlet.

13.2.9.2 Static Load Test

Parts can deform in two different ways. In elastic deformation the part can go back to the original position and shape which was an acceptable situation for this application. Other deformation is plastic. In plastic deformation the object does not return to its original shape. Breaking and cracking are the examples of this deformation. This deformation should be avoided for the mechanism to function properly [105].

Optimization for the part was wanted to be made and for this reason finite element analysis method was used. By using Fusion 360, simulation was made for the gear which was more likely to break. To improve the solution and make sure the mechanism would be left longer without any breakage, the static load was applied to the part.

In finite element, the degrees of freedom for the nodes are unknown. Nodal displacements are primary unknowns. By using structural analysis; displacements, strains, and stresses can be found. Von Mises stress failure was created on Fusion 360. For the 3D generated component six stress components was measured for Von Mises stress analysis. It was a non-negative scalar stress.

Safety factor is expressed as;

$$SF = \frac{\sigma_{limit}}{\sigma_{vm}}$$

Equation 13-3: Safety Factor

Where $\sigma_{limit}$is the yield strength and σ_{vn} is Von Mises stress [106].

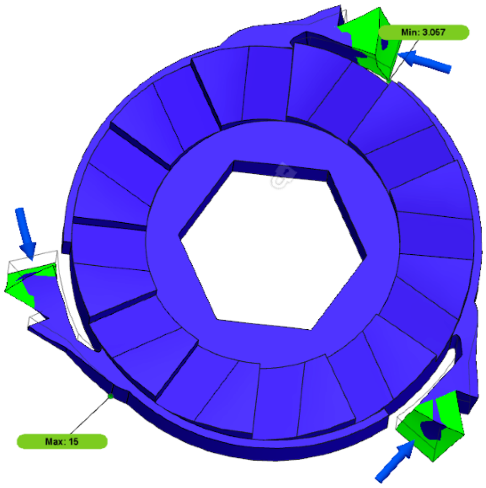


Figure 13-88: shows the safety factor by using FEA analysis

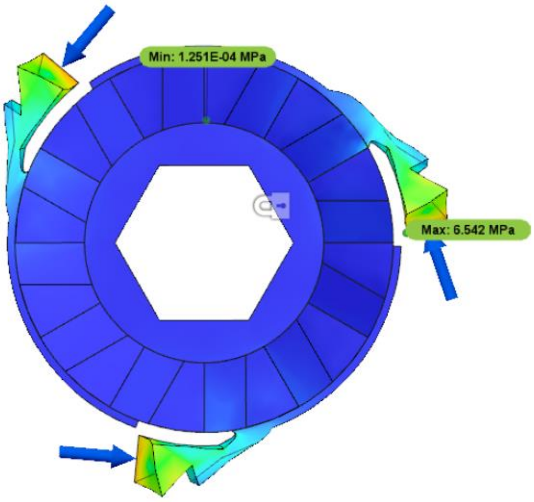


Figure 13-89: shows the stress by using FEA analysis

From the safety factor FEA, as shown in Figure 13-88, it was seen that the part can stand 1.5 kg in a safety factor of minimum 3.057. This showed that the part has a risk of breaking in 3.057x1.5=4.58kg. Also, this showed the level of confidence in the level of the accuracy within the analysis.

The stress analysis, as shown in Figure 13-89, shows the deformation of the part under a load. While doing the analysis, the software divided the part into small pieces, so the pieces were selected to be as small as possible for more accurate result. Even though the maximum stress that the gear encounters was 6.542MPa, the displacement was occurred as 0.01286mm. This analysis showed that, under the load of 1.5kg, the part was not failing, and it was safe to use it. Full report of this FEA analysis can be found in Appendix R.

13.2.9.3 Other Concept Designs

Inflatable Gauntlet Design

The inflatable gauntlet design idea was developed by the working principle of the blood pressure device. The working principle of the blood pressure's cuff is that the cuff wraps around the upper forearm and with an oscillatory device the air is pumped into the bulb and the cuff starts to inflate. As the cuff inflated enough one can stop inflating and it is so easy to release the air inside the cuff. As the blood pressure devices or the cuffs are expensive more cheaper options were researched. The inflatable bags were considered as a good option as they are so cheap and easy to find. In this prototype, the air column bag was used. The reason of this was not just having a cheap product, but also having an option to have a column to allow the air to get in through the forearm.

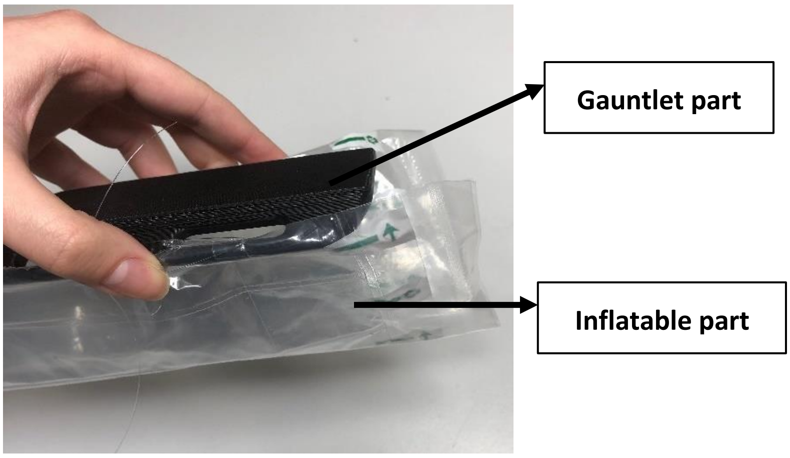


Figure 13-90 shows the concept of inflatable gauntlet

In this inflatable concept design, the prosthesis can be put on directly and then by using a small pump the patient can inflate and fix the gauntlet to his or her forearm. The part can be deflated and used repeatedly. The problem in the inflatable part, which was used in the prototype, was that the air column inflatable part was being sold as a bottle safety protection packaging. The part inflates but it seals itself, so it cannot be deflated to be reused. The strength of the material was an important aspect as well. In the prototype nylon was used. It was seen that the product can be fix in the forearm and stretch ability was helpful for a better fit. However, it was so easy to tear the part. It was concluded that more durable and applicable solution was needed to fix the prosthesis onto the forearm than the inflatable design.

Socks/Brace Type Gauntlet Support

The braces and splints were researched as the prosthesis can be fix on the forearm by using them. Brace type of design was decided to be used because it had more flexibility in the movement of the wrist than splints. The gauntlet was aimed to be put on top of the brace. To fix the gauntlet and the brace together, a strong but comfortable part is decided to be put underneath the brace. In this way by using bolts the gauntlet can be easily fixed.

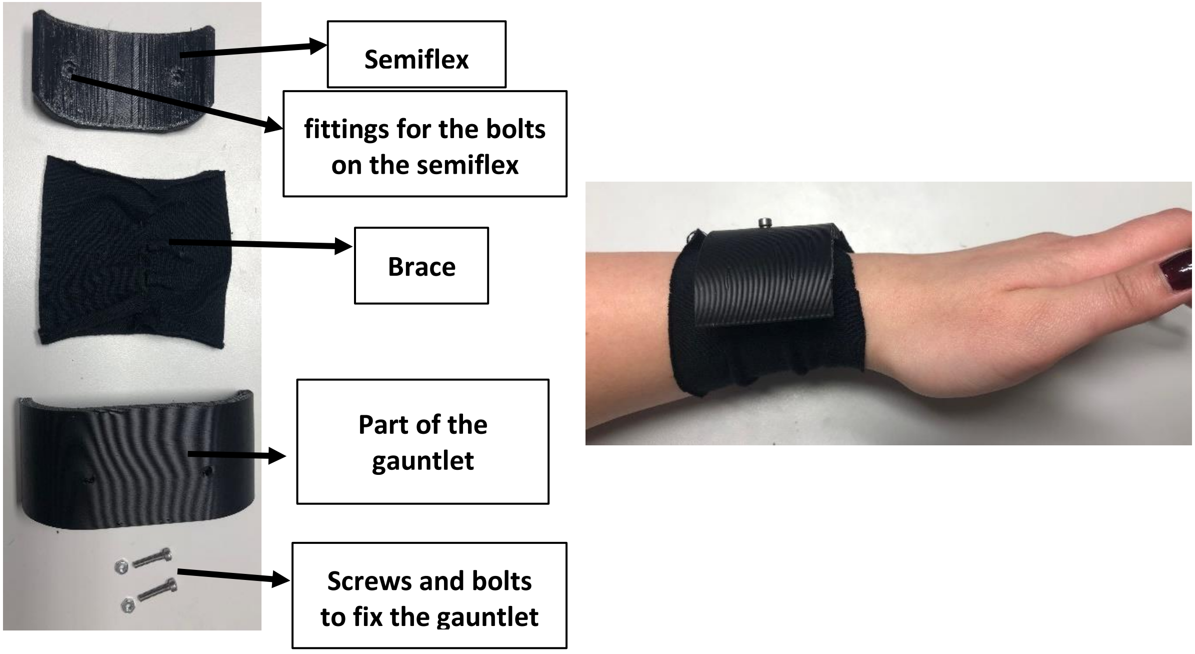


Figure 13-91 shows the concept of brace type gauntlet support

Underneath the brace couple of different materials are used including ABS, PLA, semi-flex and flex. It is seen that ABS or PLA was hard materials and because it was going to be put underneath the brace to help to secure the gauntlet on top it was not the best material to be used. Semiflex was a better option to give a more comfortable fitting on the forearm and it was also stiff enough to hold the gauntlet. Therefore, semiflex filament was decided to be used in the final prototype.

Semiflex part was good to fit around the forearm because of its capability to bend. The inner face, which was get in touch with the forearm, was made more rounded to have a better fitting on to the forearm. In this prototype the main aim was to have tight but comfortable fit on the forearm. It was seen that it was comfortable on the hand and can easily put on because of the fabrics stretch ability. However, if the brace was chosen to have a more stretch capability, it was seen that it doesn't hold the weight of the gauntlet. Otherwise, if the brace was chosen to be more stiff and tight fit to the hand, it was getting hard to put the prosthesis on. Therefore, this concept was not carried forward.

14 User Interview 2

The second interview was an opportunity for the team to meet with the user again and test concepts that had been developed since the first meeting. This interview was more structured than the last one, as the team wished to carry out testing of the prototypes.

<u>Plan</u>

1. Test the joystick controller with the user to first determine if the joystick was a viable method of control.
2. If successful, move on to testing the full device
3. Test the haptic feedback
4. Test both the mechanical and electrical attachment methods for the gauntlet

14.1 Joystick Testing (PB & TE)

Prior to the interview, the team printed a section of the palm that would allow the user to test the joystick in isolation to the rest of the design, while allowing the team to see inside.

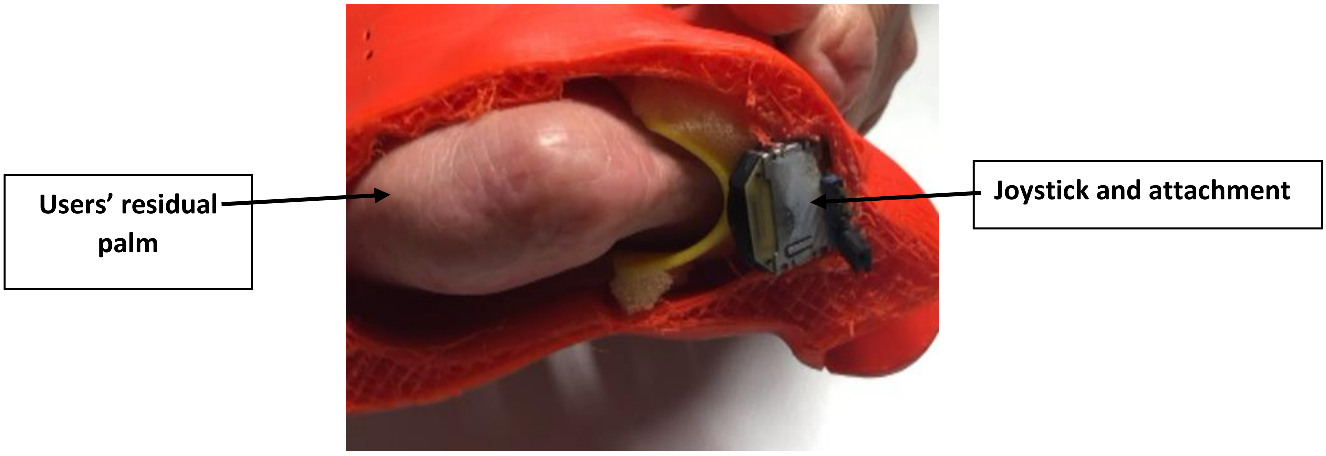


Figure 14-1: The user trialling the joystick controller [Video Appendix C]

From this initial test, it was found that she was able to complete the full range of motion of the joystick, adding it was comfortable to use. The joystick was then connected to the servo motor on the force test-rig with a finger that could be contracted based on the values read from the joystick.

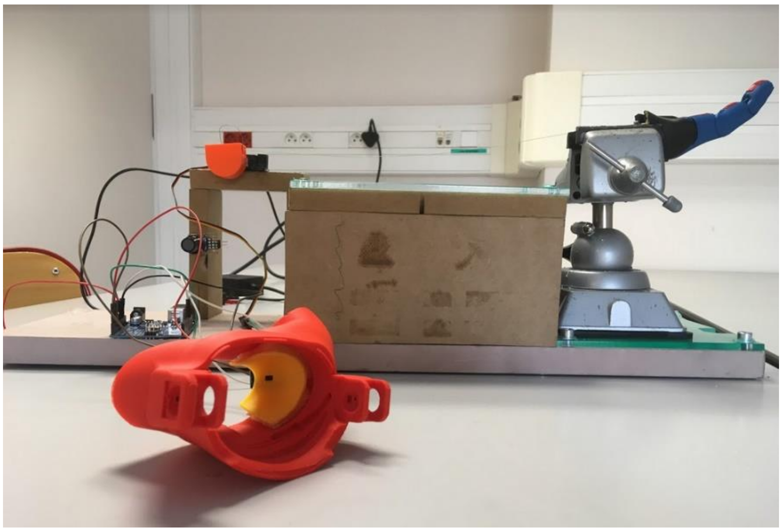


Figure 14-2: Joystick test-rig used in the second interview

Using the Y-axis configuration in section 13.1.1, the user was able to contract and extend the finger effectively, with little training. Again, this was successful, and the team therefore moved on to test the full prototype.

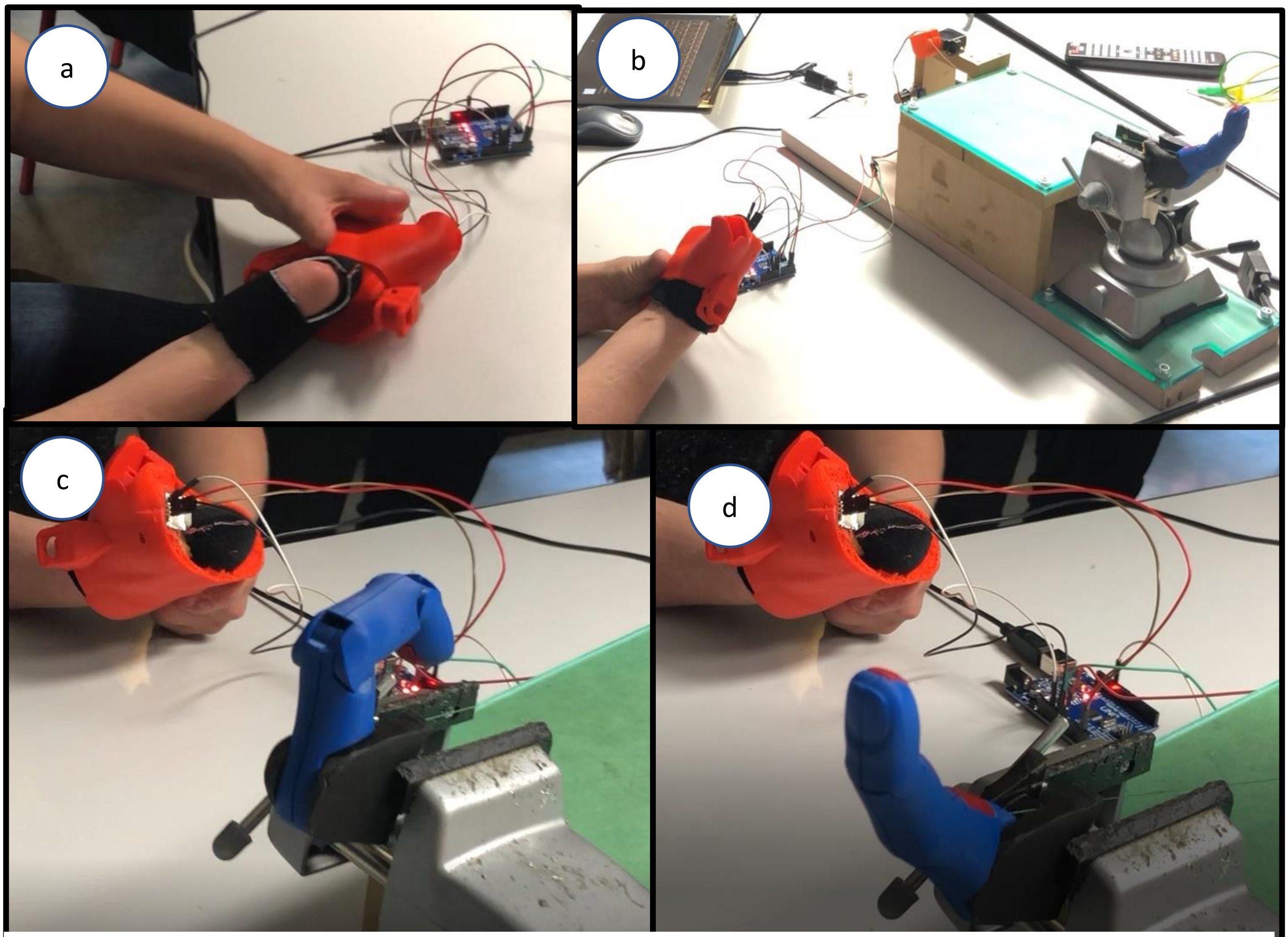


Figure 14-3: a. user with palm liner on her residual palm b. user places her residual palm inside the test palm. c. Finger contracted. d. Finger extended

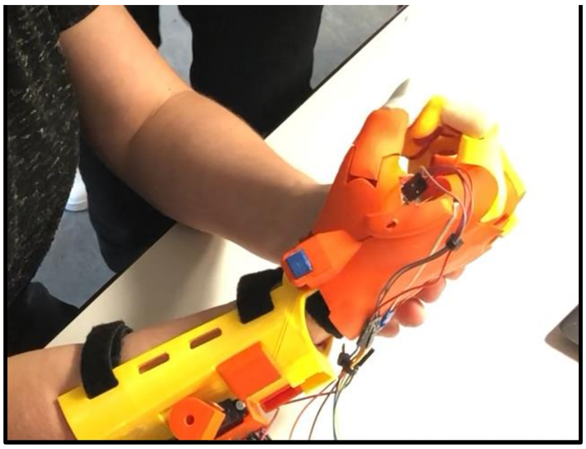


Figure 14-4: the user opening and closing all fingers using the joystick.

The pressure sensor and haptic feedback array was then briefly tested. As the prosthesis could not effectively grasp objects, the team did this manually, with a team member placing increasing pressure on the fingertip to slowly trigger the different vibration motors in order. She was then asked if she could detect all four vibration locations. She could not, stating that only vibration motor 1 and 4 were perceivable.

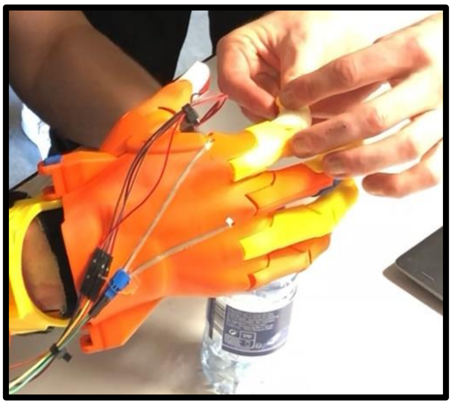


Figure 14-5: a member of the team pressing on the fingertip sensor

Finally, the user attempted to pick up an empty 500ml water bottle, but she was unable to do so.

<u>Observations</u>

- The user was not able to pick up the bottle due to the way in which the fingers contracted. The distal joint contracted first, causing a clawing motion that pushed the object away from the hand rather than grasping it, as shown in Figure 14-6.

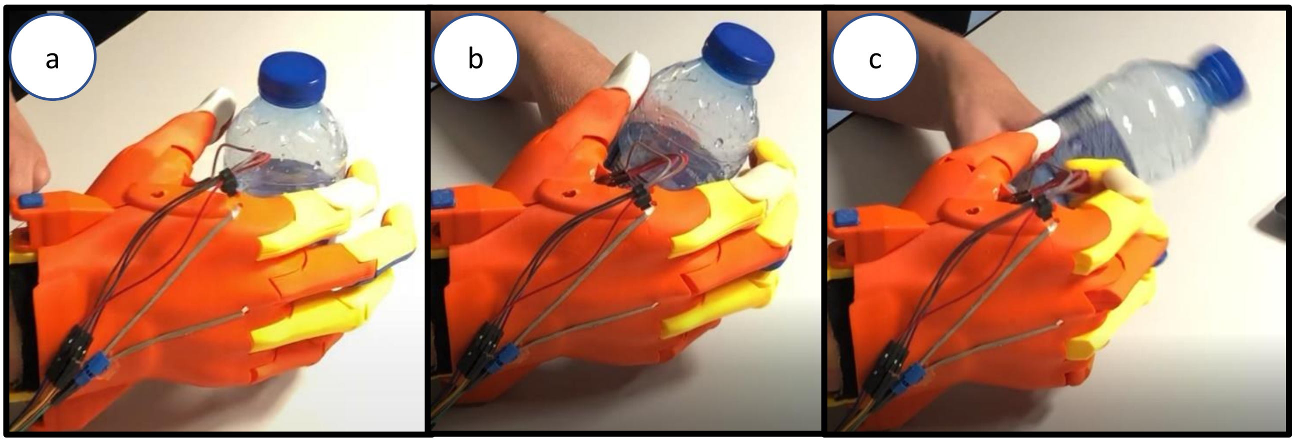


Figure 14-6: a. bottle is placed in the hand b. user contracts the fingers. C. bottle is pushed away from the hand.

- Figure 14-6.b shows how the thumb position causes the object to twist in the grasp. It also shows the distal joint contracting first.

- The user could only feel the vibration motors that were directly above the two Velcro straps. Therefore, it was likely the reason she could not detect the other two was because they were not sufficiently in contact with her arm.

14.2 Attachment Mechanism Test (SS)

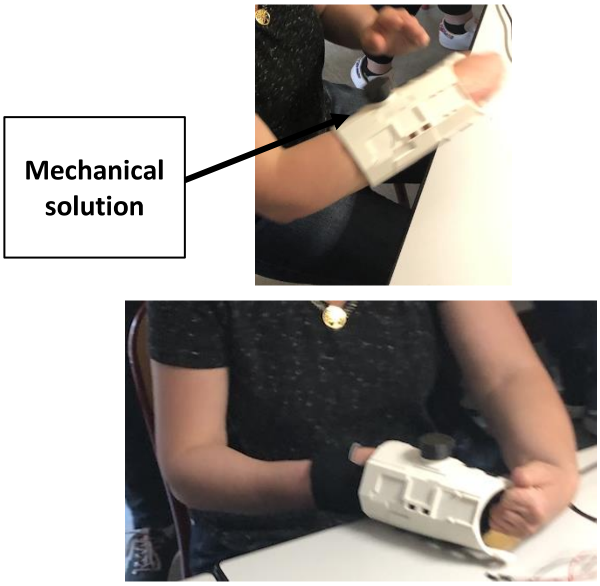


Figure 14-7: shows the user trying the mechanical solution

In the second interview with the user, both mechanical and electrical solutions were presented to her. She tried them on and gave feedback. She approved the mechanical solution to be put on the final design. She easily used the mechanism to tighten and loosen the prosthesis. She effortlessly turned the clamp and pulled to disengage the gears. The knob part didn't come off. It was seen that she can easily to put on and off the prosthesis.

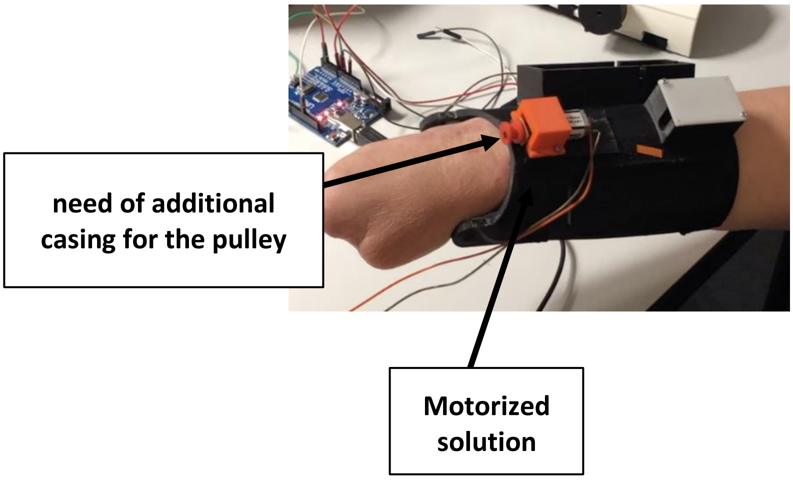


Figure 14-8 shows the user trying the motorized solution

Even though she chose the mechanical solution, she gave a feedback for the electrically assisted solution for further improvement. As she needed to use the switch to stop the movement of the motor every time, she found this really exhausting to do it every time. Or the other suggestion was manually stopping the winding but having a safety stop.

14.3 Feedback

Throughout the interview the user provided other feedback on the prototype as well as information via discussion with family members, supervisors and the team.

- The joystick was comfortable to use.
- She liked the low weight of the prosthesis.
- She found the palm liner comfortable.
- She preferred the mechanical attachment mechanism over the electrical.
- The back of the gauntlet was sharp and digging into her forearm.
- The user stated it was 'better than her myoelectric prosthesis'.

15 Stage Gate 4 Conclusions

Based on the information gathered from the interview, and testing undertaken since stage gate 3, the team discussed what should be brought forward, dropped or newly developed for the next prototype.

Brought Forward	Dropped	To Be Developed
• Joystick control • Haptic motors • Mechanical gauntlet attachment mechanism	• Locking mechanism • Motorised gauntlet attachment mechanism	• WhippleTree Pulley • Finger joint thicknesses to be altered to prevent clawing • Gripping improvement pads for palm • Gauntlet layout adapted • Gauntlet casing • Adapt the gauntlet for a better fit to the arm • Thumb position to be investigated • Circuitry to be shrunk • Battery selection
What else was Learned?		
• The user found prototype V1 comfortable to move • The user was happy with the weight of the prototype • The user found it to be better than their expensive myoelectric prosthesis		

Table 15-1: Stage Gate 4 Conclusions

16 Final Prototype

For the final prototype, many modifications were made after the second interview. The team were pleased that the prototype worked, but in its current state it looked to be quite far away from a finished product. The team believed that in the final meeting it was important to give the user a product that, although not perfect, could give them an indication of what the finished product could look like. To achieve this, the design would need to be made more compact and refined. The team therefore carried out the tasks laid out in Table 15-1.

16.1 Electrical

16.1.1 Electronics Wiring Through Palm (TE)

During the designing and making of the first prototype there were no considerations made to cable management or routing for the electronics located in the palm and fingers. The aim at that time was to show proof of concept for certain components before making the whole package neater and concealed. The wires for the joystick and conductive fabric of the pressure sensor were therefore routed outside of the palm for easy access and maintenance as shown below in Figure 16-1.

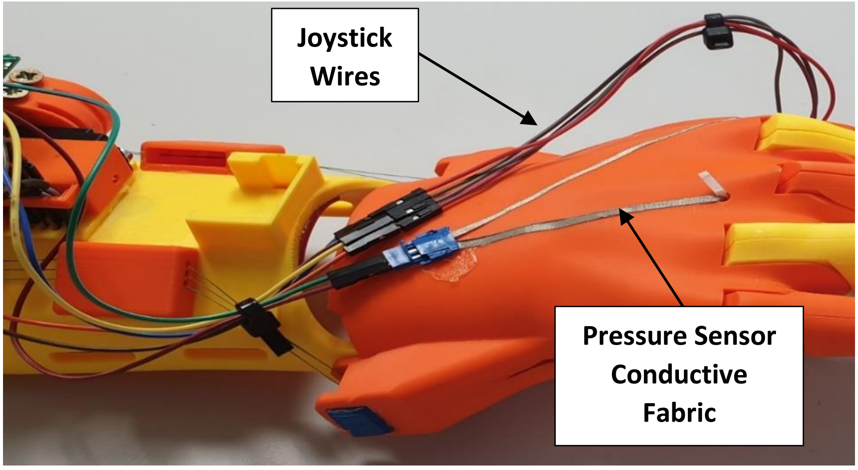


Figure 16-1: Prototype V1 Wire Routing from Palm to Gauntlet

One of the upgrades made to the palm for the final prototype was to conceal all the wires for the electronics in the palm. Due to there being a large tolerance of 6mm between the palm and the user's hand, and that there was going to be a comfortable foam insert inside the palm, as mentioned in section 13.2.5, it was decided to route the wiring on the inside of the palm between the liner.

Firstly, paths had to be created from the base of the index finger to allow the conductive fabric to enter the palm cavity. Two holes were created so that it would keep the two strips of fabric separate. If not, there was a risk of them short circuiting, prohibiting the use of the pressure sensor.

The second routing was for the wiring of the joystick through to the palm cavity. The joystick is located above the thumb within the palm as mentioned in section 13.1.1. The wires on the top are concealed in the palm and therefore need to be routed from the joystick gap to the cavity. A 3mm diameter hole was therefore implemented to allow the four wires of the joystick through.

A section view of the palm model and a view of the inside of the assembled prototype is shown in Figure 16-2 highlighting these two key features.

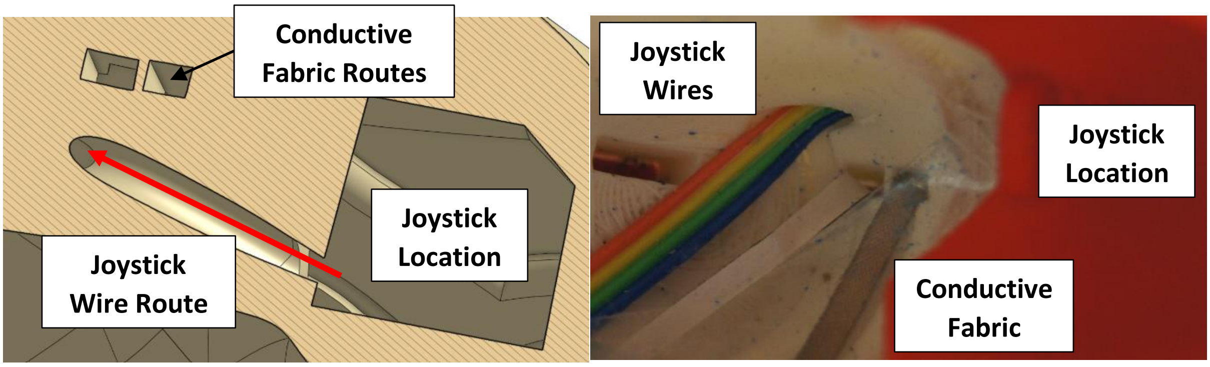


Figure 16-2: The Joystick Wires Route and the Conductive Fabric Route

To reduce the chance of the wires impeding with the user's hand in the palm cavity, grooves were added to the back of the palm to allow the wires and fabric to be inset and lay flusher with the plastic. Additionally, the conductive fabric for the pressure sensor needed a connector to convert the circuitry to wires to connect to the gauntlet and Arduino circuit. This connector was also inset into the palm to reduce impact with the user. The final routing of the wires with the connector can be seen below in Figure 16-3.

Figure 16-3: Wire Route in Palm Cavity with Conductive Fabric Connector

Finally, all six wires for the electronics had to exit the palm through the wrist to be connected to the gauntlet. A small route was created from the inside of the palm to the 4mm electronics wiring hole mentioned in section 13.2.2. The final wire route for the prototype is shown below in Figure 16-4.

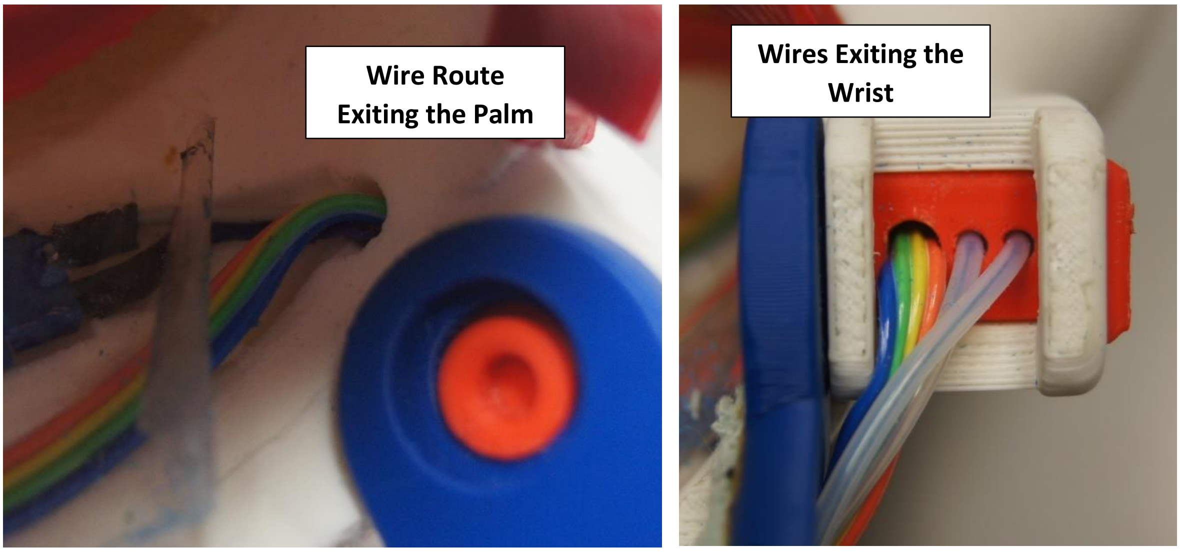


Figure 16-4: Wires Leaving the Palm Through the Wrist

16.1.2 Power (PB & TE)

16.1.2.1 Battery (PB & TE)

As this is an electronically controlled prosthetic, the whole system must be contained within the device to allow untethered use by the user. Due to the circuitry and electronics within the gauntlet and palm, a compact portable battery is needed to power the system.

Firstly, the position of where the battery will be located on the user was selected. The two possible locations were; within the prosthesis at the back of the gauntlet, or externally on the user (e.g. in their back pocket). It was decided that the battery will be located on gauntlet due to:

- Making the total prosthesis more compact.
- The ease of attaching the prosthesis to the user. An external battery would require wires to be routed through the users clothing from the gauntlet to the battery. This could be uncomfortable and a hassle for the user and reduce the likelihood of everyday use.
- To increase the position of the centre of mass up the user's forearm. Prosthetics which have a centre of mass with increased proximity to the elbow have a more comfortable weight distribution for the user, mimicking the weight distribution of a real arm [107]. It also increases the useable time of the prosthetic as a more proximal centre of mass induces as a smaller torque on the user's elbow causing less fatigue. Additionally, the user raised concerns over her current electronic prosthetic, where the heavy components are in the palm. This creates a centre of mass with a large moment arm from the elbow, making the prosthetic uncomfortable to use to the point that they have opted for use of their mechanical prosthetic.

To select a battery that would be suitable for the prosthetic, multiple criteria were defined.

a) The starting criteria was the battery life, as it had to be large enough to allow for a couple of hours of use to make the product feasible. The battery life is dependent of the mAh rating of the battery and the amount of current drawn by the circuit. A test was therefore carried out to find the worst-case scenario for the current the prosthetic circuit would conduct. This was achieved by using an ammeter in series with the circuit and the power supply to get measurements for the prosthetics activities. The results are were as follows:

Activity	Current (mA)
Arduino Powered	45
Arduino + Pressure Sensor + Haptic Motors	105
Arduino +Pressure Sensor + Haptic Motors + 2 Servo Motors Stalling	1000

Table 16-1: Current Test Results

b) The weight of the battery was to be as light as possible as the lower the weight of the total prosthetic the more comfortable the device is for the user. The first prototype weighed 400g, therefore a battery with a weight of less than 100g would allow the final prototype to weigh less than the specification point of 500g.

c) The battery should be lithium-ion as they have a great energy to weight ratio, require little maintenance, have a low rate of self-drainage over time, and are rechargeable [108].

d) The voltage rating of the battery had to be between 7-12V. This is due to multiple reasons, firstly being that lithium ion batteries only come at voltages of 7.4V and 3.7V. Therefore, if a 3.7 V battery is used, two step-up voltage regulators would be needed; one for the 7-12V Arduino micro, and another to the 6V servo motors selected in section 13.1.3. Hence, choosing a high voltage battery could power the Arduino with no regulator, reducing the circuitry to one step-down voltage converter to supply the 6V servo motors. Additionally, it is safer to step-down a voltage supplied by a battery than to step-up. This is due to voltage spikes from a battery also being stepped-up causing damage to the circuitry if a step-up regulator is used [109].

The battery chosen, based off the criteria above, was the 2s2p Lithium-ion battery from generation robots [110]. The specification of the battery is given below in Table 16-2.

Weight	116g
Price	€22.90
Voltage	8.4 – 7.4V
Battery Life	2200mAh
Charger	8.4V Power Jack Inbuilt
Saftey	PCM
Dimensions	67 x 37 x 22 mm

Table 16-2: Battery Specification [110]

This battery will allow a worse case use time of 2hrs 24mins. This is when the two servo motors are stalled, constantly drawing 1000mA. It can supply enough voltage across the whole discharge cycle to power the Arduino micro. It has an inbuilt barrel jack charger, meaning it is rechargeable without any additional circuitry. However, it must be charged by a specific 8.4V charger that can also be ordered, otherwise the battery could get damaged. Its dimensions are compact, meaning there is room for it to be implemented into the gauntlet of the prosthetic. The inbuilt PCM adds additional safety to the battery and the user, protecting the battery from over charging/discharging and short circuits. Finally, the weight of the battery is 116g therefore being greater than 100g criteria. Due to the compact size, safety and battery life, the small excess over the specification was a reasonable trade off.

16.1.2.2 Step-Down Circuit (TE)

To safely step-down the voltage from the 7.4V battery to 6V for the servo motor, a small circuit encompassing a step-down voltage regulator/converter was needed. To choose the regulator there were two compact step-up/down voltage available within the department, being the Pololu S9V11MA [111] and the Pololu S7V8A. To ensure safety of the circuit the Pololu S9V11MA was chosen based of capability of supplying a larger average output current of 1.5A, compared to the 1A of the S7V8A, which has a limit the same as the maximum current drawn by the prosthetic. The full specification for the Pololu S9V11MA is given below in Table 16-3.

Input Voltage	2V – 16V
Output Voltage	2.5V – 9V
Average Output Current	1.5A
Dimensions	12.7 x 15.24mm
Price	€7.96

Table 16-3: Step-Down Voltage Converter Specification [111]

Another component incorporated into the circuit was an ON/OFF 3-way micro switch. This would allow the user to disconnect the power supply from the circuit when not in use. This was included for both safety of the user and to increase the battery life of the device, as the battery will not be constantly having a current drawn from the circuit. The circuit and its schematic is shown below in Figure 16-5 and Figure 16-6 respectively.

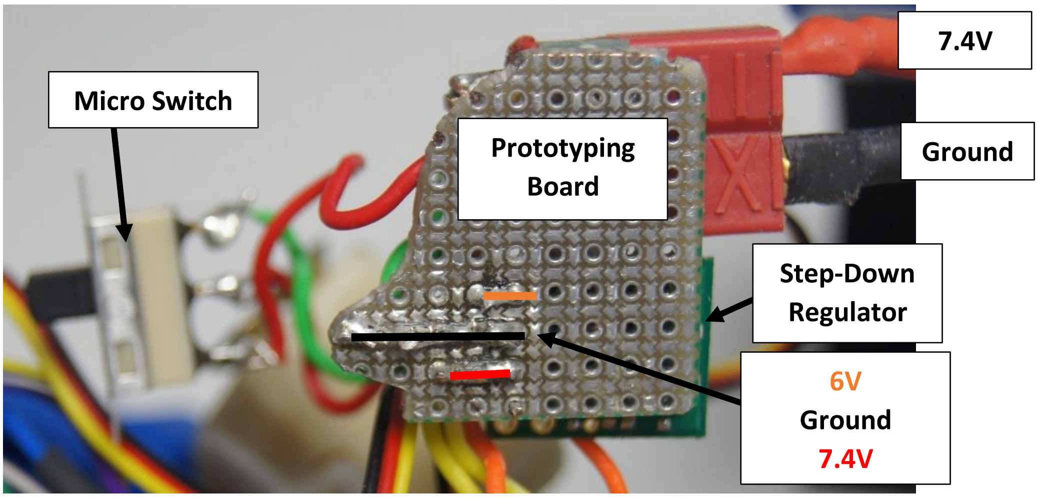


Figure 16-5: Power Step-Down Circuit from Underneath

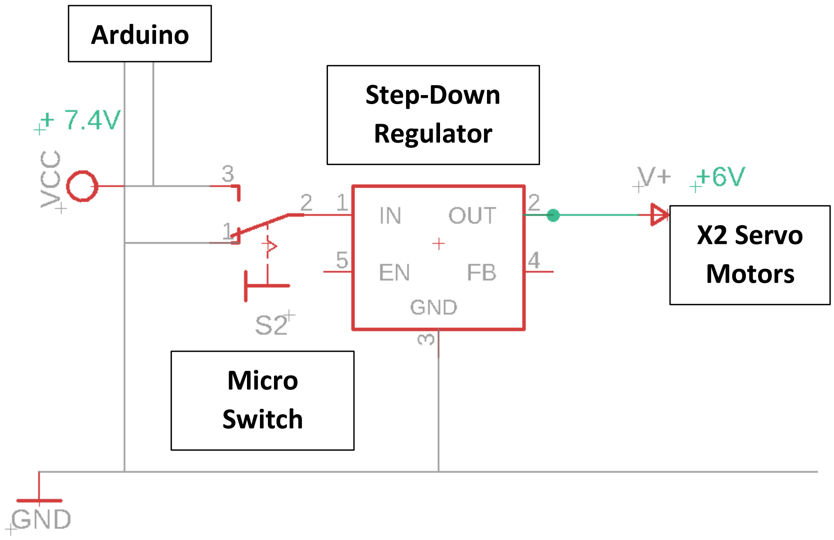


Figure 16-6: Power Step-Down Circuit Schematic

16.1.3 Final Circuit (PB)

For the final prototype, most of the electronics were kept the same. The circuit from the first prototype was shrunk using a 66x39mm prototyping board and clustering all components closer together. All jumper wires were removed along with any headers that were not necessary. Wires were instead permanently soldered to the board. The step-down circuit for the battery was also added to the schematic, as shown in Figure 16-7.

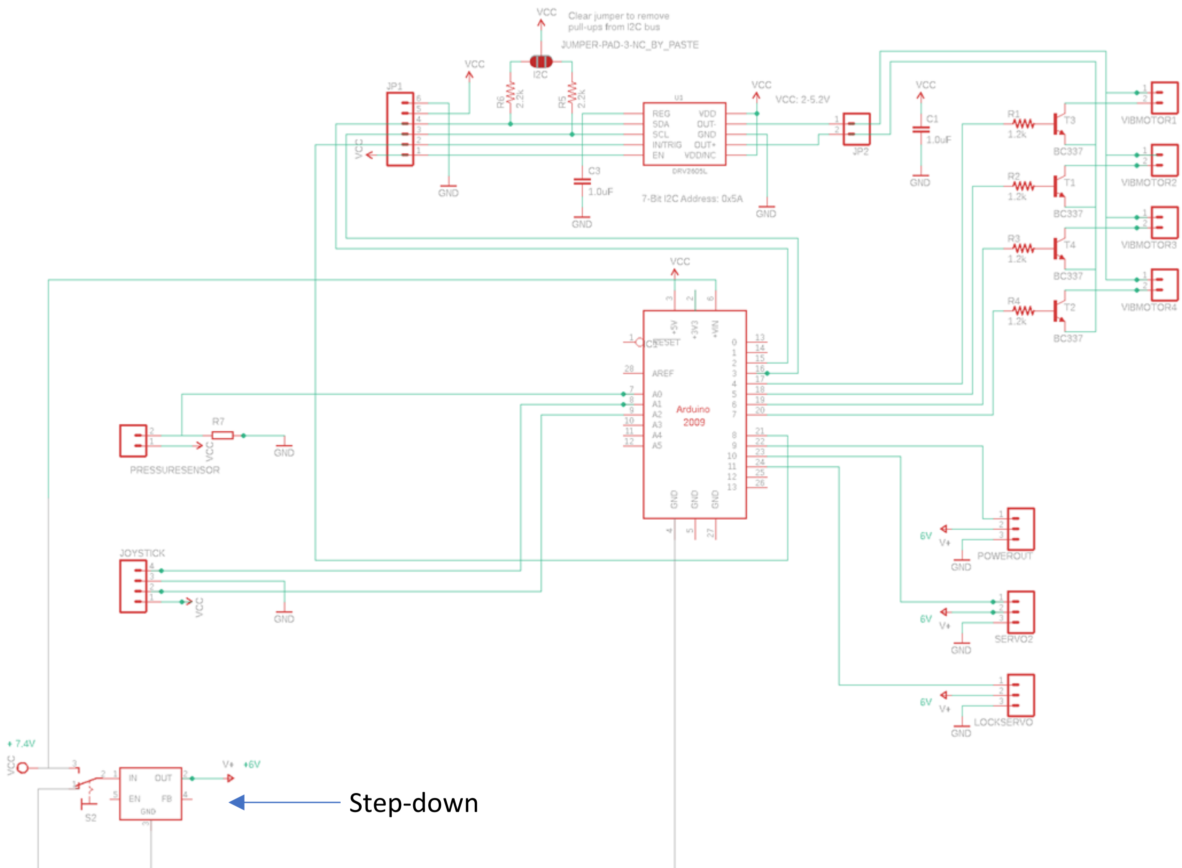


Figure 16-7: Final Schematic

Final Circuit Layout

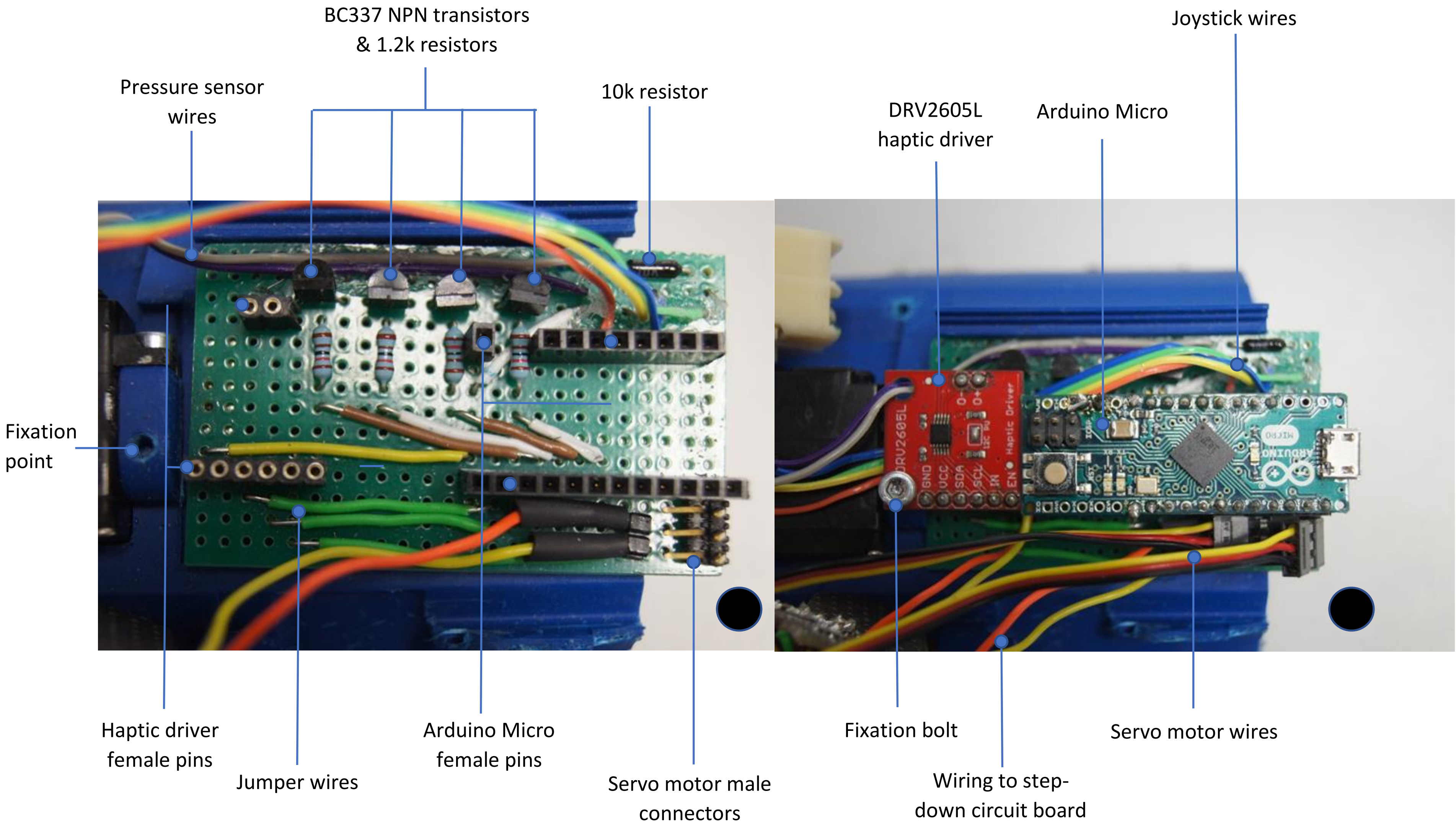


Figure 16-8: Final Circuit

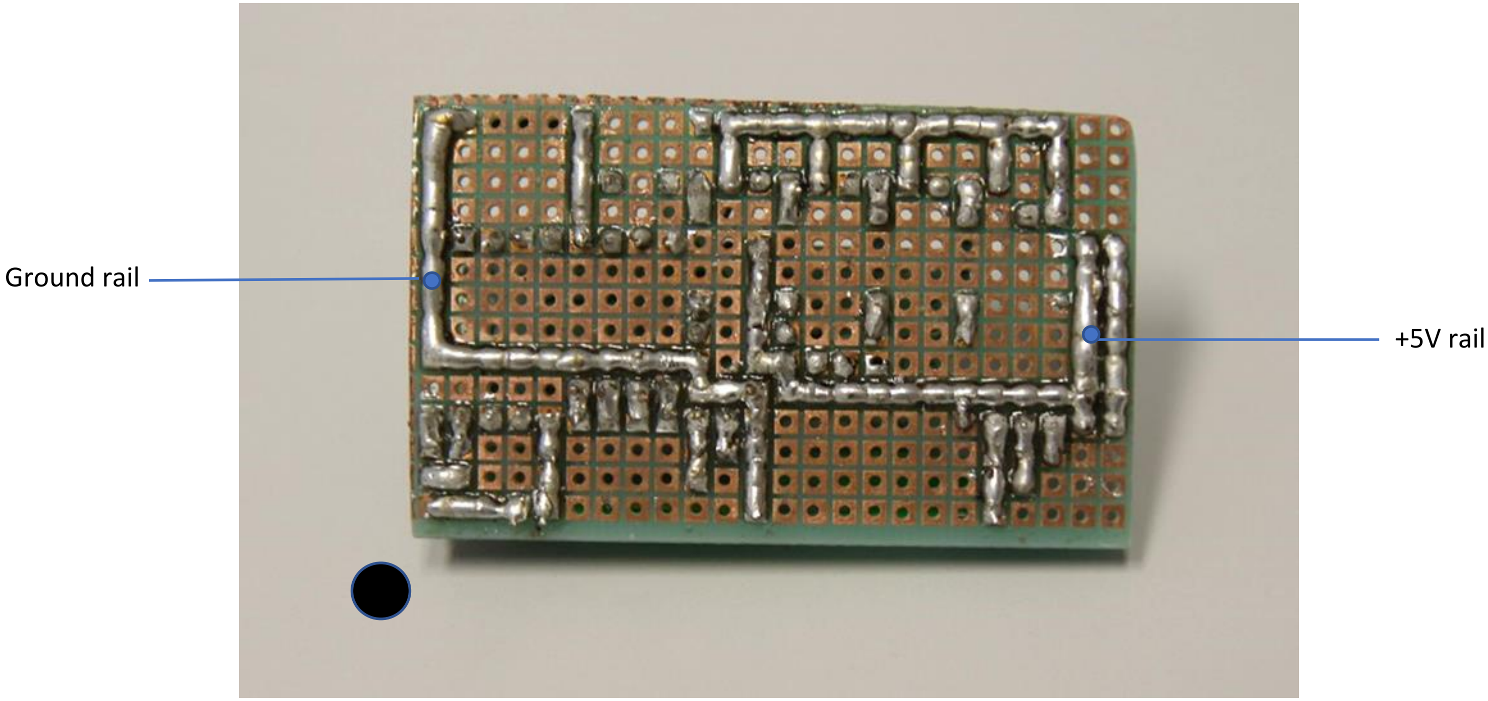


Figure 16-9: Underside of circuit before wires connected, showing circuit solder routes

16.2 Mechanical

16.2.1 Fingers Drooping (JP)

There was an issue with the fingers drooping from to their own weight when in the neutral position. This would consequently reduce the size of an object that the hand could hold because the grasping area would be reduced.

Solution

To prevent the fingers from drooping it was necessary to increase the hook angle, as shown in Figure 16-10. The hook angle was just the angle of the Flexibone hook relative to the horizontal plane. Because none of the fingers were modelled identically it was necessary to change the hook angle of each finger by a different amount. Therefore, the hook angle was varied by 10° increments between 20° to 60°. It was found that the drooping was prevented when the fingers had a hook angle of between 50° (for Little) and 60° (for rest of fingers). As an increase in the hook angle resulted in an increase in the total force required to contract the finger, it was necessary to have a compromise between the two. Hence, the hook angle for the fingers was set at 10° less than the angle that fully prevented drooping and therefore the hook angles were set at a 40° and 50° for the Little and other fingers respectively.

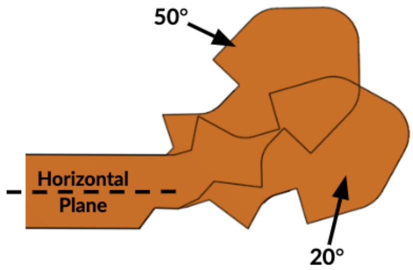


Figure 16-10: Increased Hook Angle

16.2.2 Flexibone Joint Contraction Order (TE & JP)

During the second interview with the user, it was observed that the fingers were having difficulty gripping objects, but instead were pushing them out of the palm. After viewing the prototype trying to grip multiple objects it was determined that it was having difficulty due to the contraction order of the finger's joints. They were contracting so that the distal joint rotated fully before the intermediate and proximal joints began. This led to the distal bone making perpendicular contact as seen in figure Figure 16-11, followed by the object being pushed away from the palm.

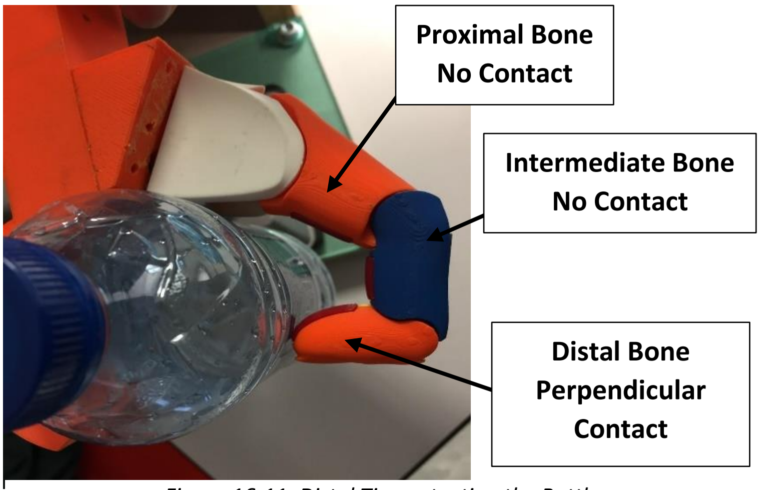


Figure 16-11: Distal Tip contacting the Bottle

To allow the prosthetic to grip the objects, a more natural order of contraction was needed to be achieved. Due to the mechanics of the Flexibone joint, as explained in section 8.1.2, it was decided to change the cross-sectional area of the joints by reducing the size of the cut-out, hence increasing the thickness of the joint. This should increase the torque needed to contract each one and therefore change the order in which they contract. The order that was wanting to be achieved was for the proximal to contract, followed by the intermediate and finally by the distal. This order will allow the fingers to wrap around the object and then be pushed into the palm by the distal bone.

<u>Testing (TE)</u>

As the torque needed to contract the joints was being increased, the force needed to fully contract the fingers would become larger by proxy. As the motors had been selected and the prosthetic still needed a large grasping force, it was decided to carry out preliminary testing on the middle finger to measure the force while changing the order of contraction. Due to the time constraint of finding this issue late on in the project, a thorough test was not planned. It was carried out using the methodology and test set up from the force test in section 8.1.2. The design from the prototype V1 middle finger was first analysed to find the force taken to contract and the order in which it did. The result is shown below with the order of contraction.

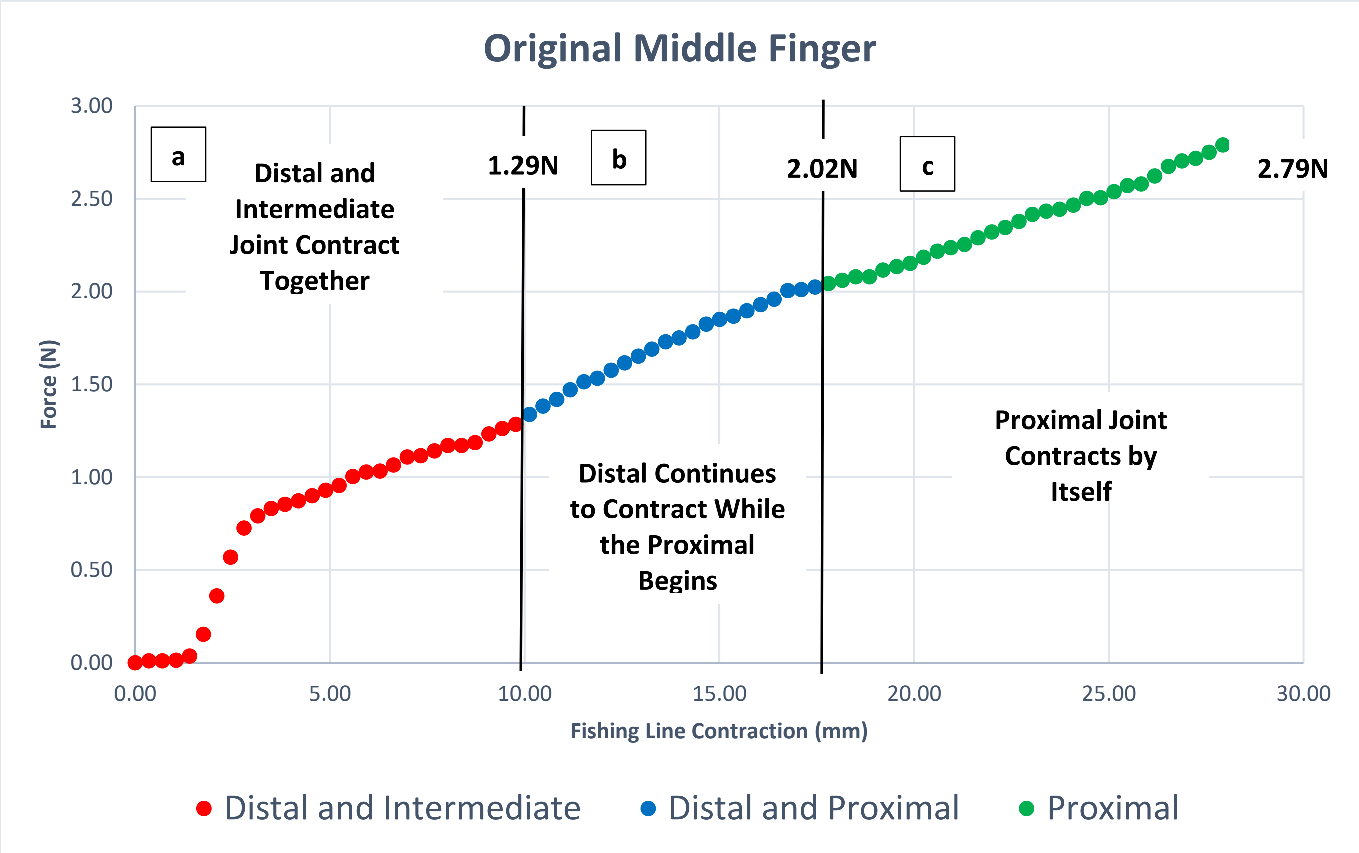


Figure 16-12: Graph Showing the Original Designs Contraction Forces and Order

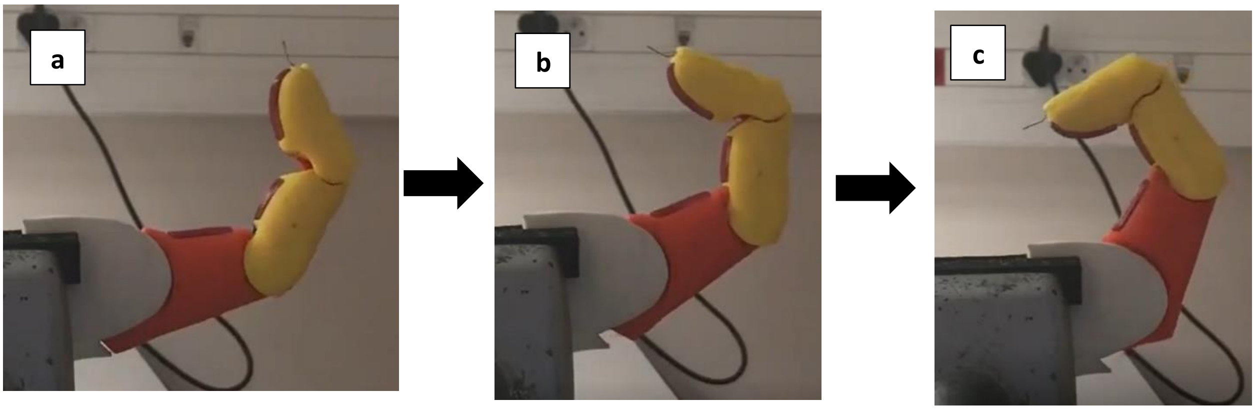


Figure 16-13: Images of the Contraction Points of the Original Design

As highlighted in the Figure 16-12, the total contraction force is low at only 2.79N, but the contraction order is incorrect for a good grip on objects. To get the distal joint to contract last, the force to contract needs to be greater than 2.79N. Therefore, to find a suitable thickness, the first test carried out was to reduce the distal joint cut-out by; 25%, 50% and 75%, while the other two remained the same, and analyse the effect on order and maximum force, see Figure 16-14.

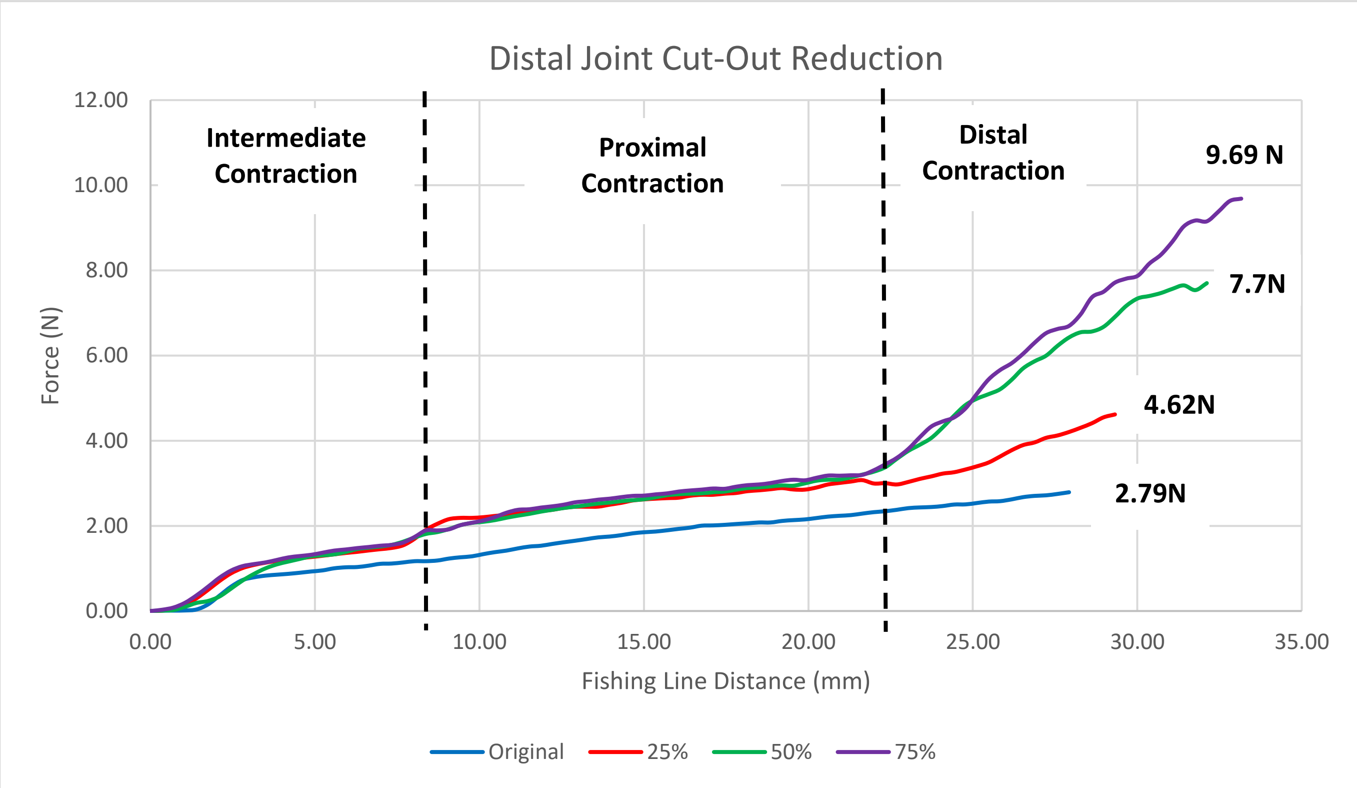


Figure 16-14: Distal Joint Thickness Variation Results

From the test results and video analysis, see Appendix S, when the distal joint was increased to 25%, it changed the contraction order but not enough. The distal joint was no longer contracting first but would start contracting once the intermediate had contracted, along with the proximal joint. In Figure 16-14 this can be seen in the intermediate zone as the 25% now goes higher than the original, as just the intermediate is contracting with no distal contraction force.

Looking at the 50% and 75% reduction, the order is now correct with the distal contracting after the intermediate and proximal joints have finished. However, the maximum contraction force has increased to 7.7N and 9.69N respectively. As the order has been achieved but the minimum contraction force is required, the 50% reduction was selected to be used in the updated distal joint.

After the update to the distal joint, the intermediate joint was also fully contracting before the proximal had started rotating. This was still not the ideal contraction order, as ideally the proximal would contract first in conjunction with intermediate to allow the fingers to wrap around. As when the distal joint's cut was reduced by 25% it started contracting along with the proximal joint, the intermediate joint's cut was then reduced by 25% and tested with the new distal thickness, see Figure 16-15.

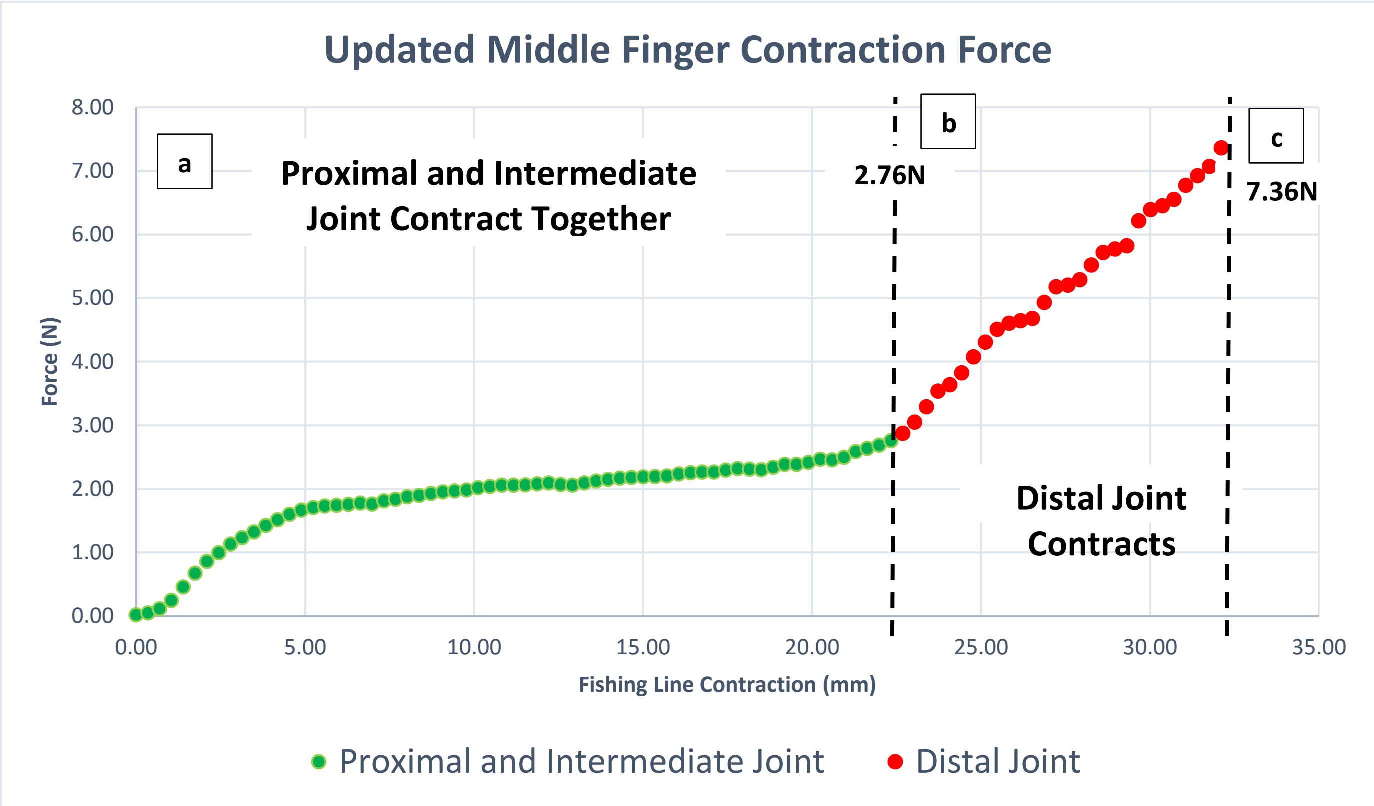


Figure 16-15: New Finger Design Contraction Order and Force Taken

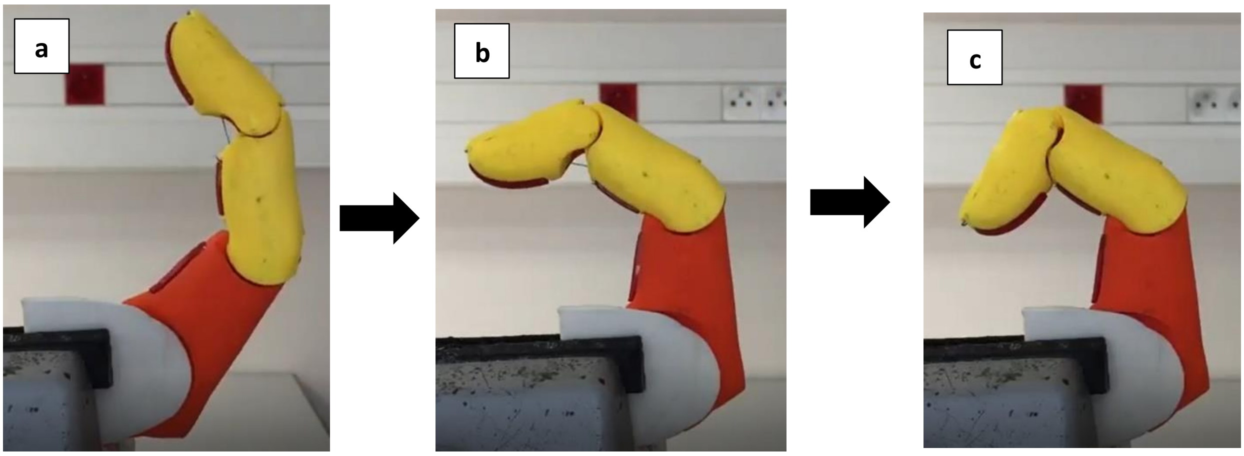


Figure 16-16: New Finger Designs Contraction Order

As seen in figure Figure 16-16, the reduction in the intermediate cut-out by 25% has achieved the desired contraction order in the finger. This order was also helped by the change in the Flexibone hook mentioned in section 16.2.1, also decreasing the amount of force needed to contract the proximal. This new thickness of joints was then applied to the remaining fingers for the final prototype.

Design Updates (JP)

The results from the testing confirmed that the ideal joint angles were a distal joint thickness with a 50% reduction from the original and an interim joint thickness with a 25% reduction from the original for all of the fingers. This meant keeping the joint the exact same shape but simply reducing it by either a 0.5 or 0.75 ratio. The difference between the original and the modified fingers is shown in Figure 16-17 for the middle finger. The extra material beyond the black line in the joints in Figure 16-17 is the additional material added to increase the thickness from the original model.

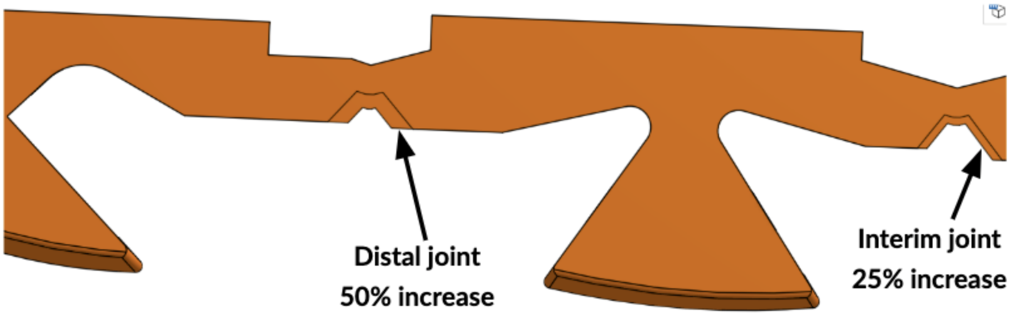


Figure 16-17: Increased Joint Thicknesses

16.2.3 Finger Contraction Order (TE)

During the second interview with the user, while watching the prototype being used, problems were noticed with the contraction order of the fingers and the amount of contraction that takes place in each finger before the motor stalls.

Thumb and Index Finger Pulley

The servo motor and pulley for the thumb and index finger was experiencing a problem which stopped the index finger from contracting early in the cycle. The cause of the problem was the servo motor stalling due to the thumb reaching full contraction. As the thumb can move no further, the torque experienced on the servo motors exceeded the stalling torque. The pulley no longer could rotate, stopping the contraction of the index finger as an affect.

To understand the contraction lengths of each of the fingers, testing was carried out. The test setup and methodology were the same as used for the force test, except for this test the whole palm was constrained and each finger was tested individually, as seen in Figure 16-18 . The fishing wire length for maximum contraction was found for each of the digits, shown below in Table 16-4.

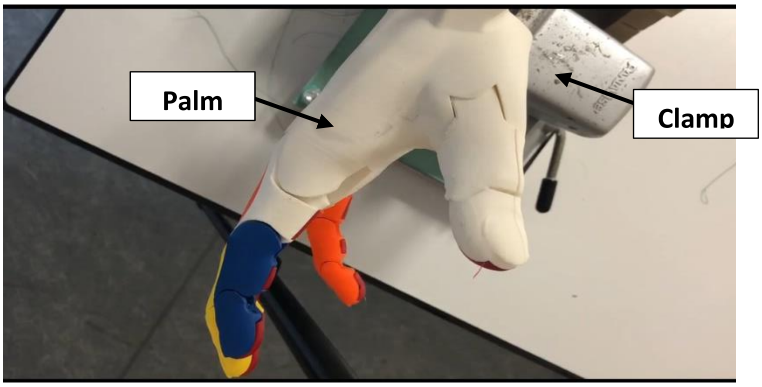


Figure 16-18: Whole Palm Clamped for Testing

Digit	Fishing Wire Length (mm)	Maximum Contraction Force (N)
Thumb	14.7	7.47
Index	35.3	9.69
Middle	32.1	8.55
Ring	35.3	8.09
Little	30.4	6.23

Table 16-4: Fingers Contraction Lengths and Force when Assembled in the Palm

The results of the test clearly highlighted that the contraction distance for the thumb is only half that of the Index finger. This imbalance in lengths on the same pulley will always lead to the index finger not being able to contract before the servo motor stalls.

A solution for this problem comes from a widely used mechanism in the E-Nable community. The whippletree, if implemented, helps distribute the load between the fingers to ensure all the fingers contract [112]. As the diagram below shows, two of the fingers are connected by the same piece of fishing wire. This wire goes through a whippletree, which is where the contraction force acts on the fishing wire, but also where the load is redistributed between the two fingers. When both fingers are free to move it contracts both fingers at the same time as the whippletree is moved backwards. However, when one of the fingers becomes fully contracted, the tension in that side of the fishing wire becomes much greater than the side of the one still contracting. This imbalance of tension causes the fishing wire to slide around the whippletree as it continues to move backwards, therefore continuing to contract the other finger, see Figure 16-19.

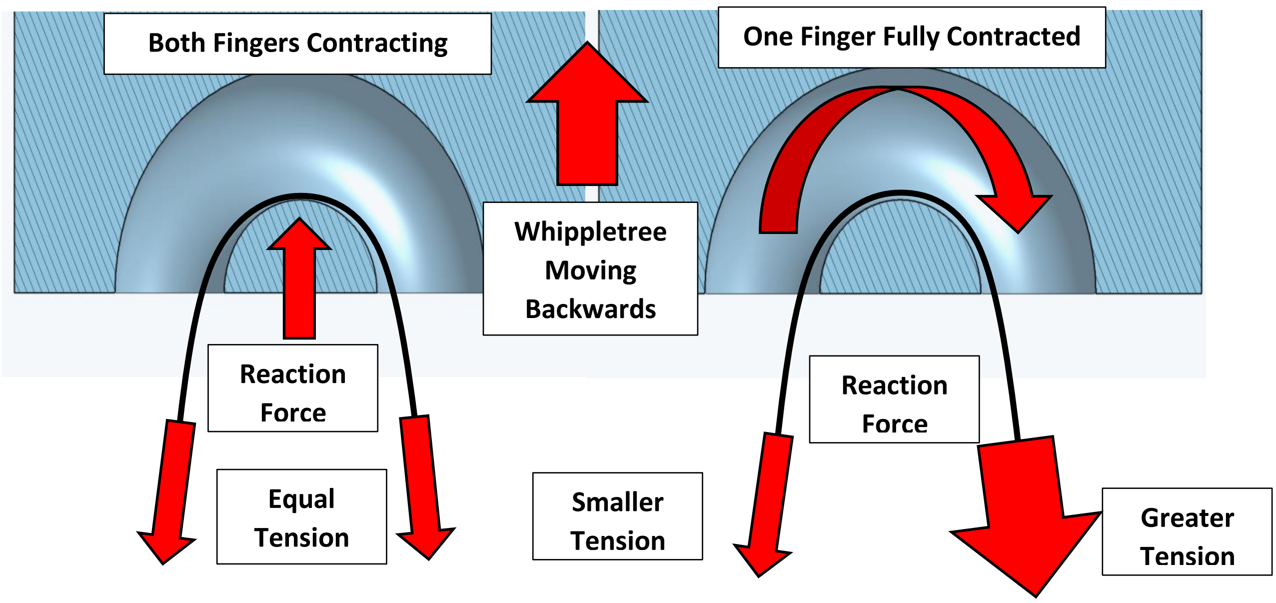


Figure 16-19: Whippletree Mechanism

A whippletree was therefore implemented into the pulley for the thumb and index finger, as this mechanism would allow the index finger to keep on contracting once the thumb's contraction was completed. The whippletree was implemented into one tensioner box with a piece of PTFE tubing inside to reduce friction and make the whippletree more efficient, see Figure 16-20. The whole whippletree system can therefore be pretensioned once assembled, however its implementation removes the ability to pre-tension the index and thumb individually.

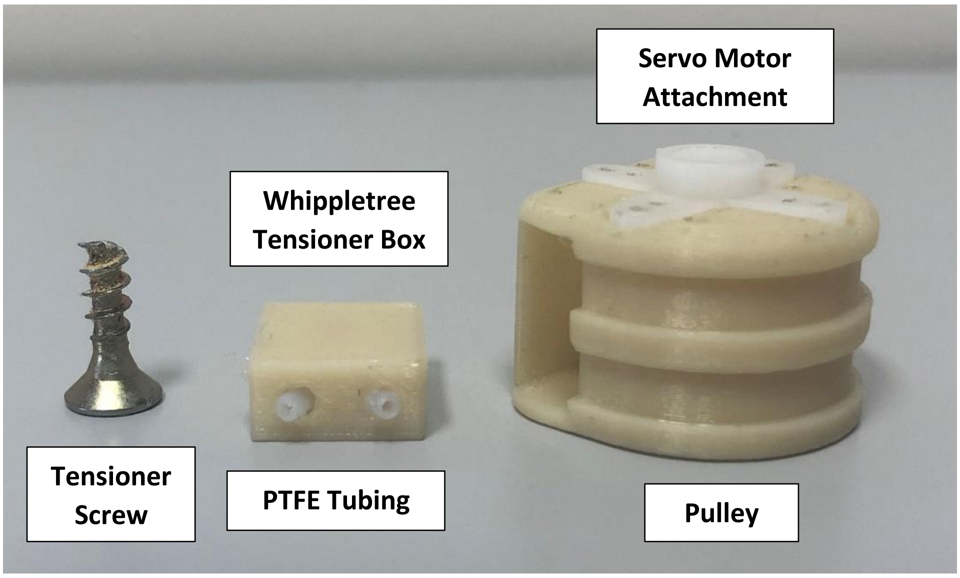


Figure 16-20: Left Pulley Disassembled

An additional change was made to the pulley to ensure it was securely attached to the servo motors and prevent any slipping. The design was edited to incorporate the cross-head attachment into the side of the pulley. The cross head has the correct teeth to mesh with the servo motor output gear preventing it from slipping. Additionally, it allows the pulley to be screwed onto the output gear, preventing it from being pulled off by the fishing line tension.

Finally, looking at the contraction force of the fingers, with the new Flexibone hinge thicknesses in Table 16-4, as described in section 16.2.2, the force to contract all the fingers fully had increased. However, the radius of the pulley did not need to be modified to supply more force as the thumb and index finger pulley needs to provide 17.16N to contract both fully, whereas the force that can be supplied by the pulley is 35.8N.

<u>Middle, Ring and Little Finger Pulley</u>

A similar mechanism was also implemented into the pulley for the middle, ring and little finger. However, a triple whippletree system is a lot more complex to implement. The current width of the pulley is not able to change due to all the elements of the gauntlet and actuation system being designed to work with these dimensions. It is therefore too small to implement a triple whippletree.

The decision was to implement a two finger whippletree, for the middle and ring finger, into one tensioner box, and to have the little on its own tensioner box, see Figure 16-21. This was due to it being beneficial to pre-tension the little finger separately, as a possible configuration of a prosthetic is to use the little as a support finger as mentioned in section 13.2.6.

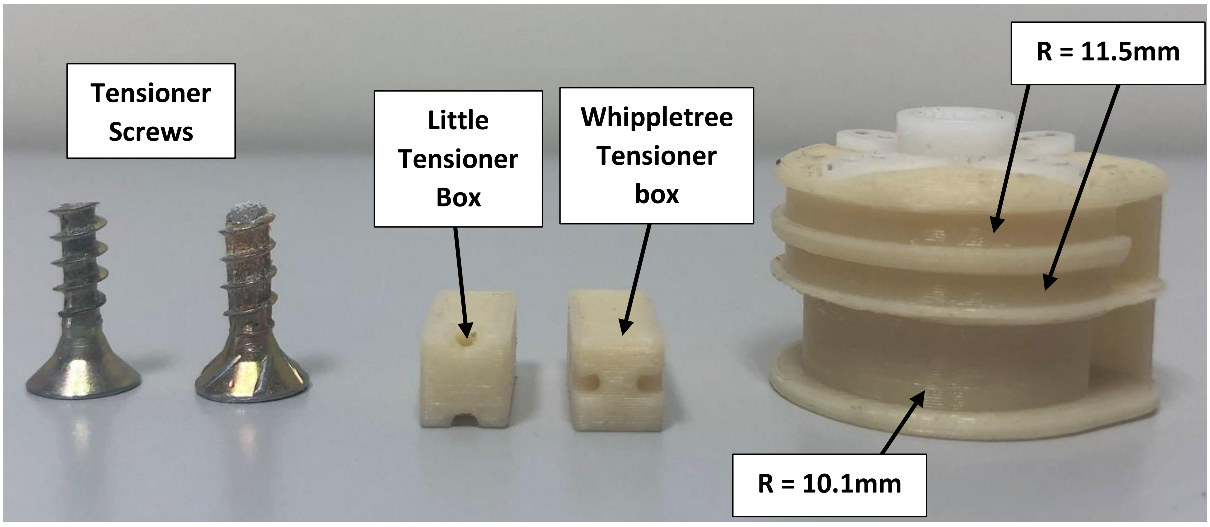


Figure 16-21: Right Pulley Disassembled

To prevent the same problem experienced by the thumb and index finger happening with the little finger, an additional change was made to the pulley. The radius of the groove for the little finger was reduced, therefore reducing the arc length, in turn reduces the rate at which the little finger contracts.

The new radius was designed by finding the ratio between the contraction length of the little and the largest finger out of the middle and ring finger. The ratio had to be with the largest as the little must be the last to contract. This is because when observing the first prototype being used, the little finger was contacting the object before the middle and ring. This was pushing the object out of the palm before it had been stabilised by the middle and ring ringer. A radius of 10.1mm for the little groove was chosen from the following calculations.

$$\frac{31.4}{35.3} = 0.88$$

Equation 16-1: Groove Ratio

$$11.5mm * 0.88 = 10.1mm$$

Equation 16-2: New Radius

The radius of the grooves did not need to be altered for the middle and ring finger due to both the contraction lengths from Table 16-4 being less than the 36.1mm, which the pulley can currently contract, as calculated in section 13.2.6. Additionally, the sum of the force to contract the middle, ring and little fingers fully was 22.87N, which is lower than the 35.8 being supplied by the pulley. Therefore, these pulley dimensions were suitable for the updated finger designs.

16.2.4 Final Gauntlet Layout (PB)

The final gauntlet design changed quite a bit due to the removal of the locking mechanism and introduction of the battery. Fully dimensioned diagrams of the gauntlet and it's casing can be found in Appendix T.

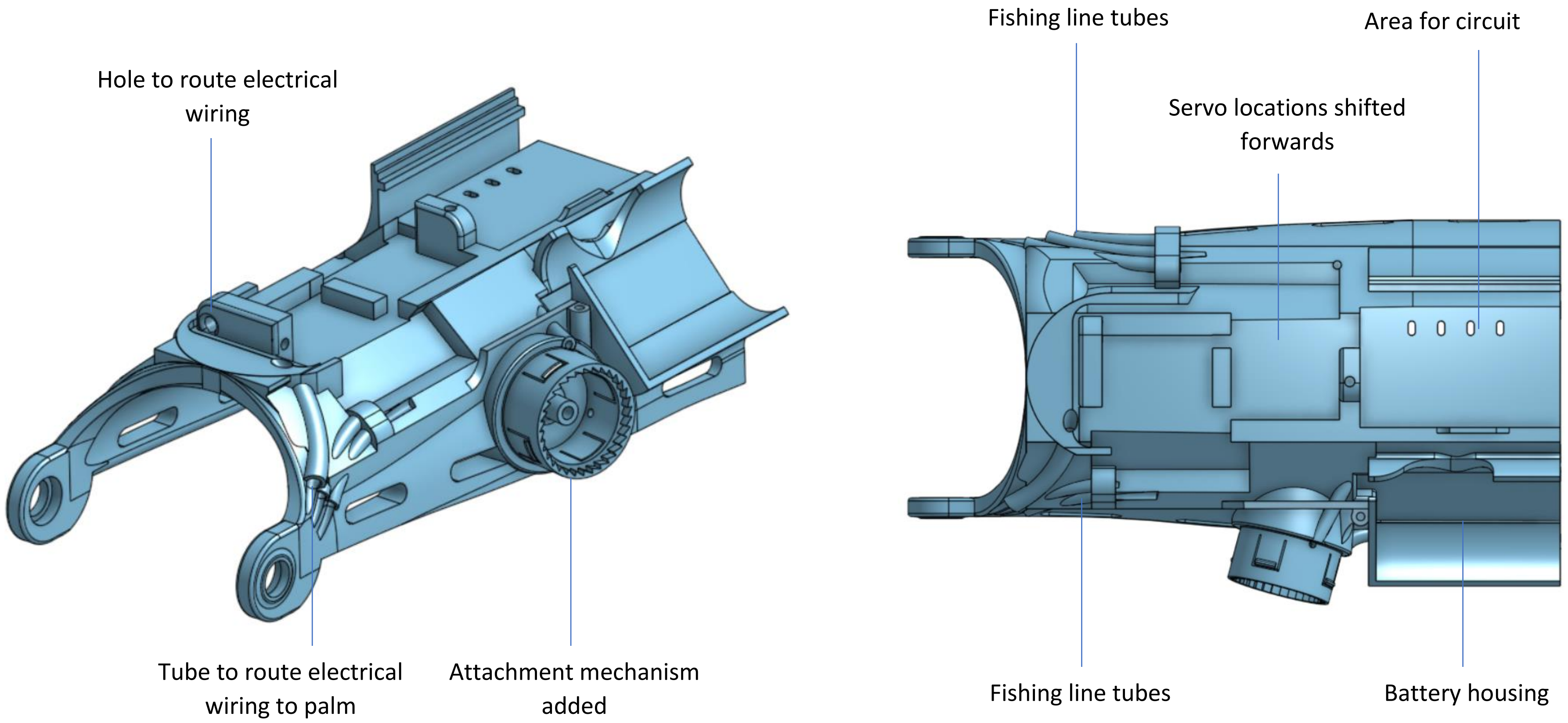


Figure 16-22: Final Gauntlet Layout

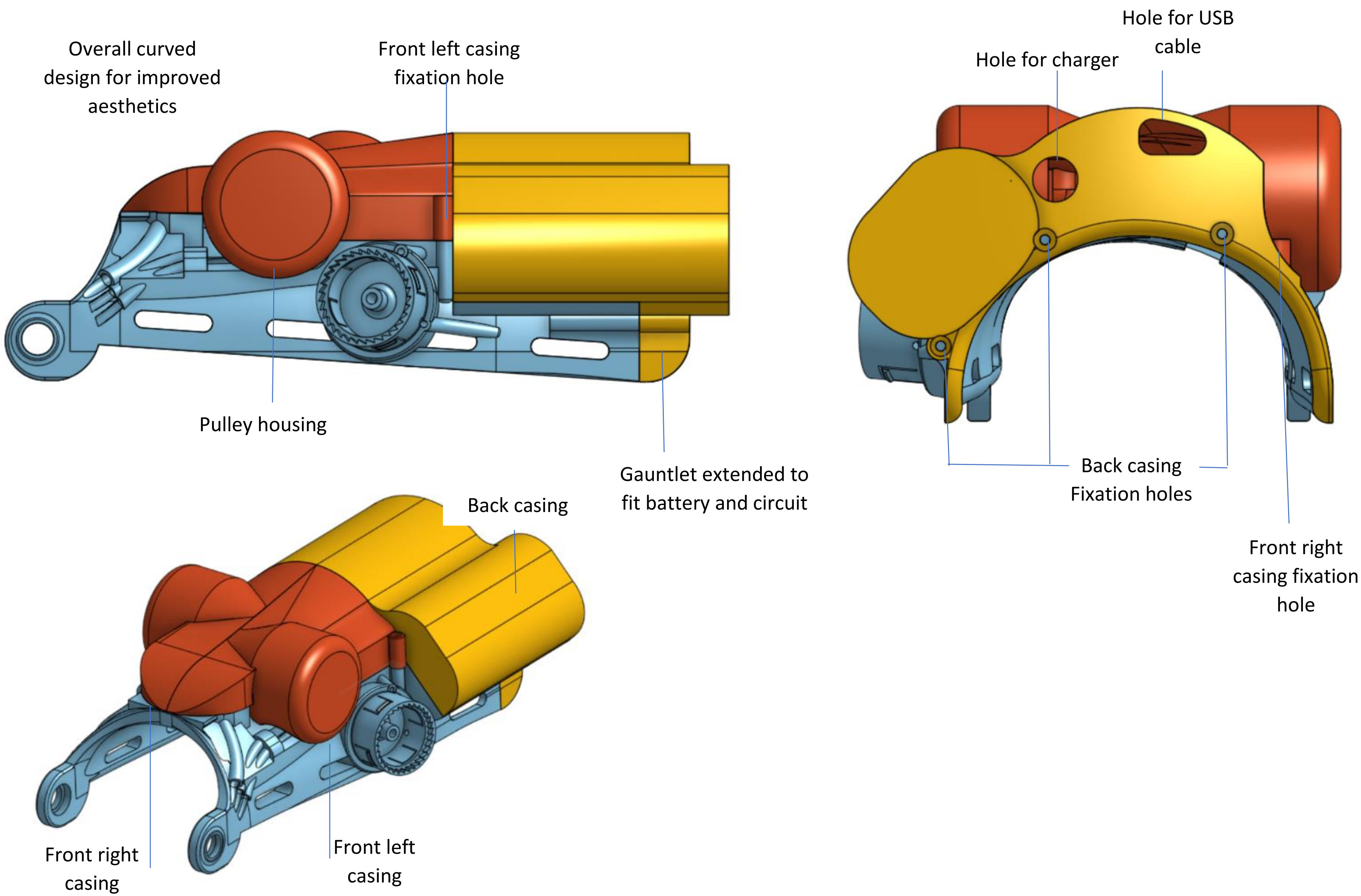


Figure 16-23: Gauntlet Casing

The gauntlet required many modifications for the final prototype. This was a long process that required the team to think about every aspect of the design for them to fit together well. Tolerances were kept quite tight to make the design as compact as possible. The following changes were made:

1. Removed the locking mechanism and moved all other features forwards
2. Interfaced closely with the circuit design to determine where it would be housed and how best to route the wiring.
3. Neaten and contained all wires, including fishing wire.
4. Designed casing to conceal all circuitry, mechanisms and the battery.
5. Improved the fit to the user's arm
6. Integrated the attachment mechanism to the gauntlet.
7. Attempt to make it aesthetically pleasing.
8.

16.2.5 Gauntlet Moulding (TE)

One of the modifications made to the gauntlet was to mould the inside of the gauntlet to the user's arm, as it was currently a generic curved arch. The decision to mould the gauntlet came from feedback and testing of the prototype with the user during the second interview. The feedback stated that the back-left edge of the gauntlet was sharp and impeding on the user's arm. Secondly, during the haptic feedback testing it was noted that the user could not feel two of the haptic motors, only the first and fourth were perceptible. This was due to the second and third motor not sitting on the user's arm because of the shape of the gauntlet.

The gauntlet moulding was carried out by firstly creating a 3D model of the user's forearm, Figure 16-24. This was achieved by using the 3D scan of the user's arm as discussed in section 13.1.1. The model's thickness was increased by 4mm compared to the original scan, giving a 4mm gap between the gauntlet and the user's arm. This was to allow for, tolerancing, room for padded foam for comfort and space for the haptic motors to protrude from the inside of the gauntlet.

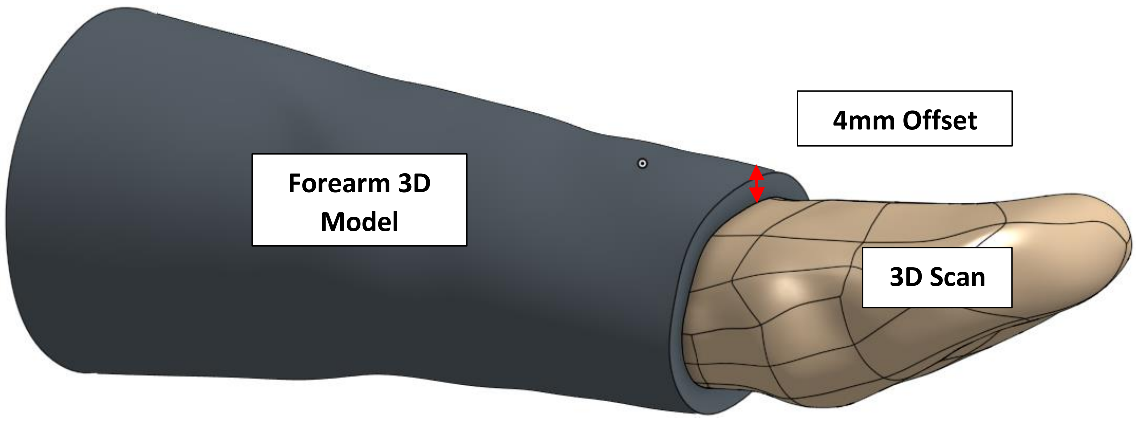


Figure 16-24: Offset 3D model of the Users arm

The forearm model was then used to hollow out the inside of the gauntlet, therefore cutting the inside curvature to the shape of her forearm as shown in Figure 16-25.

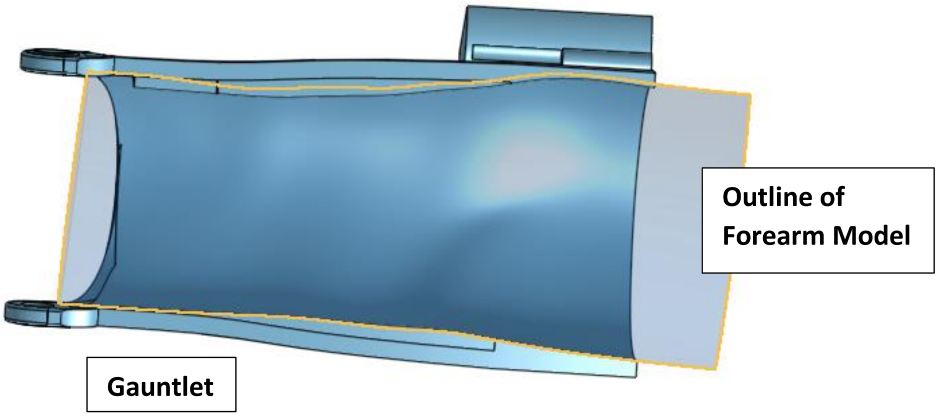


Figure 16-25: Gauntlet Moulding to the Scan

16.2.6 Integrating Attachment Method into the gauntlet (SS)

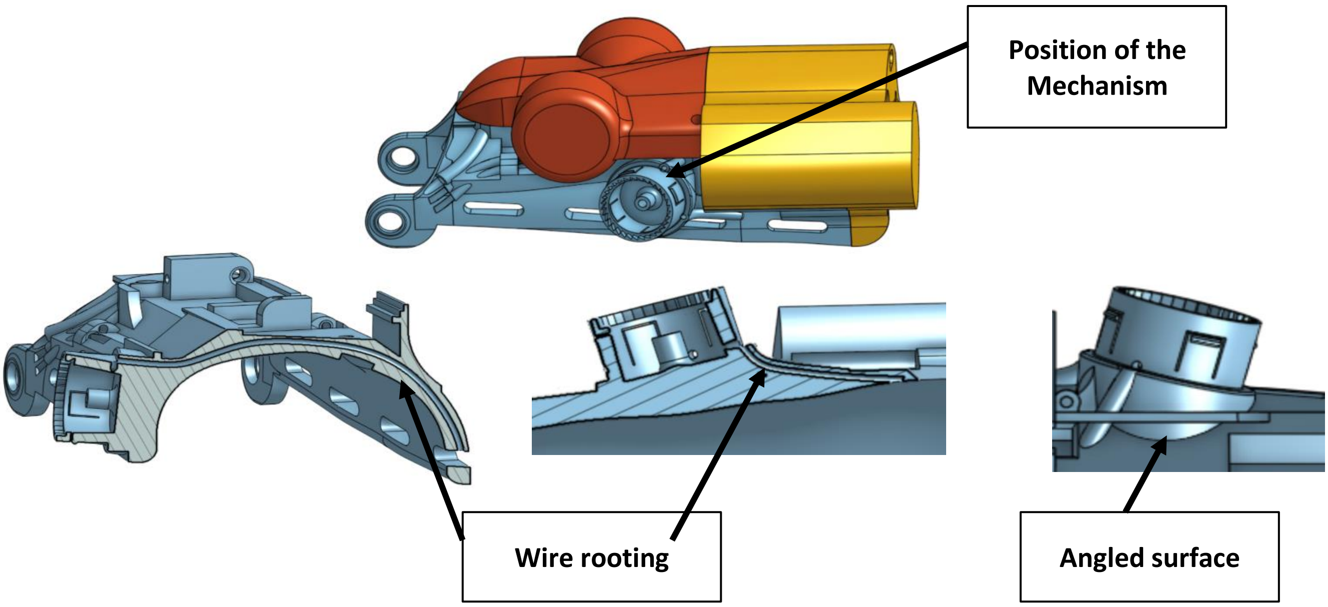


Figure 16-26 shows the gauntlet modifications for the twistable locking mechanism

As for the gauntlet support, the locking mechanism was chosen by the user so it is integrated to the final version of the gauntlet design. On the final design of the gauntlet, the modifications for the locking mechanism was made. As the thickness of the gauntlet was increased, the wire routings were also increased from 1.5 to 2mm in diameter to improve the print quality.

The position of the gauntlet was kept on the right side of the gauntlet as it was so much easier for the user to turn the knob. The mechanism was put in front of the battery on the side of the gauntlet. Therefore the casing was taken into account while positioning the mechanism. For the user to easily grip and turn the mechanism, it was decided to put the mechanism in an angled surface. The surface was inclined 10% and with further prototyping, it was seen that one can easily hold and turn the knob.

Figure 16-27 shows the fabric part that was being attached to the gauntlet

To improve the comfort of the user, underneath the wires the fabric part was designed to reduce the contact of the wires with the forearm. To the fabric cotton part two Tissu 3D foam was put and on top of it wire routing was made. Cross hatches are made to route the wires. By using this method, the prosthesis can be fix on the forearm by using the whole forearm to support. Whereas, in the current prosthetics application with the Velcro straps the support are all comes from the specific points were the straps are attached. The foam parts come together as the wires were being tighten.

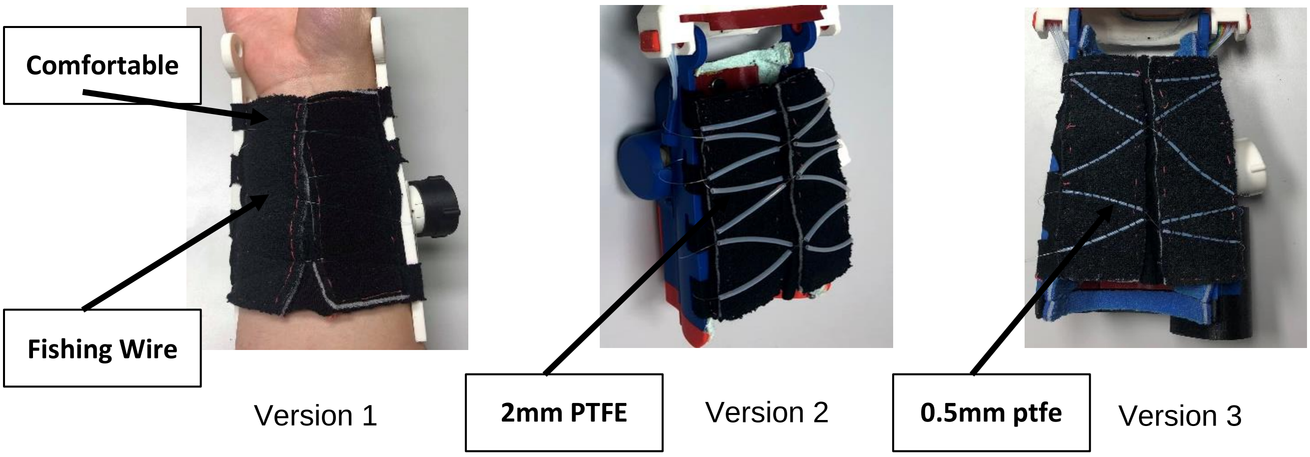


Figure 16-28 shows the different ways of the wire routing

To reduce the friction on the wires due to the fabric and reduce the risk of coughing the wires, PTFE tubing was used. The crosshatches were reduced to have an easy loosening of the wires for the user. The PTFE tubing diameter was reduced to have more compact prototype and as the outer thickness was 1.6mm in the 0.5mm PTFE tube, it made it hard to break or tear the tube whereas outer thickness was 3mm in the 2mm PTFE tubing, was so easily tearing off when it was pulled [113] [114].

17 Mode of Operation (PB)

17.1 Code (PB)

As the joystick was determined to be an effective method of control, the ideas presented in section X in terms of turning the device on and off and toggling between grip patterns were implemented in the final code using the X-axis of the joystick. This on/off code was kept the same as section 13.1.5, but with the addition of haptic feedback to alert the user to when this was triggered.

17.2 Grip Patterns (PB)

With two servo motors controlling two groups of fingers, it is an easy task to turn one off and merely activate a single group of fingers. The difficulty lies more in the controller, and how the user communicates the chosen grip pattern to the device. Fortunately, the joystick design permitted this, with one direction left solely for this purpose (section 13.1.1). The chosen configuration had the index and thumb on one motor, and the remaining three fingers on the other. This meant that the following grip patterns were possible:

- **Finger point grip**

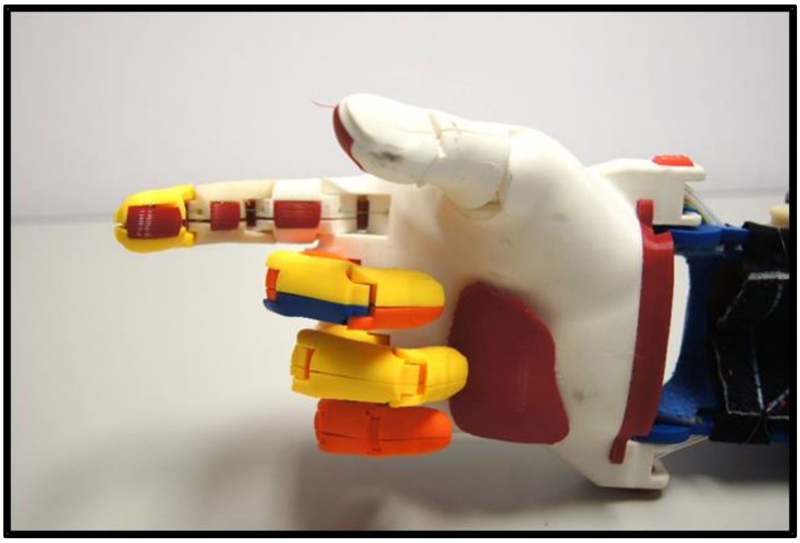


Figure 17-1: Finger Point Grip

Power grip – A stable grasp, defined as when the tips of the fingers oppose the palm. Ideal for holding cylindrical objects such as poles and bottles.

Figure 17-2: Power Grip

Two-point tip pinch – a precision grip used to handle small objects. A precision grip is defined as when a fingertip opposes the thumb to grip an object, in this case the index finger. Arguably, however, due to the position of the thumb this grip is almost a lateral grip, whereby the thumb opposes the side of the index finger rather than the tip.

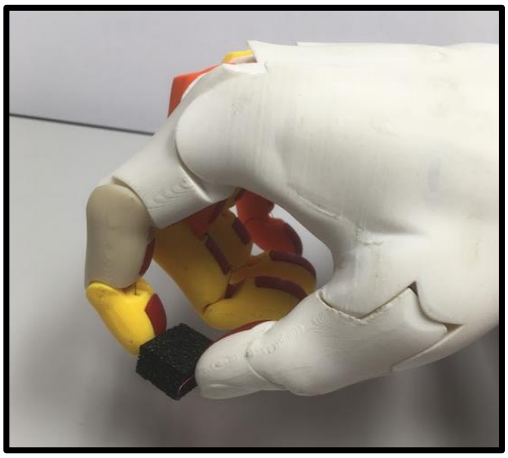


Figure 17-3: Two Point Pinch

Lateral grip– a grip in which the thumb opposes the side of the index finger. To achieve this, the user would need to lift the thumb with the other hand to allow the index finger to slip past. Otherwise the index finger and thumb form a two-point tip pinch.

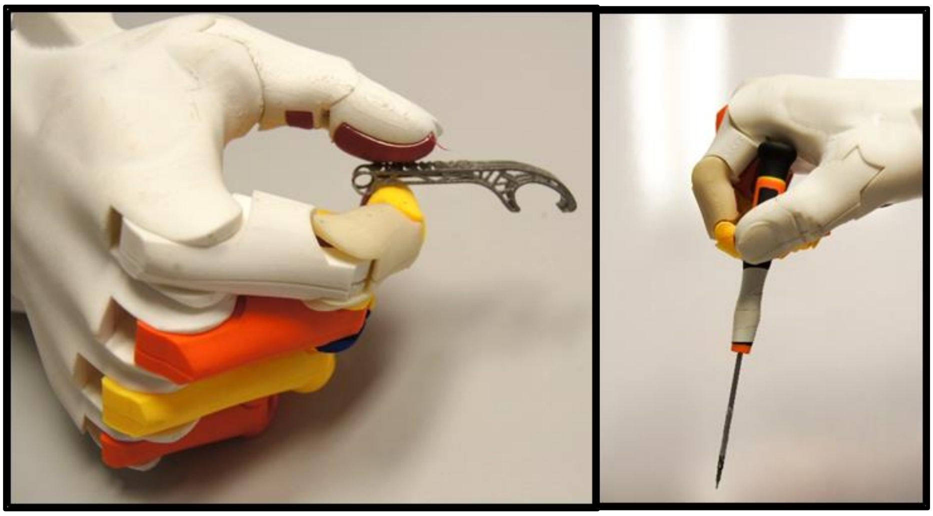
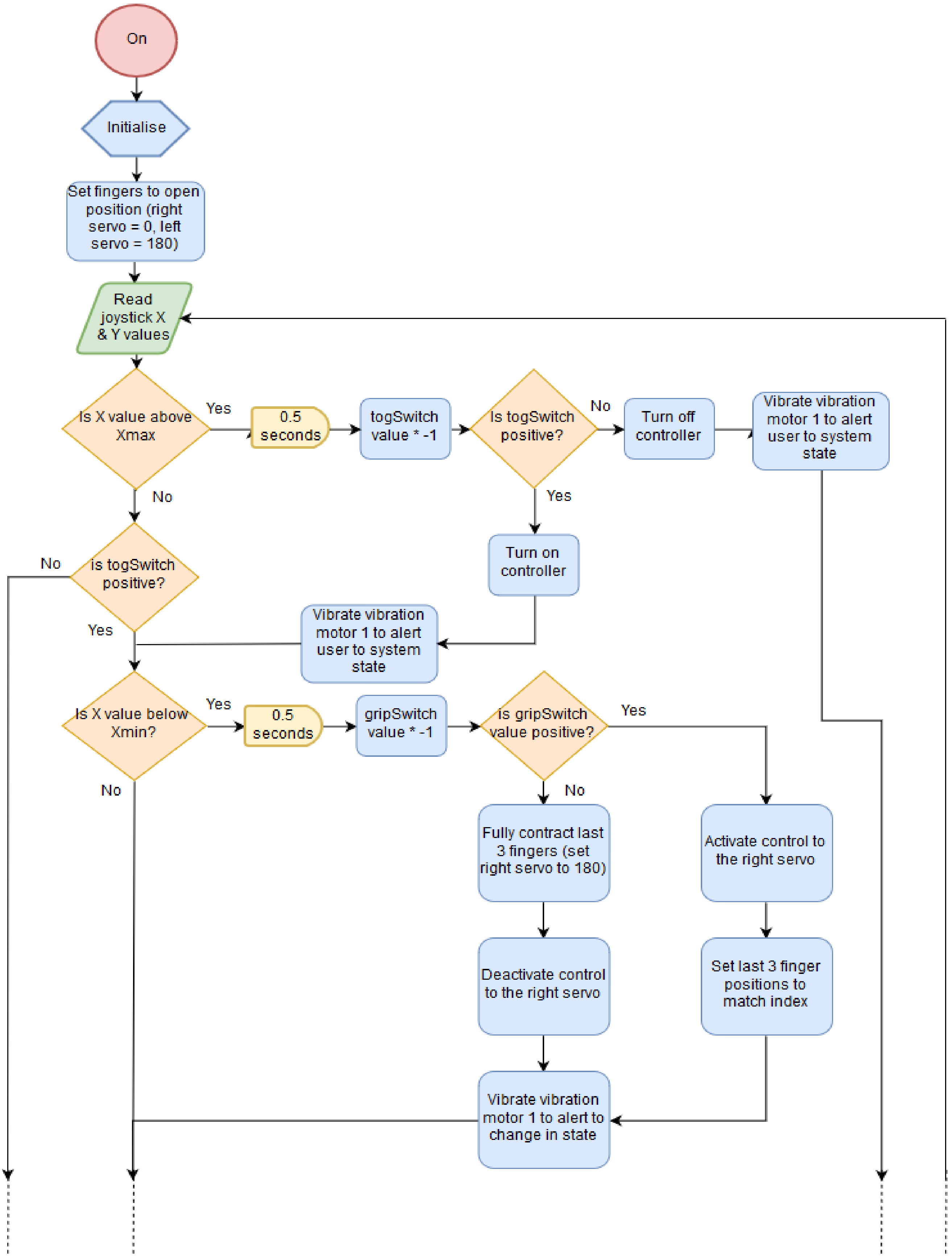


Figure 17-4: Lateral Grip

Primate grasp – where the thumb is not used for grasping. The other four fingers are used in any configuration to grasp an object [115]. In this case, all fingers except the index. It is not a grasp commonly used by humans but may still be useful.

17.3 Flow Chart of Operation (PB)



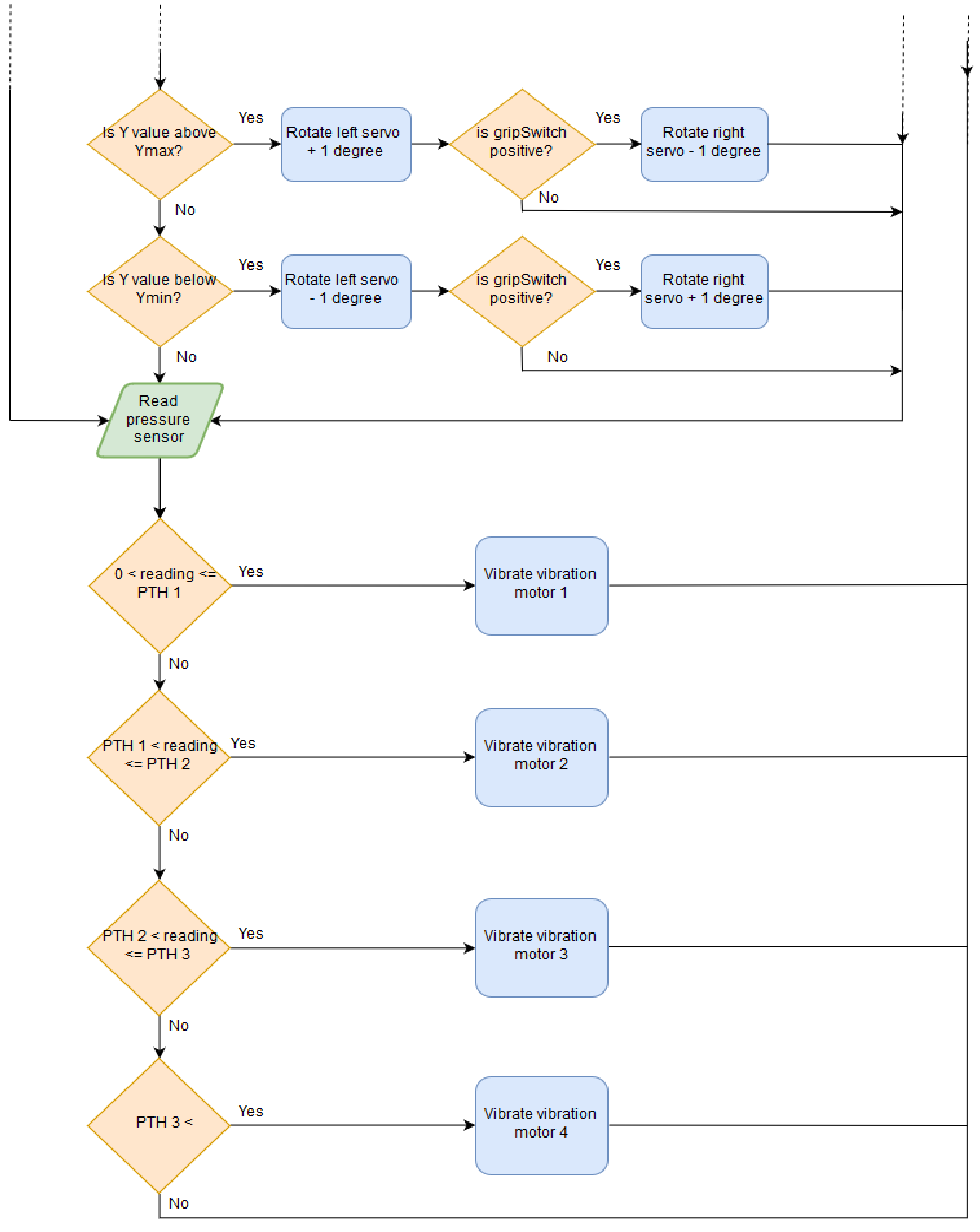


Figure 17-5: Flow Chart of the Operation of the Prototype

Haptic feedback was also implemented to alert the user to when the grip pattern changed. For the final code, see Appendix U.

18 Final Prototype Testing (PB & TE)

Due to the joystick design, the team were able to easily test the functionality of the prosthesis by placing their hands inside the palm and moving the joystick to control its. Although a bit awkward, it allowed the team to discern what objects the prosthesis could hold effectively. Several generic objects were found and tested using the prosthesis.

Object	Grip Pattern	Held	Comments
Empty 500ml bottle	Grasp	yes	Twisted by thumb
400ml water in 500ml bottle	Grasp	yes	
Full 500ml bottle	Grasp	Partially	Object initially gripped but eventually slipped from grasp. Believed to be due to the combined low friction of bottle and NinjaFlex bone.
Hiking pole	Grasp	yes	Firmly grasped with no slippage.
Empty plastic cup	Grasp	yes	Did not twist when grasped gently.
50mm diameter foam cylinder	Grasp		Securely gripped by thumb, index and middle finger.
Feather duster	Grasp	No	diameter too small to grasp
Small sponge	Pinch	yes	
Plastic cap 20mm diameter	Pinch	yes	
Screwdriver	Pinch	yes	But not securely, it pivoted around the fingers.

Table 18-1: Test Objects

Overall, it performed well for most objects, but struggled with those that had small diameters due to the physical limit the fingers could contract to. It was also difficult to grasp objects that had low friction. This was in part due to the NinjaFlex fingertips having a low coefficient of friction.

Figure 18-1: 50mm foam cylinder picked up by prosthesis.

Interestingly, when the foam cylinder was picked up using the grasp pattern, the index, middle finger and thumb contacted the object and secured it firmly. Despite being connected to the same pulley as the middle finger, the ring and little could continue to flex. This showed that the whipple-tree mechanism is effective in adapting the grip for different objects.

19 Final User Meeting/Feedback on the Final Prototype

The final meeting took place on 17th June 2019. The user, supervisors and senior members of staff at the University were present along with Patrick from team Gre-Nable. Prior to the meeting, the team designed a plan:

1. Present the full prototype to the user with only the servo control code implemented in the joystick. This was to allow her to get used to the joystick configuration again.
2. Test the prosthesis with a range of objects to assess its performance using only the grasp pattern.

Objects		
Hiking pole	Screwdriver	Small sponge
500 ml water bottle – empty, 100ml, 200ml, 300ml, 400ml, 500ml	4x8x4mm plastic box of bolts	Board pen
Bottle opener	Empty plastic cup	Fork

Table 19-1: Objects prepared for demonstration

Re-upload the code with the pinch toggle switch and allow the user to test.

3. Repeat 2. with the pinch grip pattern
4. Re-upload the code with the on/off toggle switch and allow the user to test
5. Feedback/discussion
6. Questionnaire for the user to evaluate the prosthesis, provide additional feedback and compare against her current myoelectric hand and her mechanical Kwawu prosthesis.

The final meeting was an opportunity to present the final prototype to the user and obtain feedback. Unfortunately, on the day of interview there were multiple technical issues that meant it could not perform to its maximum capacity and as a result the interview was cut short.

The servo motor responsible for contracting the middle, ring and little fingers broke within minutes of the user testing the prosthesis. With no spare motors or ways to fix it, the prosthesis was left with only the pinch function. Stage 2 was therefore not possible. The team moved directly to stage 4, and the user was able to successfully grasp and release the following objects:

- Empty plastic cup – the user was able to pick this up with ease, inverting it as shown in Figure 19-1.b without it slipping or dropping, then placing it into her other hand.

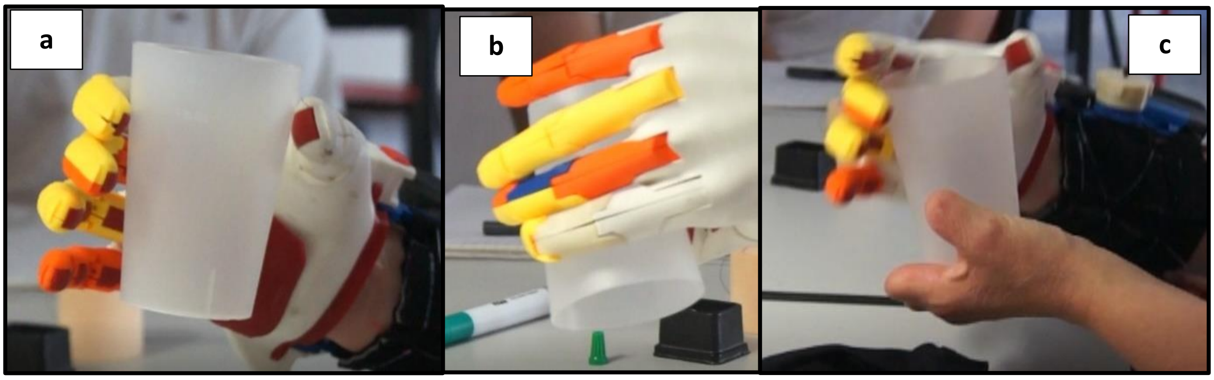


Figure 19-1: Objects prepared for demonstration

- 50mm diameter cylinder – the user was also able to pick this up immediately, demonstrating precise control of the pinch grasp. Interestingly, even though the object was firmly grasped, the user used her other hand to readjust its position in the finger's, so they provided more solid contact. Again, she was able to invert the cylinder without it slipping, and then proceeded to open the fingers and intentionally drop it into the cup.

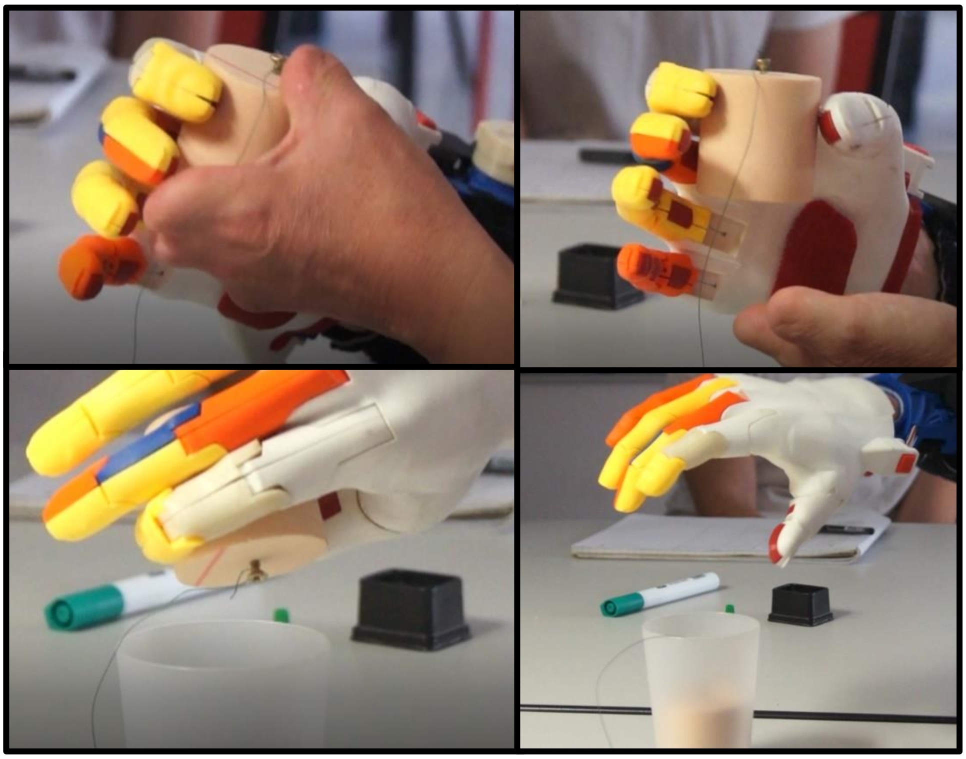


Figure 19-2: user handling a 50mm diameter foam cylinder

- 100ml water in a bottle - 100ml was used as only the index and thumb could be used to grip, and therefore the total gripping force was lower. The prosthesis performed well, however, with the user confident enough to remove the lid and pretend to drink from the bottle.

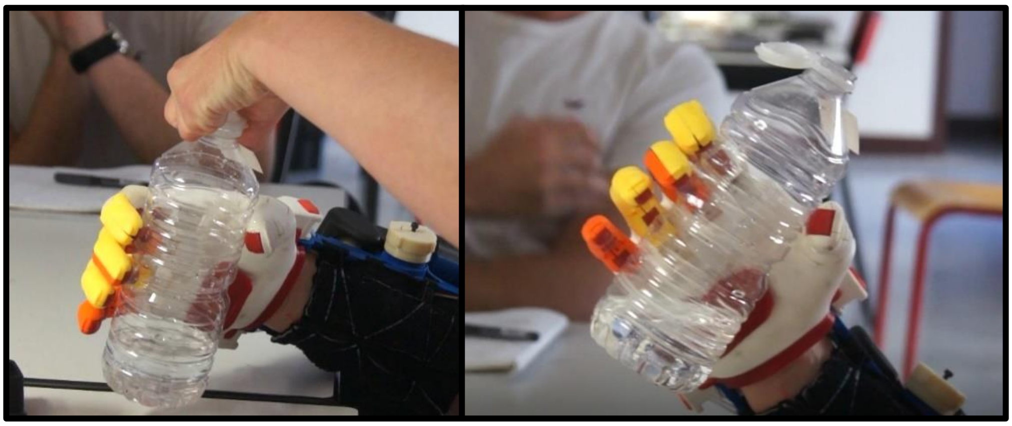


Figure 19-3: user handling a plastic bottle with 100ml water

- Plastic box of bolts – this object was slightly more difficult to grasp due to its small size, low friction surface and the fact that using the pinch meant the object rotated when not grasped along the axis of its centre of mass. The user consequently struggled with this at first, but using her other hand was able to adjust it until the thumb and index pinched along the axis of rotation and the object no longer rotated.

Figure 19-4: user handling a plastic box of bolts

At this point, the second servo motor also broke, leaving the prosthesis completely un-operational. This was frustrating for the team, but the tests that were completed, along with the feedback and discussion with the user afterwards, provided some useful insights.

19.1 Observations and Feedback

- At the beginning of the interview when both motors were functioning, the user lifted the thumb with her other hand to allow the index finger to fully contract with the other fingers. This would bend the index finger towards the middle finger because it was hitting the thumb/palm.
- She frequently uses her other hand to assist the prosthesis, for example by readjusting objects
- She initially found it difficult to use the joystick but found it easy once she figured out the configuration.
- In terms of the pointing grip, she said she would use this for typing, however stated it would be better if instead of having the other three fingers fully contracted they should be completely straight, as in the current configuration they get in the way.
- She liked that most of the weight sat at the back of the gauntlet, unlike her current myoelectric prosthesis.
- The pressure sensor was not well calibrated, with the thresholds too close together. She also found it difficult to discern between vibrations, other than between the first and last motors.
- The attachment mechanism for the gauntlet was effective, with the user easily able to attach and detach it unaided. She mentioned, however, that an extra strap might be needed at the rear of the prosthesis as it raised up slightly from her forearm. This also meant the last vibration motor did not always contact her skin.

19.2 Conclusions

- The cause of the first servo failing was due to the teeth shearing on a gear inside the motor. This was found to be a consistent problem with the plastic geared motors, even when powered at a voltage lower than it's maximum.
- The suspected cause for the second servo failure was a damaged wire. During the latter stages of the interview the user began to find it difficult to control the prosthesis, with it jumping between unresponsive and responsive. Initially it was thought that this was a problem with the control code and the on/off code being left in, meaning the user had accidentally turned it off, but it was later found that this was not the case. Instead, no current was being drawn by the servo. This servo had metal gears and

was therefore stronger in this sense, but rigerous testing with it over the prior weeks likely lead to its failure. The team were unable to diagnose if a faulty wire was to blame.

20 Stage Gate 5 Conclusions

- The cause of the first servo failing was due to the teeth shearing on a gear inside the motor. This was found to be a consistent problem with the plastic geared motors, even when powered at a voltage lower than it's maximum.

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- It's clear that thumb closure plays an important role in grasping objects. Because the thumb joint contracts at the same time as the index finger, as they contract they form a pinch grasp that stops the index flexing further into a power grip. During the final interview, the user overcame this by manually lifting the thumb and allowing the index to flex beneath it in line with the other fingers.

- The haptic array requires significant development before it can be used effectively.

21 Safety

During the design process of the prototype there were some key choices made to ensure the safety of the user. It was extremely important to uphold the safety of the device as firstly it was for a user whom it will be attached to. Secondly, the device is electronically assisted, which if not properly protected, can be incredibly hazardous if damage occurs to the battery or circuitry.

There were four main design implementations to ensure a safe design, these being:

1. Micro switch to disconnect the battery. This allows the user to turn off the design completely, allowing them to wear the prosthetic without fear of activating the system. Additionally, it stops the over use of the battery, which causes degradation over time, meaning the battery is only draining when the user is using the device.

2. PCM in the battery. This is a 'Protection Circuit Module' located in the battery pack, monitoring the behaviour of the circuit and power supply. It protects the battery against; over charging, current over draw and short circuits, creating a protected and robust power supply system for portable devices.

3. Step-down voltage regulator. This component is in the power management system to ensure the correct voltage is being supplied to the servo motors. A step-down converter was chosen as it will protect the circuitry against voltage spikes from the battery. Additionally, it includes short circuit protection, protecting the rest of the circuit as well.

4. Gauntlet Casing. A casing was created to conceal all the circuitry and actuation system. It provides protection to the battery and circuit against impacts, while ensuring the electronics cannot come into direct contact with the user and other objects. As well as the electronics, the casing prevents the mechanical system getting jammed or caught on local objects. This is due to the pulleys being completely concealed inside the casing.

22 Method of Assembly

22.1 List of Materials

Thumb

Name	Quantity
Distal Left	1
Distal Right	1
Proximal Left	1
Proximal Right	1
Bone Distal	1
Bone Proximal	1

Index Finger

Distal Left	1
Distal Right	1
Intermediate Left	1
Intermediate Right	1
Proximal Left	1
Proximal Right	1
Finger Bone	1
Conductive Nylon Fabric Tape ()	2
Pressure Sensor (400 round short tail) []	1
Clincher Connector	2

Middle Finger

Distal Left	1
Distal Right	1
Intermediate Left	1
Intermediate Right	1
Proximal Left	1
Proximal Right	1
Finger Bone	1

Ring Finger

Distal Left	1
Distal Right	1
Intermediate Left	1
Intermediate Right	1
Proximal Left	1
Proximal Right	1
Finger Bone	1

Little Finger

Distal Left	1
Distal Right	1
Intermediate Left	1
Intermediate Right	1
Proximal Left	1
Proximal Right	1
Finger Bone	1

Fishing Line Assembly

700mm	2
400mm	6
M2 Nut	4
4mm Plastic Disk	1

Palm

Palm	1
Wrist Pin Left	1
Wrist Pin Right	1
Pin Cap	2
OD 2mm PTFE Tube 300mm	5

Gauntlet

Gauntlet	1
Front Casing Left	1
Front Casing Right	1
Back Casing	1
Haptic Motor Ninjaflex Housing	4
Tissue 3D Foam ()	1
M3x12mm Bolt	2
M2x25mm Bolt	3

Actuation

Hitec HS-5087MH Servo Motor	2
M3x15mm Bolts	2
White Attachment Cross	2
Servo Attachment Screw	2
Pulley Left	1
Pulley Right	1
Left Pulley Whippletree Insert	1
Right Pulley Whippletree Insert	1
Right Pulley Little Tensioner Insert	1
M3x12mm Screws	3

OD 2 PTFE Tubing 15mm	1

Main Circuit

Prototype Board	1
Arduino Micro	1
Joystick	1
Joystick Attachment	1
DRV2605 L Haptic Driver	1
1.2k Resistor	4
BC337 NPN Transistor	4
Vibration Motor	4
Male Headers	
Female Headers	
Jumper Wires	
Wire	

Power Circuit

Prototyping Board ()	1
7.4V Lithium-Ion 2200mAh Battery	1
8.4V Barrel Jack Charger	1
ON/OFF Micro Switch	1
S9V11MA Step-Down Voltage Regulator	1

Attachment Mechanism

Teklon Hi-Tech Fishing Wire	1
Wheel	1
Gear	1
Case	1
M3x20 Screw	1

Fabric Under the Wires

Cotton Fabric	1
Tissu 3D	1
PTFE Tubing 0.5mm diameter	1
Snap fasteners	8

Foam Padding

Tissu 3D Foam Padding	1
Sticky Back Velcro	1

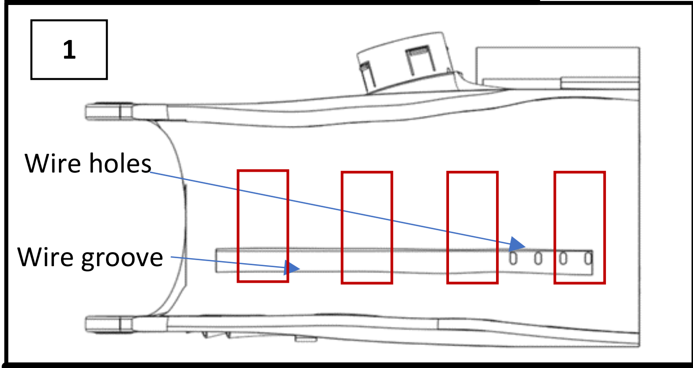
Gripping Improvement

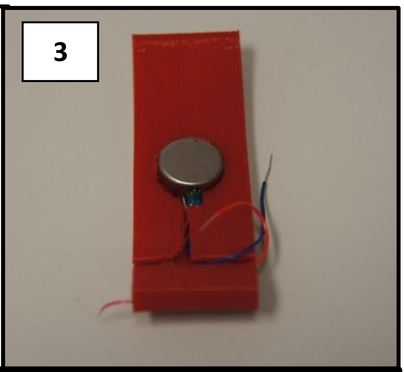
Flexible Gripping Improvement part	1
Glue	1

Table 22-1: List of Materials for Prototype Assembly

22.2 Assembly Guide

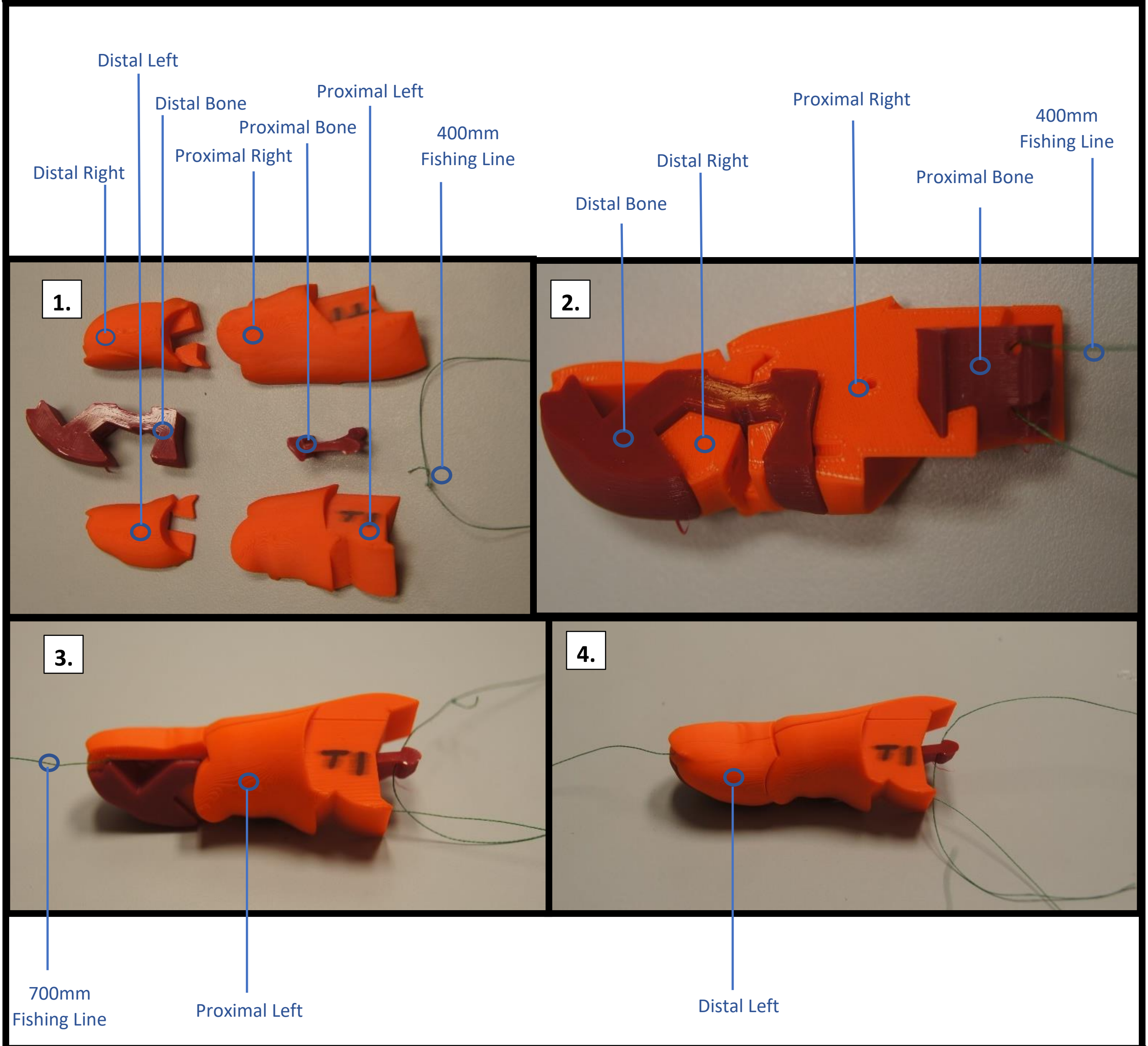
Haptic Motors Assembly





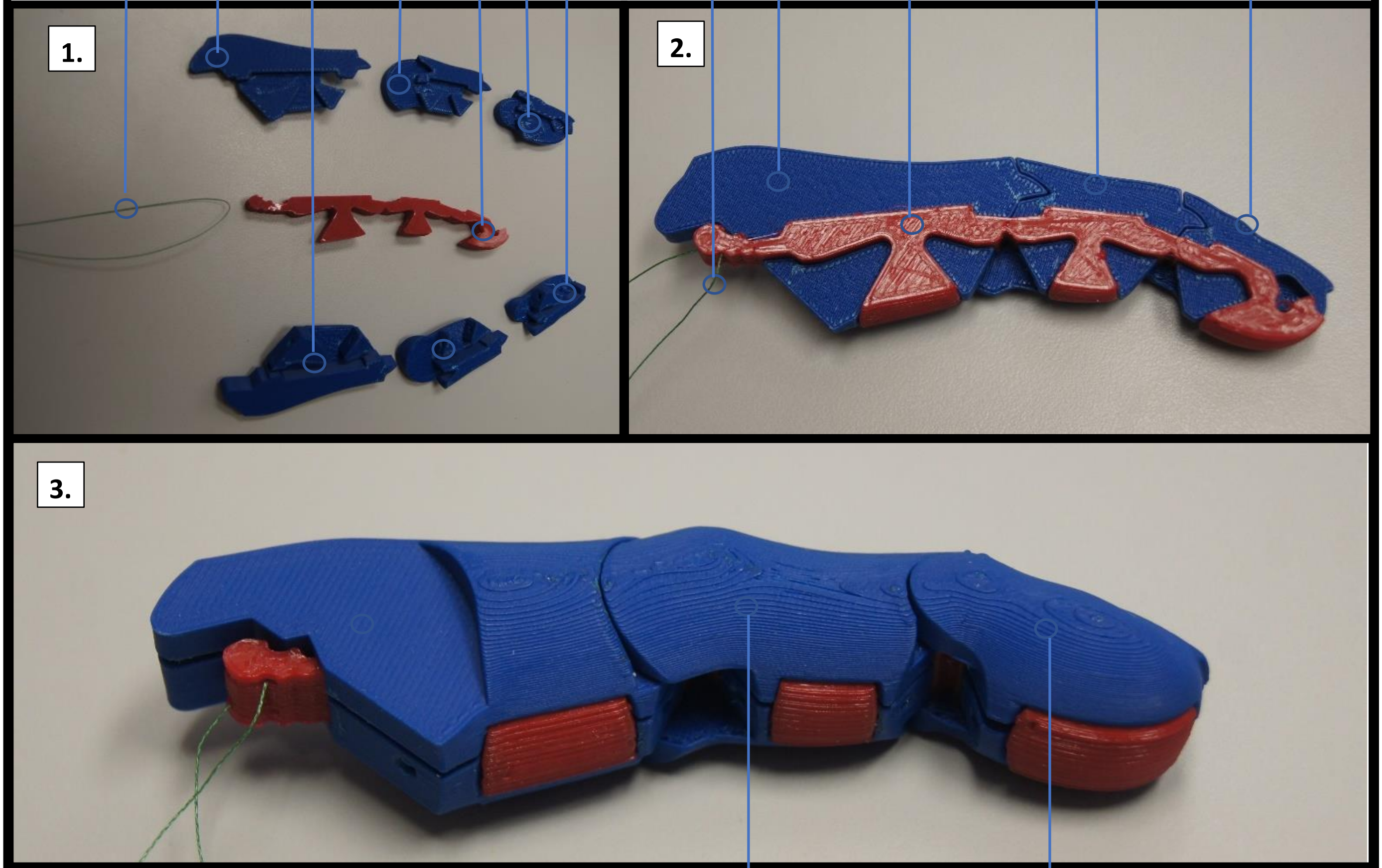
1. Glue on haptic motor housing to the inside of the gauntlet in the desired arrangement.
2. Solder wires to the vibration motor wires and shrink wrap to insulate.
3. Insert vibration motors into housings, and thread wires through the groove provided in the gauntlet up until the holes. Solder all positive wires together into one common wire. Shrink wrap and thread this wire through one of the holes. Thread all negative wires through holes.

Assembling the Thumb



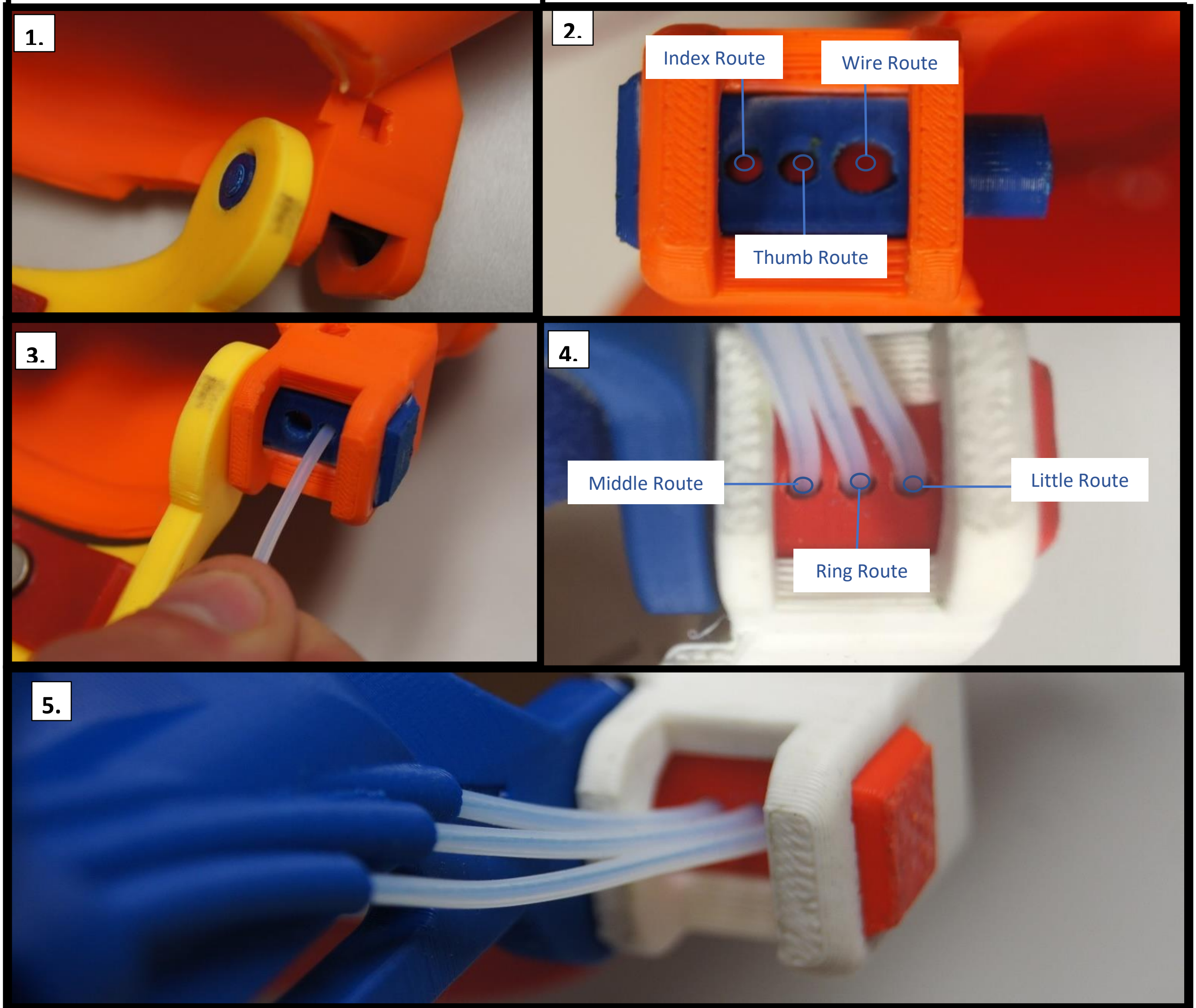
1. Gather all the parts for the thumb and one piece of 400mm and 700mm fishing wire.
2. Assemble the right distal and proximal shells to the distal bone. Insert the proximal bone into the right proximal shell. Thread the fishing wire through the two holes in the proximal bone.
3. Attach the left proximal shell to the thumb. Thread the 700mm fishing line through the shaft running through the length of the palm. Pull the fishing line out of the gap between the right distal shell and distal bone.
4. Attach the left distal bone to the thumb to complete the thumb.

Assembling the Middle, Ring and Little Fingers



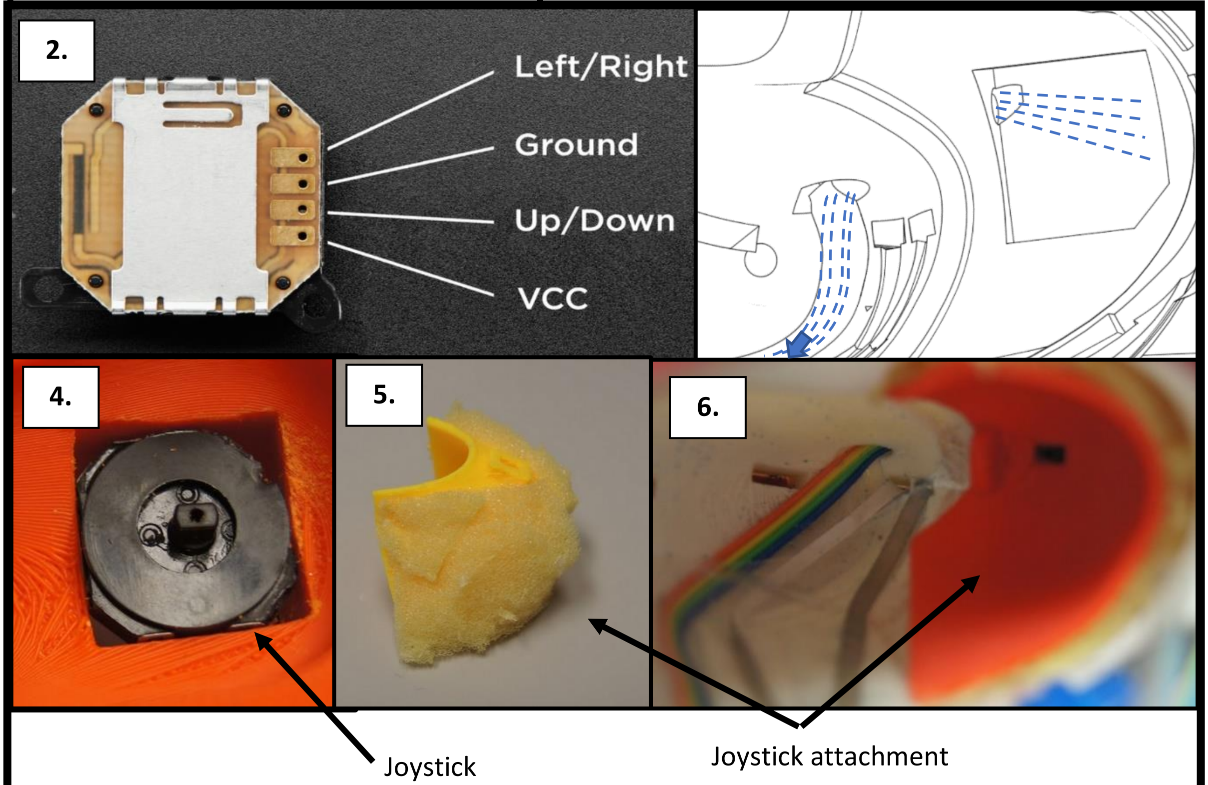
1. Gather all the pieces for the middle finger and one piece of 400mm fishing line.
2. Attach the left proximal shell, then the intermediate and finally the distal to the finger bone. Thread the 400mm fishing line through the two holes at the end of the finger bone.
3. Attach the right proximal shell, then the intermediate and finally the distal shell to the finger bone to complete the finger.
4. Repeat these steps for the ring and little fingers.

Gauntlet to Palm Assembly

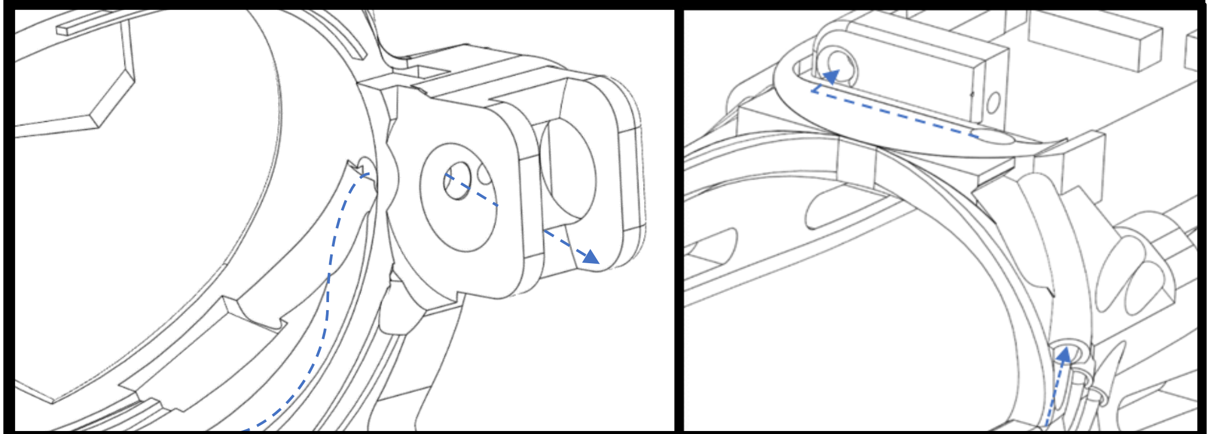


1. Assemble the gauntlet to the palm by aligning the holes at the top of the gauntlet with the holes at the wrist of the palm. Ensure that the outside of the gauntlet is facing the same direction as the outside of the palm.
2. Insert the left joint pin so that it goes through the left side of the wrist and the gauntlet. The left pin's inside hole is larger than the other two holes. When inserting the pin make sure the flat side is facing out from the palm and is therefore flush with the cut out of the wrist joint. Make sure the square pin head has been pushed into the square slot on the outside of the palm. Insert the right pin in the same fashion.
3. Take a piece of 300mm PTFE tube and thread through the middle hole in the left wrist pin to the thumb. Thread until the tube has gone all the way through the palm to the base of the thumb. Repeat for the index fingers route in the wrist pin until fully inside the palm and at the base of the index finger.
4. Thread the remaining three 300mm PTFE tubes through the three holes in the right wrist pin. Ensure that each one goes through the palm to the base of the middle, ring and little fingers.
5. Thread the PTFE tubes on both sides into the holes located on both sides of the gauntlet. Make sure they are all the way to end of the route in the gauntlet. Cut to the correct length so that the PTFE tubing does not bulge out.

Joystick Assembly

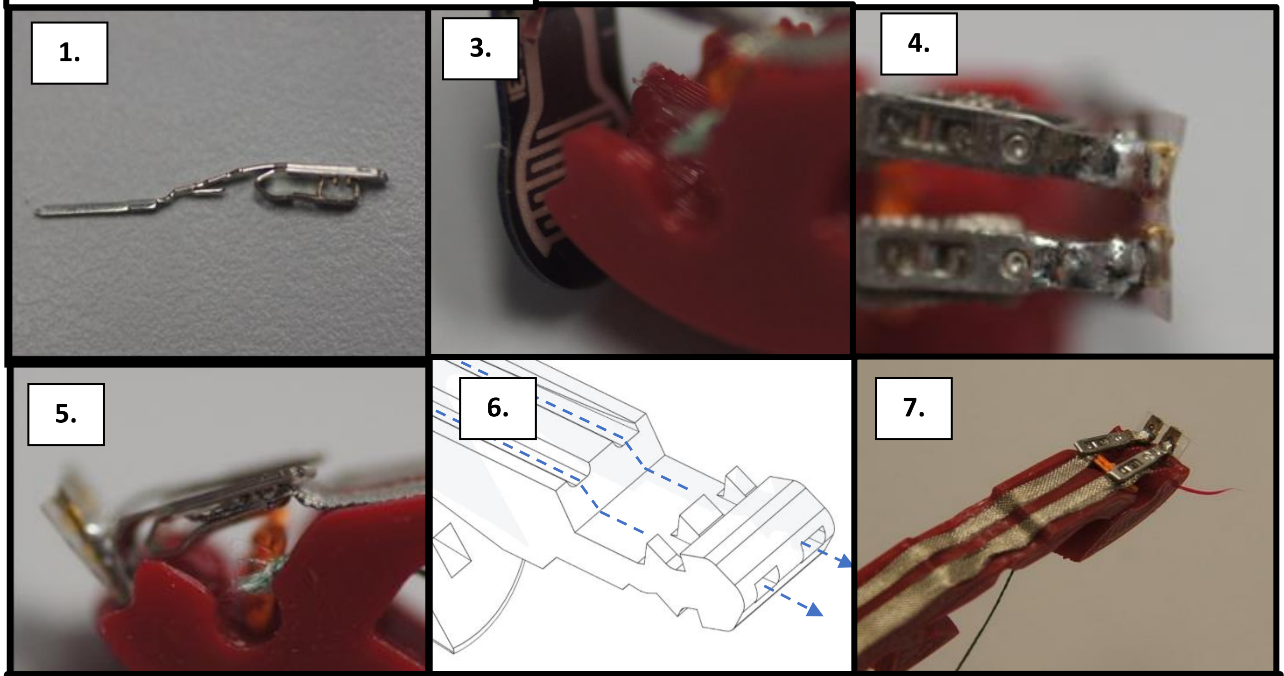


1. Remove standard joystick attachment and cut off joystick mount tabs
2. Solder wires to joystick pins and glue down wire to back of joystick for added strength.
3. Thread wires through inside of palm until joystick is almost in place.
4. Place glue inside the joystick housing and fully insert the joystick, gently pulling the wires taut. The pins should be on the right side
5. Cut small strips of sponge approximately 5mm thick. Stick onto the outside of the joystick attachment.
6. Place a small amount of glue inside the attachment hole and insert onto the joystick in the palm.

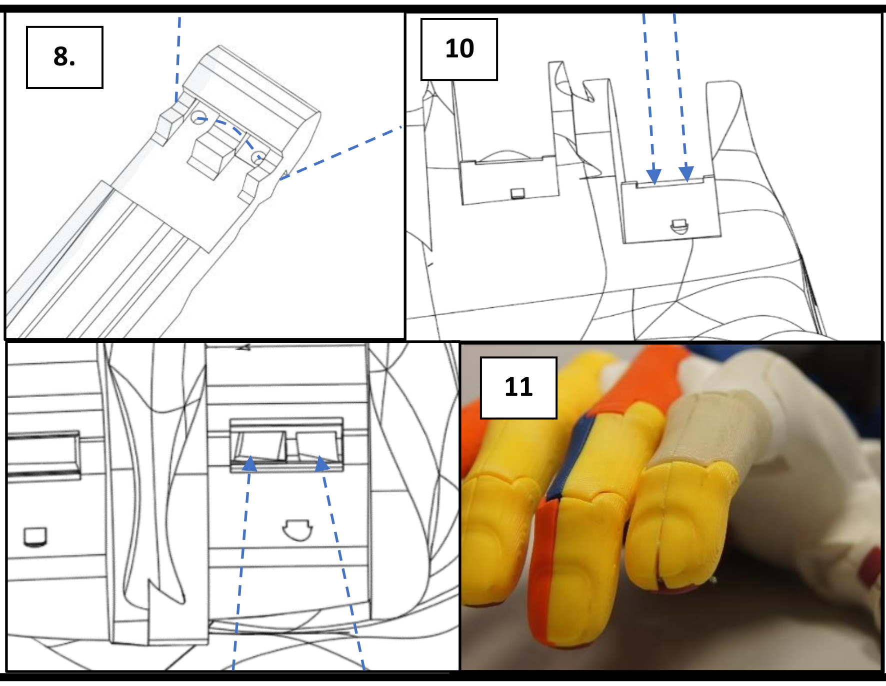


7. Glue down the wires along the route inside the palm and thread through the route to the gauntlet.

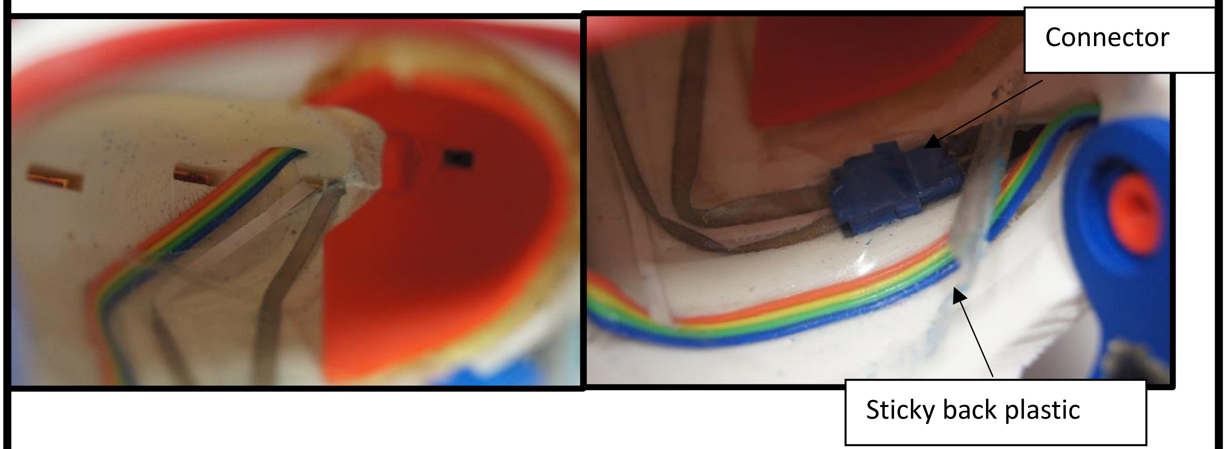
Index Finger Assembly



1. Dismantle/cut the blue connector to obtain the two metal connectors.
2. Using a Stanley knife and a ruler to help flatten, cut the conductive tape in half along its length, forming two strips.
3. Take the pressure sensor and gently insert into the fingertip, with the active sensor area facing towards the rails.
4. Take the two connector pins and solder to the pressure sensor as low as possible on its metal pins. Trim the tail of the sensor up to the solder.
5. Peel off approximately 3 mm length of the adhesive cover on a strip of conductive tape and place inside a connector, ensuring the strip is in directly in line with the connector. Using a pair of thin plyers or tweezers, squeeze the connector together. Repeat with the other strip and connector, ensuring the strips aren't touching each other.
6. Thread the end of the conductive tape through the corresponding holes at the base of the NinjaFlex bone, leaving some slack between the tip and the base.
7. Remove the adhesive cover on the fabric in between the tip and base and cut off. Stick the adhesive to the rails. Pull the end of the fabric gently until almost taut.

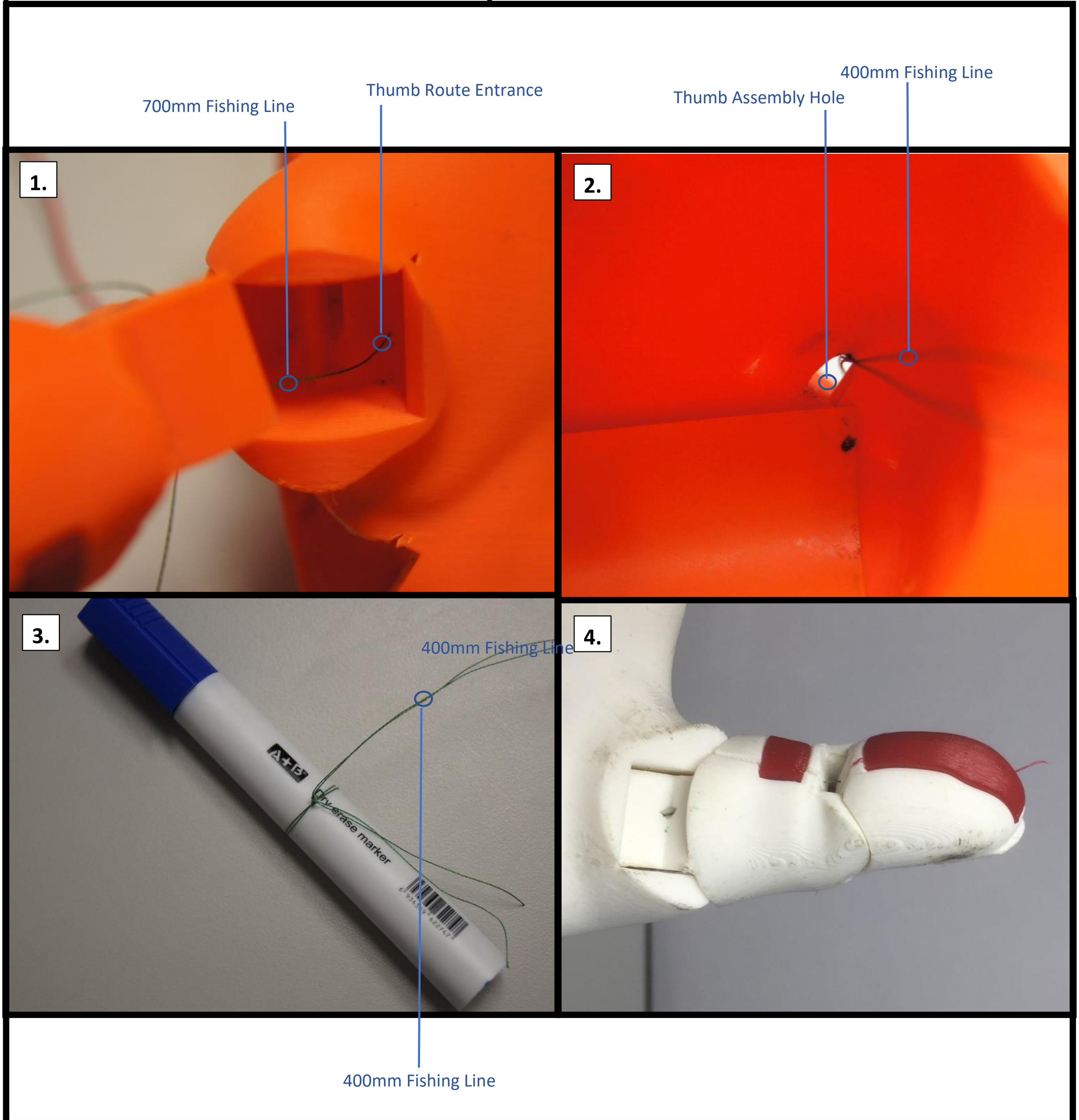


8. Thread the fishing line through the assembly holes beneath the fabric in the way shown.
9. Attach ABS finger covers.
10. Thread conductive fabric and fishing line through holes in palm. Ensuring the fabric goes through separate holes. It does not matter which hole the fishing line goes through.
11. Keeping the conductive fabric taut, pull fishing line as shown in thumb assembly until index finger is fully in place.



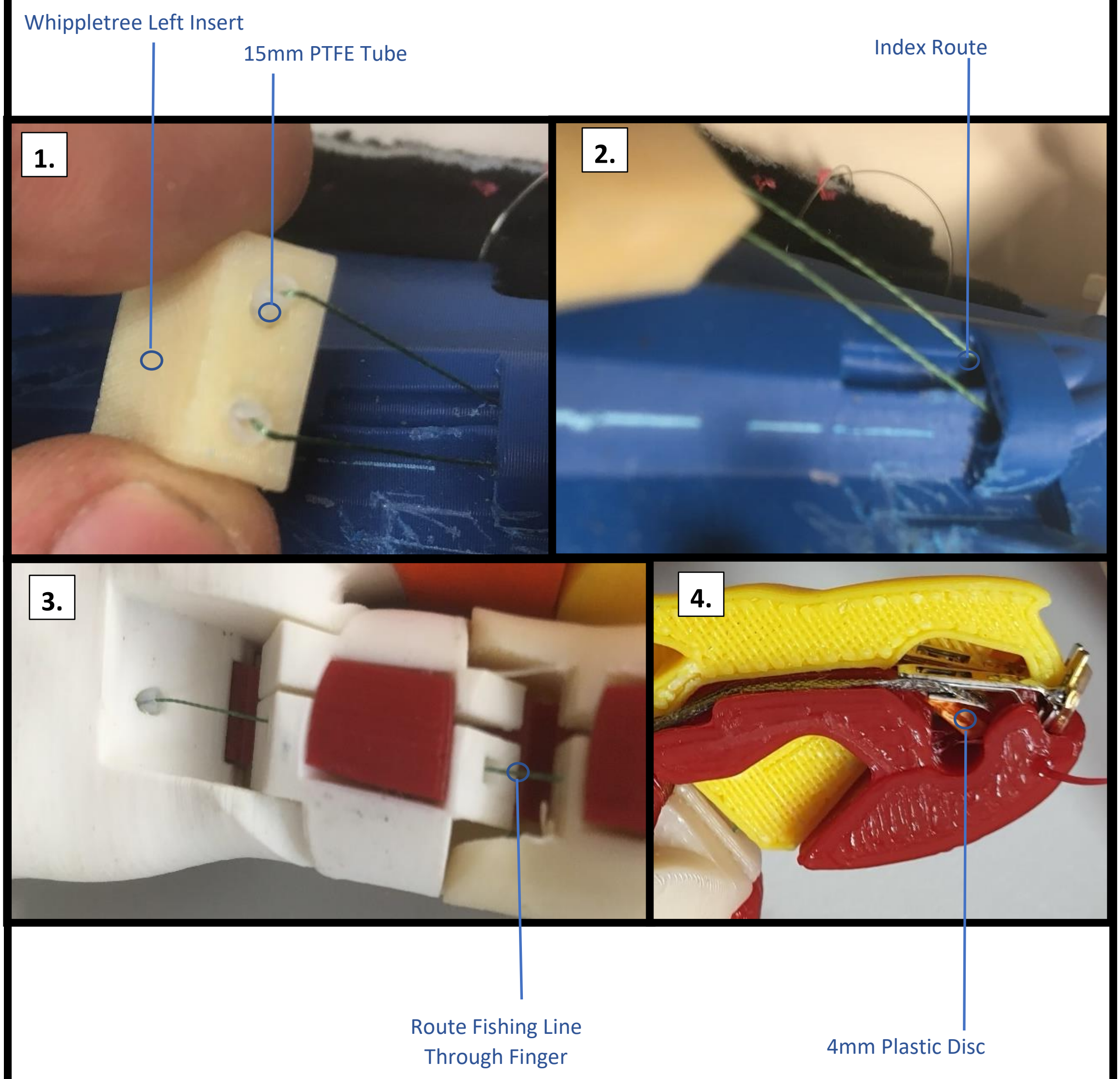
12. Solder two wires to the blue connector and route the wires from the inside of the palm to the gauntlet in the same way as the joystick. Stick the blue connector into the slot inside the palm.
13. Route the conductive tape along the inside of the palm up to the connector– the adhesive is quite weak so keeping the cover on and applying glue is a better alternative.
14. Cut the fabric to size and crimp inside the connector in a similar way to step 4.
15. Cover electronics inside the palm with sticky-back plastic for protection.

Thumb to Palm Assembly



1. Thread the thumbs 700mm fishing line through a small hole located inside the thumb joint. Thread through until the fishing line has appeared out of the end of its corresponding PTFE tube.
2. Thread the both ends thumbs 400 mm fishing line through the large hole in the thumb's assembly slot. Pull through the palm and out of the palm entrance hole.
3. Tie both ends around a thick cylindrical object using a triple knot.
4. Hold the palm with one hand and pull the cylindrical object with the other until a click is heard, and the palm is fixed within the palm.
5. Repeat steps 2, 3 and 4 for the middle, ring and little finger so that the palm has three fingers and a thumb assembled.

Threading the Fishing Wire to the Index Finger



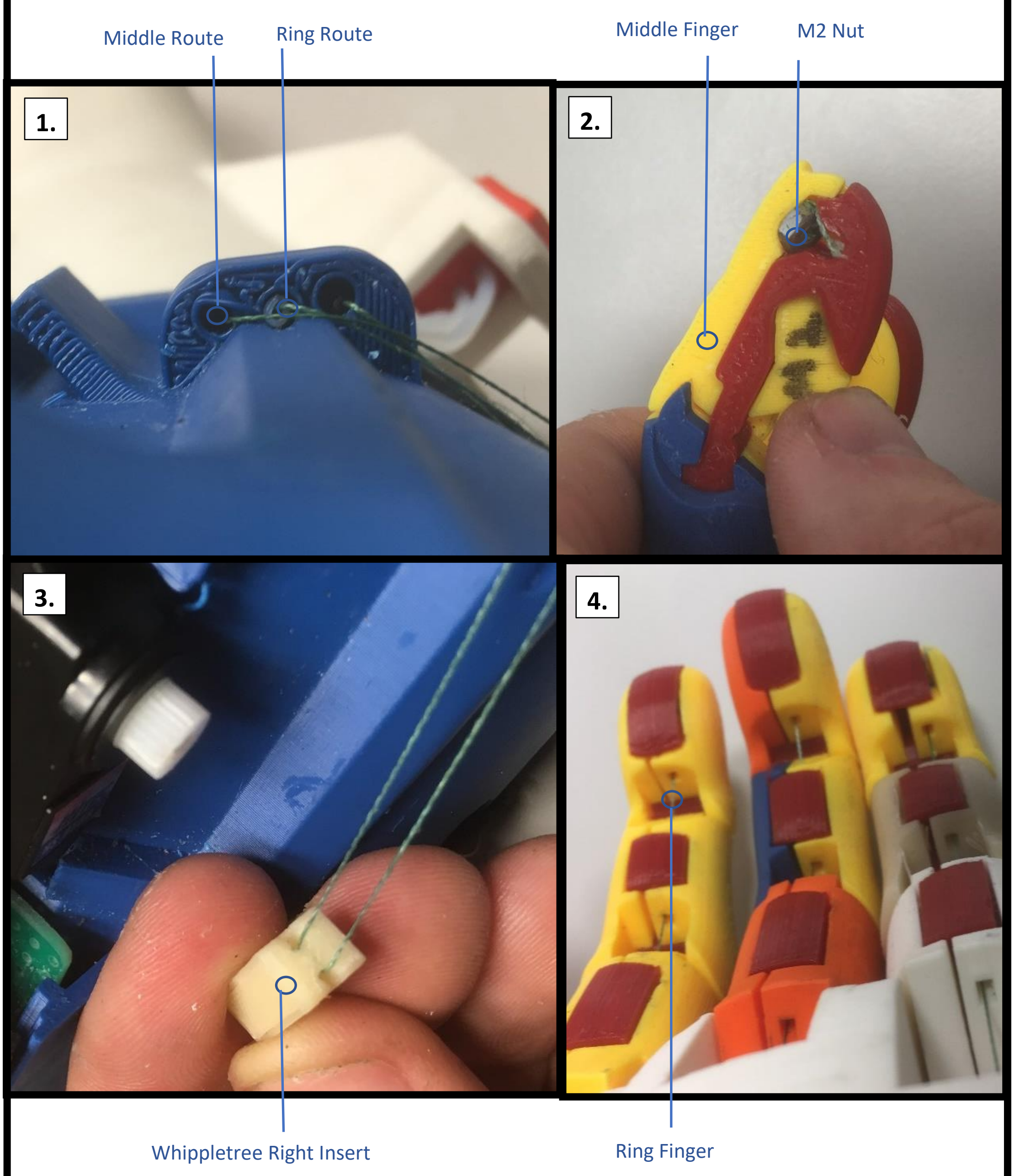
1. Assemble the PTFE tubing inside the left pulley whippletree insert. Thread the thumbs 700mm fishing line leaving the gauntlet through the PTFE tube insert and pull through the exit of the PTFE tube.

2. Thread the fishing wire into the PTFE tube for the index finger. Thread until it is appearing from the top of the of the palm by the index finger.

3. Remove the right distal and thread the fishing wire to the top of the finger.

4. Make sure that the fishing wire comes out in between the pressure sensor and the flexibone and tie the fishing wire to the 4mm plastic disc and insert in between the pressure sensor and flexibone.

Threading Fishing Wire to the Middle and Ring Fingers



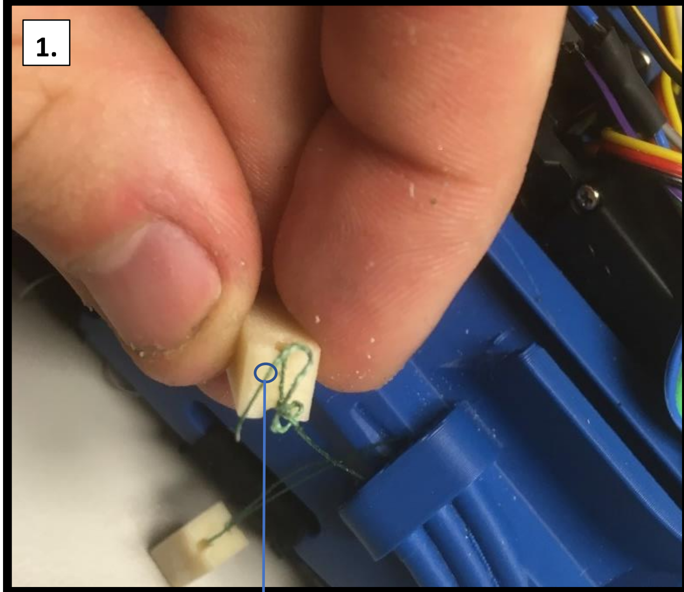
1. Take the other piece of 700mm fishing wire. Thread it through the middle finger gauntlet hole until it appears out of the top of the palm at the base of the middle finger.

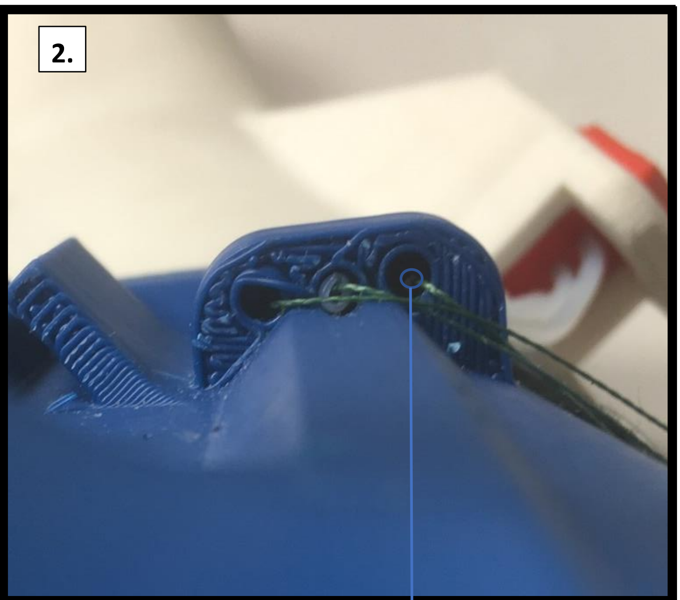
2. Thread through middle finger and tie around a M2 nut. Place nut in middle finger distal bone and replace the left distal cap.

3. Thread the other end of the 700mm fishing line through the right side whippletree insert.

4. Thread this back into the gauntlet through the ring finger ptfe tubing until it appears at the top of the palm. Take of the right distal cap of the ring finger and thread the fishing wire until it appears out the top of the finger.

Threading the Fishing Wire to the Little Finger





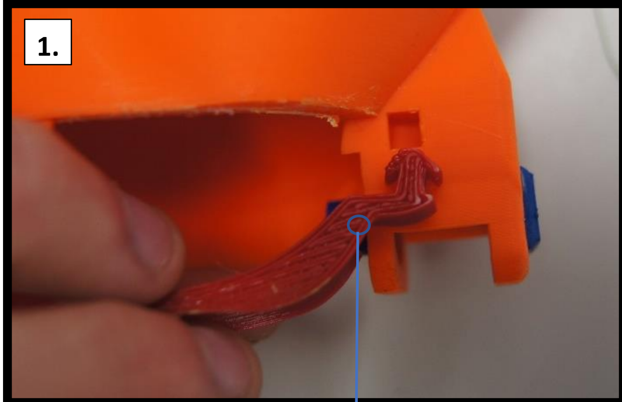
Right Tensioner Insert

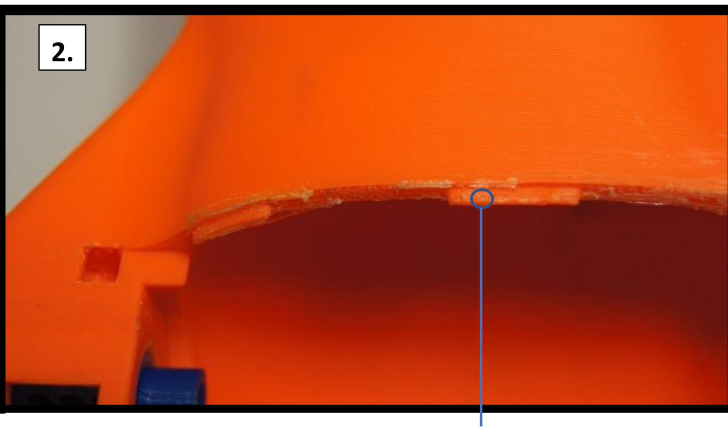
Little Route

1. Tie a piece of 400mm fishing line to the right tensioner insert.

2. Thread the fishing line through the gauntlet PTFE tube to the little finger until it appears at the base. Remove the right distal shell for the little and thread the fishing wire all the way through the finger.

Ninjaflex Palm Assembly





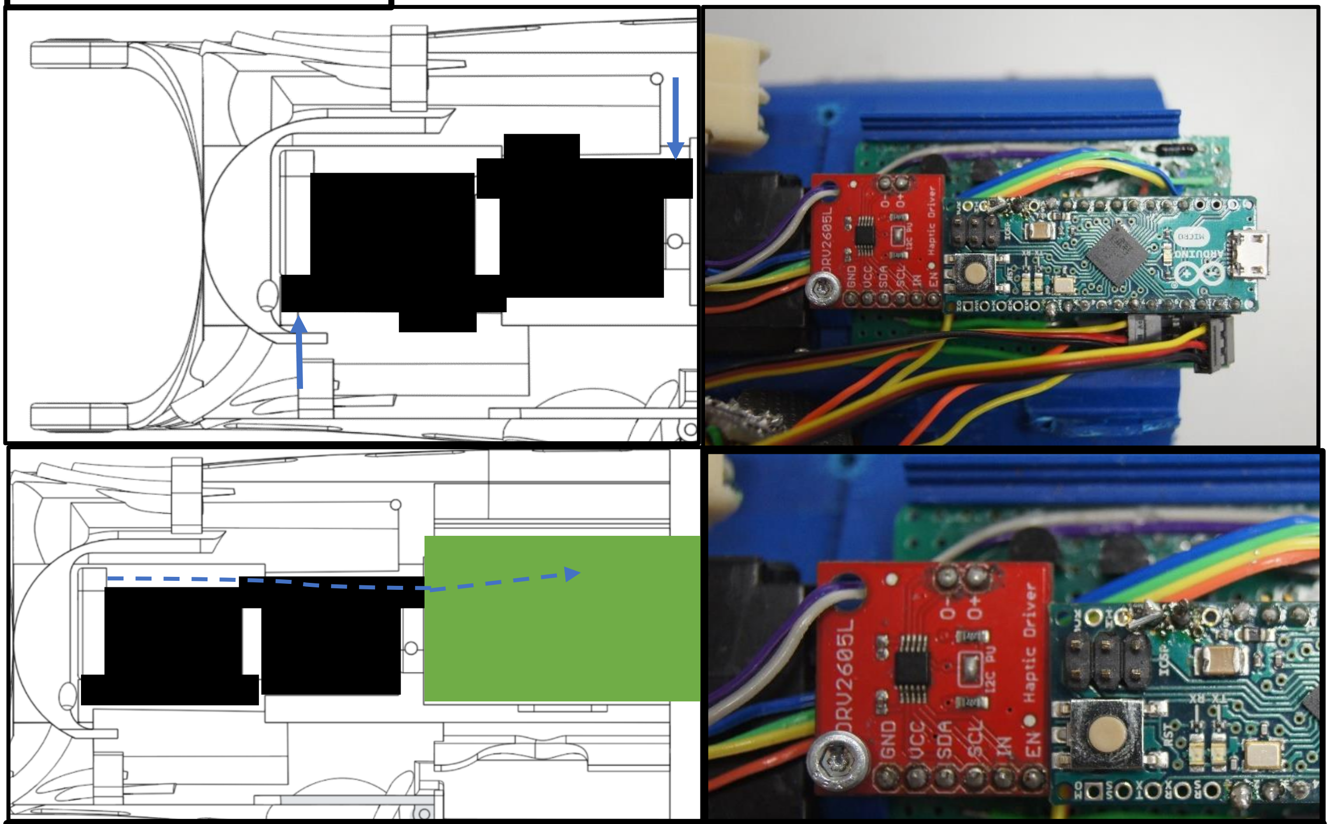
Ninjaflex Palm

ABS Extrusion

1. Insert the flexible arrow heads into the slots either side of the wrist joint, with the flat surface against the palm edge.

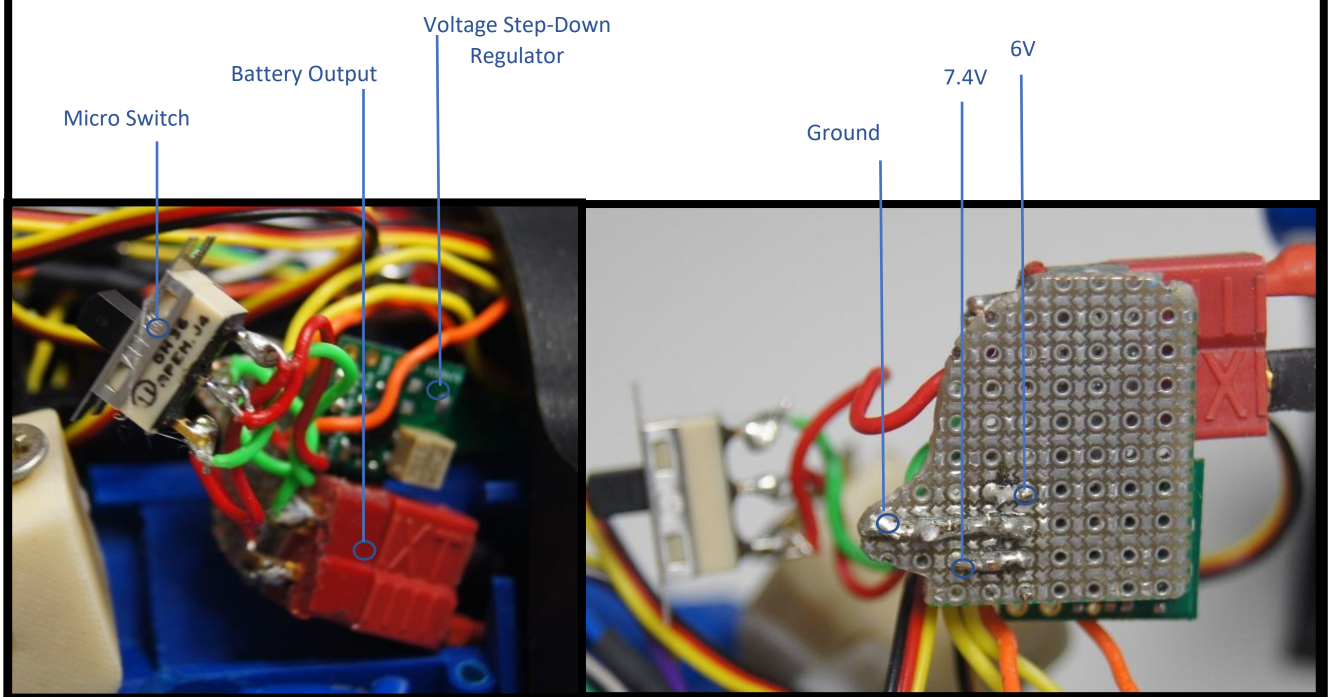
2.Insert the extruded ABS edges into the slits in the Ninjaflex palm. Super glue the two parts together.

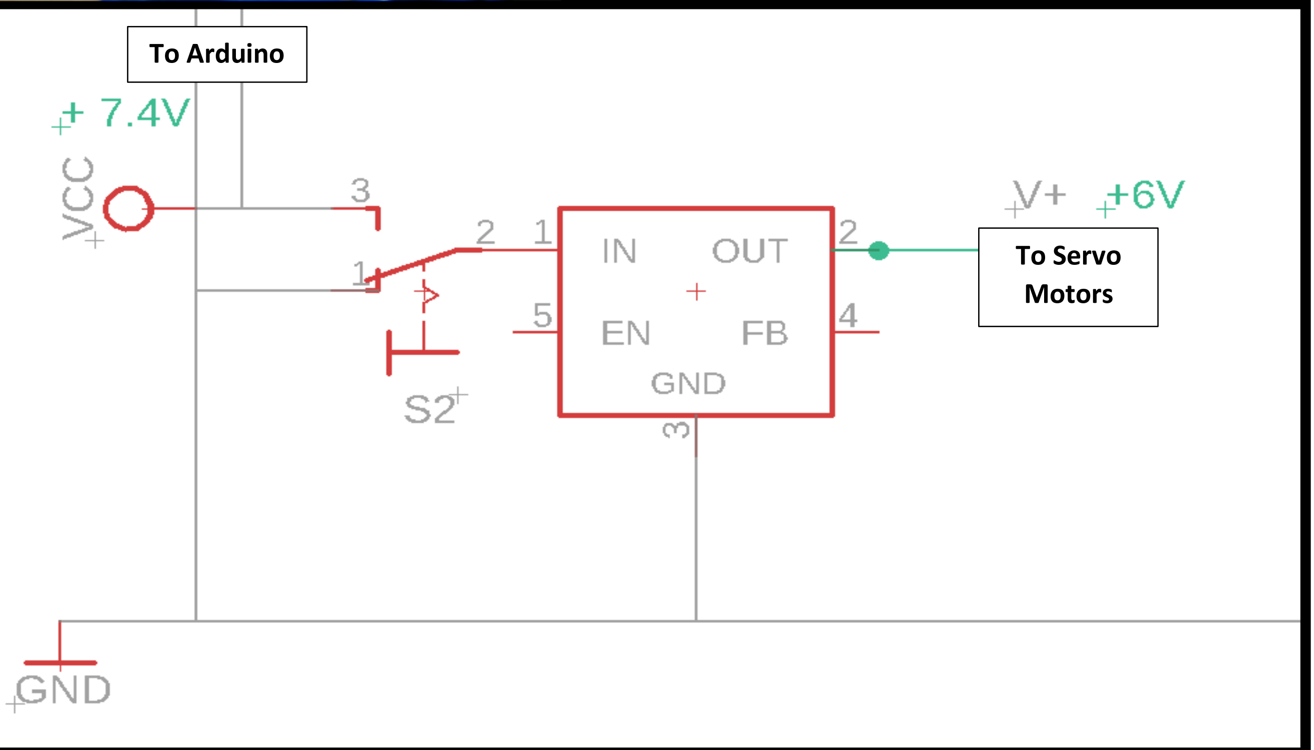
Circuit Assembly



1. Place servo motors into location holes on gauntlet with a small amount of glue on the underside. Ensure they are orientated as shown. Fix into place with bolt.
2. Use schematic to build circuit, for the layout of the final circuit used in this prototype see section 13.1.4.
3. Route joystick and pressure sensor wires through rest of gauntlet and solder to board along with haptic motor wires, trimming where necessary.
4. Connect wires of servos to male pins on circuit board.

Power Circuit



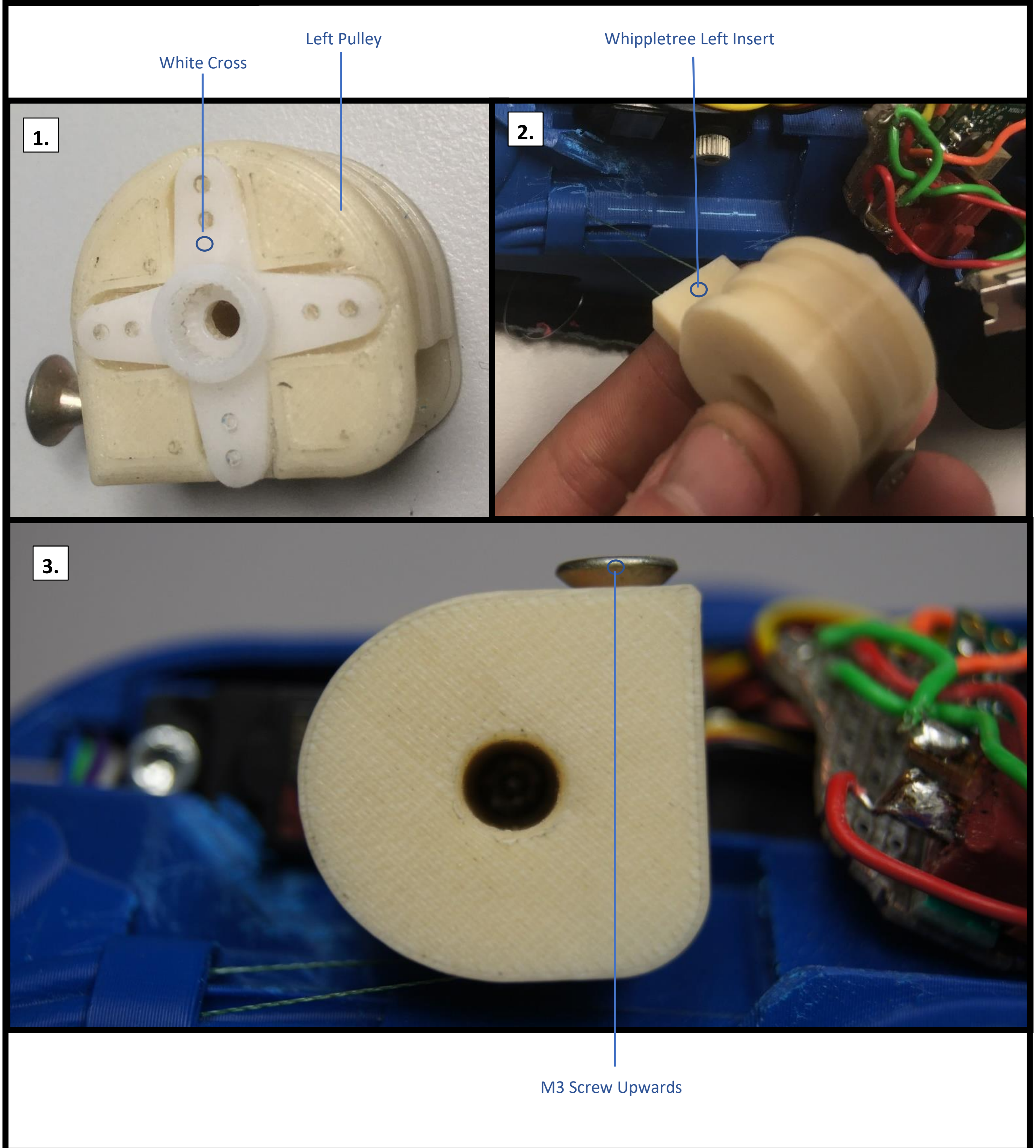


1. Gather the components for the power circuit.

2. Copy the schematic and solder how you see fit. The final circuit from above and below should look like this.

3. Solder the power circuit to the main circuit

Left Pulley Assembly

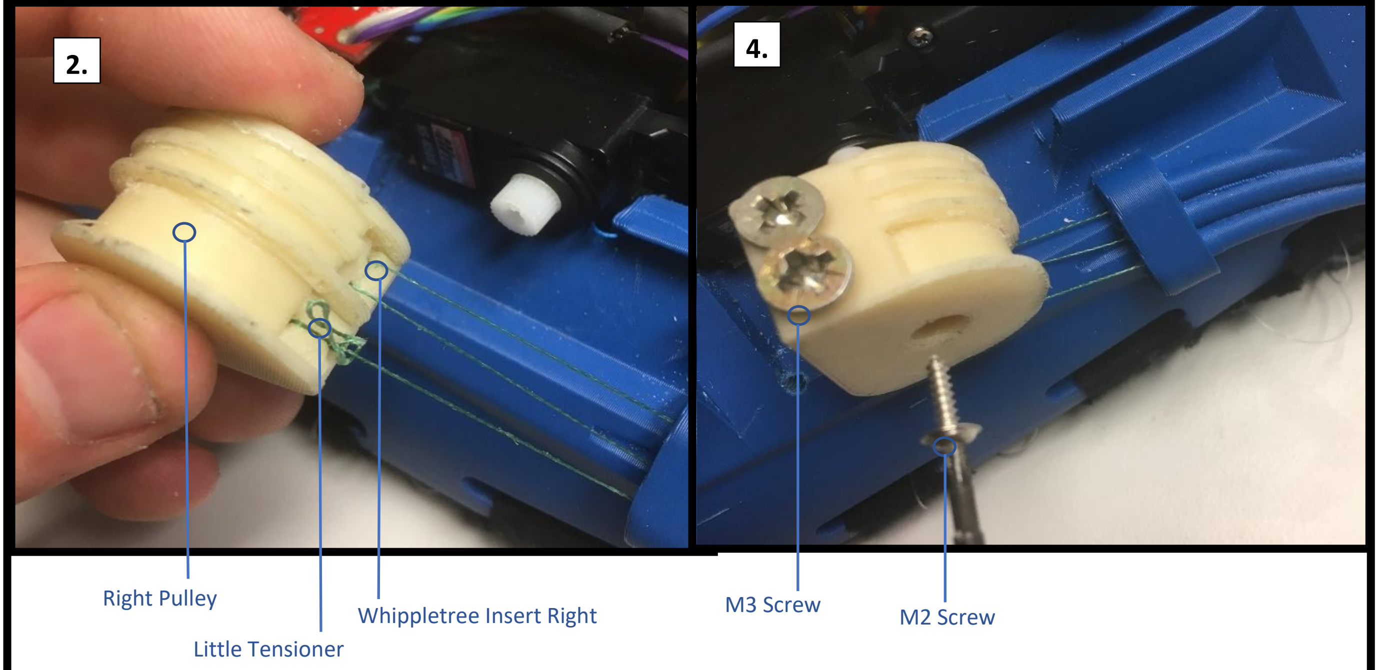


1. Take the left side pulley and super glue the white cross attachment into the cross cut out of the pulley.

2. Insert the left whippletree insert into the pulley and screw in place with an M3 screw. Make sure the white cross is facing towards the servo motors, and the fishing lines are not crossed over.

3. Attach the pulley using the small M2 screw to the servo motor. Make sure the screw is facing upwards when the servo is in its 180° position.

Right Pulley Assembly

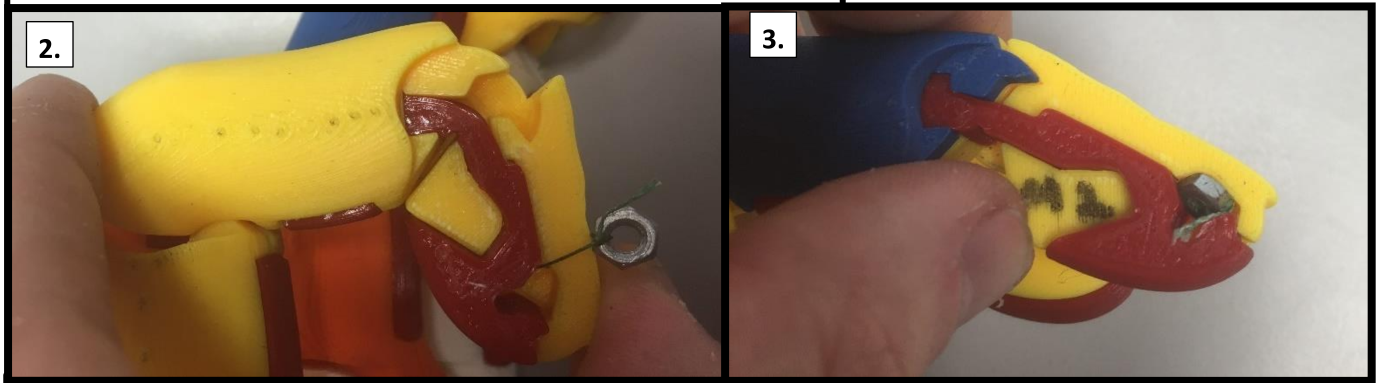


1. Attach the white cross to the right pulley using super glue.

2. Insert the right side whippletree into the slot which has two grooves. Make sure you insert it so the fishing line is horizontal and so the wires are not corssed. Insert the little tensioner insert into second slot. Fix both in place with M3 screws.

3. Attach to the pulley to the servo motor using an M2 screw making sure the screws are facing up when the pulley is in its 0° position.

Attaching the Fishing Wire to the Thumb, Ring and Little Fingers

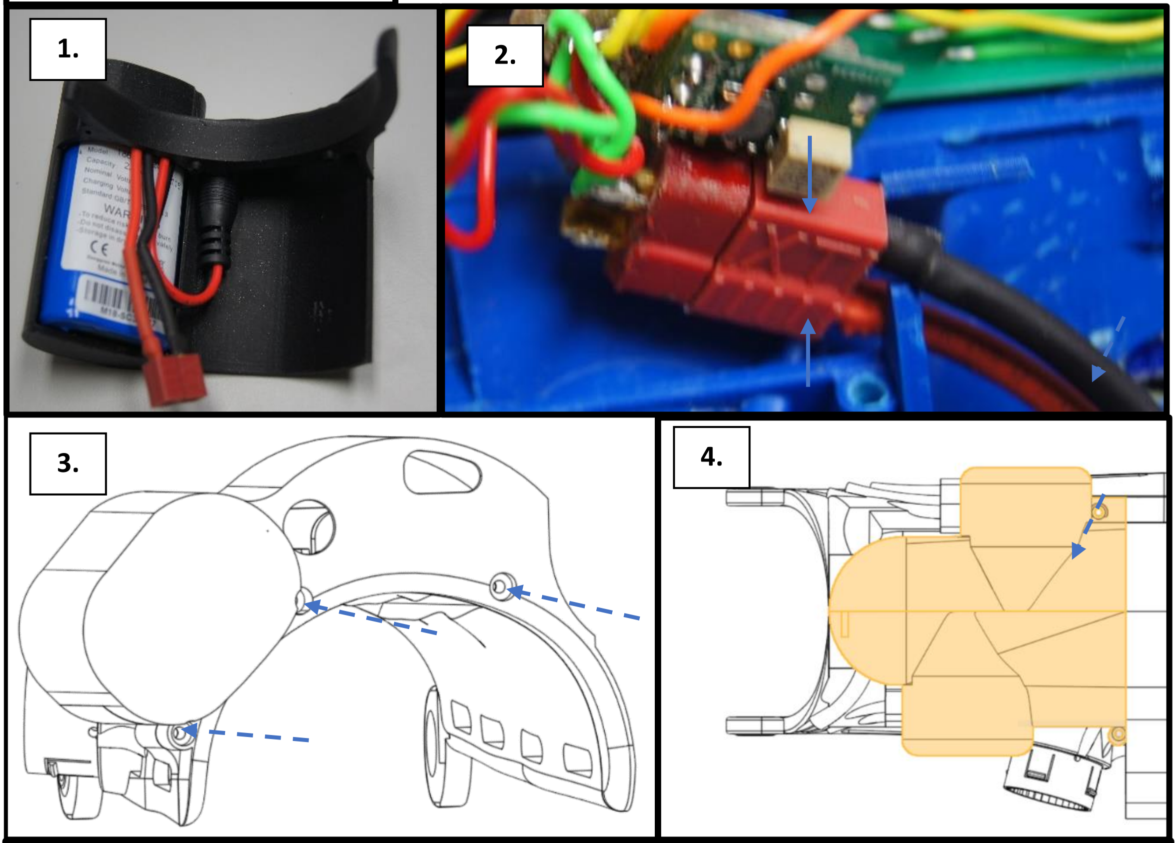


1. Take the fishing coming from the end of the finger and pull until very high tension.

2. Contract the finger and pull the fishing line into tension again. Tie around an M2 nut while the finger is contracted.

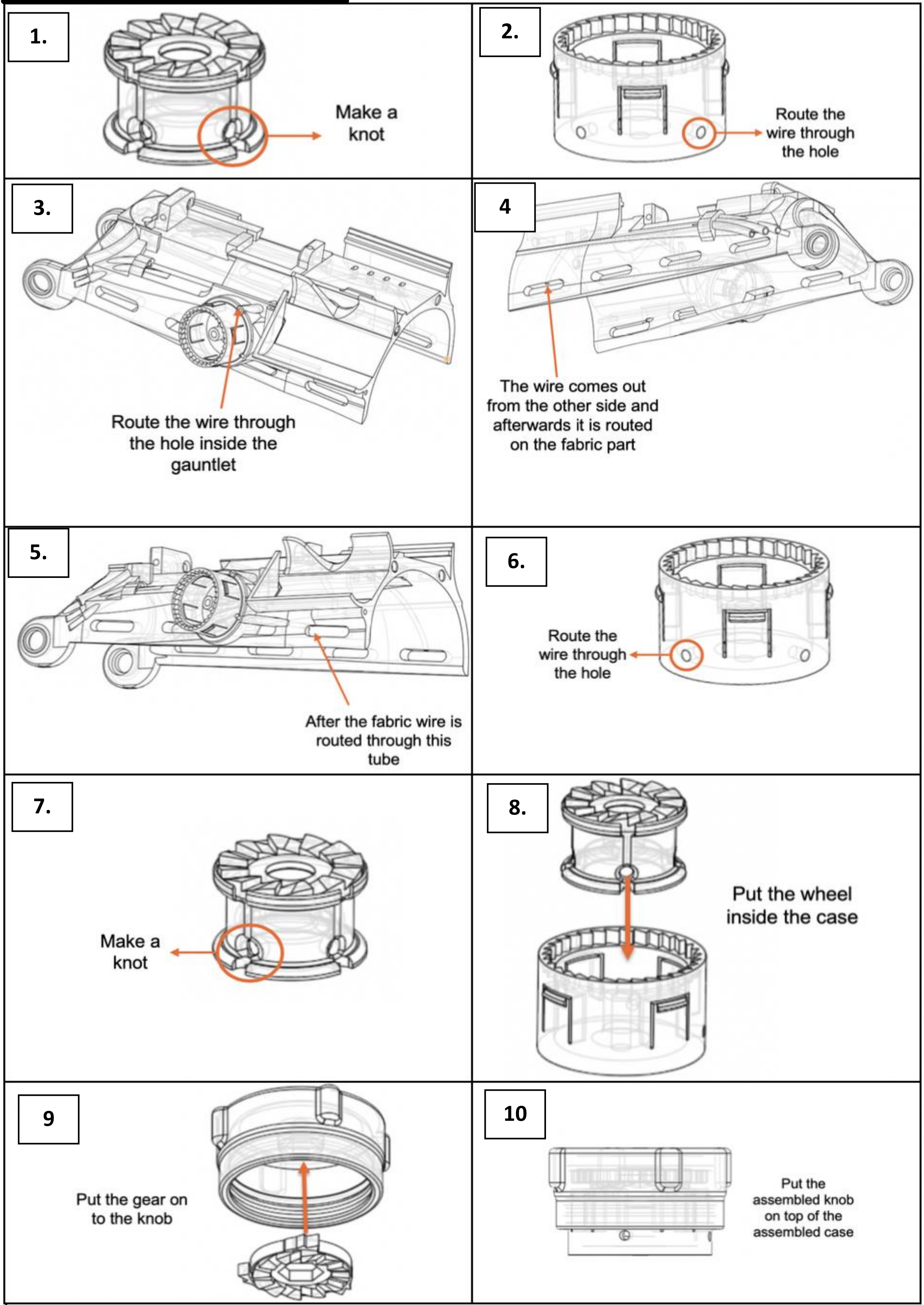
3. Let the finger extend, and if it has too much tension remove nut and repeat process with less contraction of the finger. Do this until there is a little tension in the wire.

Casing Assembly



1. Insert battery into back casing.
2. Attach battery connector to step-down circuit.
3. Attach back casing with bolts.
4. Attach front casing with bolts and glue down front to gauntlet.

Attachment Method Assembly



***M3x20 screw can be use if the top of the mechanism is getting out. In the final application the screw was used in order to fully secure the mechanism.

23 Trouble Shooting (PB & TE)

As this is prototype, there are some areas which are prone to going wrong, either after assembly or after an extend period of use. Therefore, Table 23-1 breaks down some of the problems that could be experienced and the solution to fix them.

Problem	**Solution**
Servo motors on but pulleys do not rotate.	The pulley has been attached at the end of the servo motors rotation. Remove the pulley, set the motors to their starting position and retry.
Servo motors not powered.	Remove the back casing and check that the servo motor connection pins have not disconnected.
Pulleys are rotating but fingers not contracting.	Fishing wire tendon may have fatigued and broken. Remove side casing for the side of the finger and remove the broken fishing line. Replace and reassemble the fishing line through the pulley.
Fingers have a delayed rotation.	The initial tension in the fishing line is not high enough. Either increase the tension via turning the screw on the tensioner in the pulley, or undo and reassemble the fishing line.
Battery charged but Arduino not receiving power.	Remove the back casing and reattach the battery output head to the male input pins, ensuring it is fully pressed on.
Electronic Components are not working	Check all wires are firmly soldered and that there are no shot circuits.
Pressure Sensor not responding	• Conductive fabric may be touching/short circuiting, or they may be damaged. • Metal connectors may not be secured to the fabric. • Pressure sensor may be damaged • May be connected to the wrong analogue pin in the Arduino
Joystick not Responding	• Check that the soldered wires on the joystick are not short circuiting. • Check that the four wires are connected to the correct Arduino pins. • Check that the X and Y output pins are connected to the correct analogue pins of the Arduino.
Arduino is not Turning On	• Using a multi-meter, check that the Arduino is receiving at least 5Vvto the VIN pin. • Try powering from the micro-USB port, if still does not turn on then it will need replacing.
Servo Motors not Responding or Getting hot	• Measure the voltage that the servo motors are receiving using a multi-meter. It should read between 4.8 – 6V. • Check that there is a common ground between the Arduino and the battery.

Table 23-1: Potential Problems that the Prototype may Face, and the Solution to Fix Them.

24 Adapting the Product for Other Users (PB & TE)

As the prototype has been developed with the idea that it can be adapted to multiple users, this section goes through steps to aid the developer in personalising the Flexibone V2 design for a new user.

24.1 Scaling (TE)

As known, each user will have a different physique that the design must be scaled to fit. This is possible for the palm but not for the gauntlet, due to the component's locations being mapped out precisely on the top of the gauntlet. If the gauntlet was to be scaled the components would no longer be located or constrained correctly. To scale the palm, ensure that the model with no cavity for the user's residual palm is selected. Using the scaling method provided by the e-Nable community [116] to then adapt the model to a suitable size for the user.

24.2 Moulding to the User (TE)

To obtain a comfortable and secure fixture to the user's residual limb, both the palm and gauntlet can be moulded to the user's body geometry. To achieve this a 3D scan of the user's residual limb is needed. This can be obtained either from a prosthesis expert, which is expensive, however professionally done, or via the use of a 3D scan app on a mobile phone [117]. The app is a cheap an accessible option, however it is not very accurate and requires a good quality camera on the mobile device.

After obtaining a 3D scan it can be used to make a 3D model in Onshape. The scan will provide a complex mesh .stl file which will allow cross-sections sketches of the scan to be drawn with an offset to allow a tolerance between the user's limb and the device, see Figure 24-1.

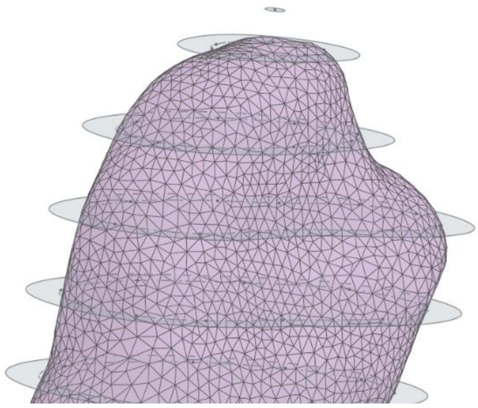


Figure 24-1: Sketches Around the User's 3D Scan of Their Palm

Using the loft function, a solid model can be made with the same geometry of the scan, see Figure 24-2 . A scan of the user's residual palm can be lined up inside the model of the solid palm at the required orientation with the same being done for the forearm model in the solid gauntlet model. Using the Boolean function in Onshape, this 3D model of the user's residual limb will remove the material from the palm and gauntlet to leave a 3D model moulded to the user.

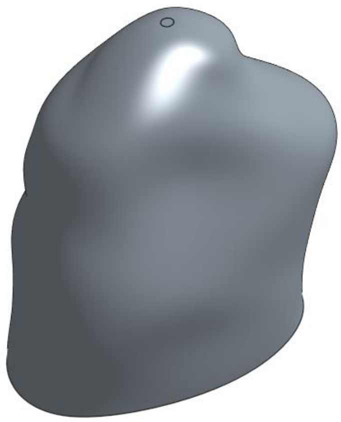


Figure 24-2: 6mm Thick Model of the User's Palm

24.3 Control (PB)

The current control method is quite specific to the user in this project. It is likely that it would still be an effective method of control for users with a residual CMC joint, and so the attachment could be adapted to each case. Again, a 3D scan would be a good way of doing this, but also designing a generic joystick attachment, or a set of joysticks could be a good solution. Having multiple sizes and shapes available that can be printed and swapped out, for example.

For this specific design, a user would require a residual thumb joint of a similar level of amputation to control the device. However, as the joystick attachment is designed from a 3D scan, it is very feasible to copy the process used to obtain the 3D scan and copy the process used to design the attachment. The team did not create the 3D scan, and therefore for anyone wishing to repeat this they would need to determine the process used to obtain and insert it into a CAD software such as Onshape. The process used in section 13.1.1 should then be repeated to create it.

For a user that does not have this joint, a myoelectric sensor could be implemented inside the gauntlet as an alternative method of control. In this sense, the design is modular, as the control mechanism changing does not greatly impact the rest of the design. Some changes in the code would need to be made, however, as well as finding the optimal myoelectric sensor placement for the user and potentially some redesign of the gauntlet.

25 Future Developments

25.1 Waterproofing (JP)

Unfortunately, it would be very difficult to completely waterproof the entire prosthesis in its current design, as there are too many holes where water can seep through particularly in the palm and wrist area. However, measures could be taken to waterproof the gauntlet and minimise water exposure in other areas of the device.

Any electrical components could be coated in a layer of 'silicone modified conformal coating' to waterproof them and provide an extra layer of protection [118].

A clear Silicone waterproof sealant could be used to provide the gauntlet and its internal housings with a waterproof seal.

To prevent water entering the prosthesis through the fingers the device could be fitted with an external glove. Perhaps like a rubber latex kitchen glove that would fully waterproof the palm and fingers and could possibly be implemented over the entire device. This may also have the added benefit of providing more grip. However, covering the fingers and wrist in such a way could result in increased friction in the system. Additionally, the user may not like the fact the entire device is covered in a rubberised glove and they may find it stigmatising.

25.2 Locking Mechanism (TE)

Even though removed from the final prototype, the re-implementation of a locking mechanism into a future iteration would be greatly beneficial for; longevity of use, reduction in component degradation and user satisfaction.

However, a new concept for the mechanism was developed, as the previous mechanism was still not a proven concept and unreliable. Additionally, the method of clamping the fishing wires was causing abrasion of the lines, reducing their time until failure. The new conceptualised design was to instead lock the pulley at its current position, as it does not fatigue the fishing line.

The idea was to create a friction break to work against the side of the pulley by using micro solenoids [119] controlled by an Arduino. The solenoid works by retracting a shaft when powered and then releasing it when off. It would allow a break pad to be removed when on, allowing the pulley to move freely, then engaging the break pad, locking the pulley, when turned off. This would still allow it to work in combination with the control system as the solenoids can be controlled by an Arduino. For the break, an extremely high friction surface, such as sand paper, could be applied to the pulleys side and the break pad. See figure Figure 25-1 for a diagram of the potential locking mechanism.

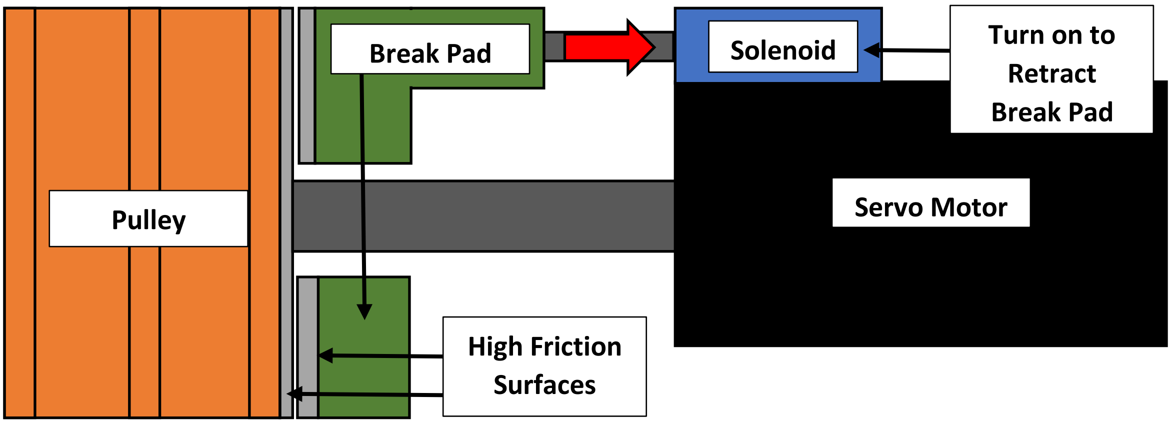


Figure 25-1: Diagram for a Potential Electronic Locking Mechanism

25.3 Reduction of Wrist Joint Thickness (TE)

The current wrist joint on the prototype has a width of 19.5mm on each side. The left side joint does not protrude further than the thumb and therefore does not impact how the prosthetic lays on the table. However, on the right side, the wrist joint protrudes further than the little finger edge by 12mm, see Figure 25-2. This protrusion impacts the way the palm sits on a surface when placed on its ride side. The width of the joint must therefore be reduced to allow the prosthetic to lie naturally for the user.

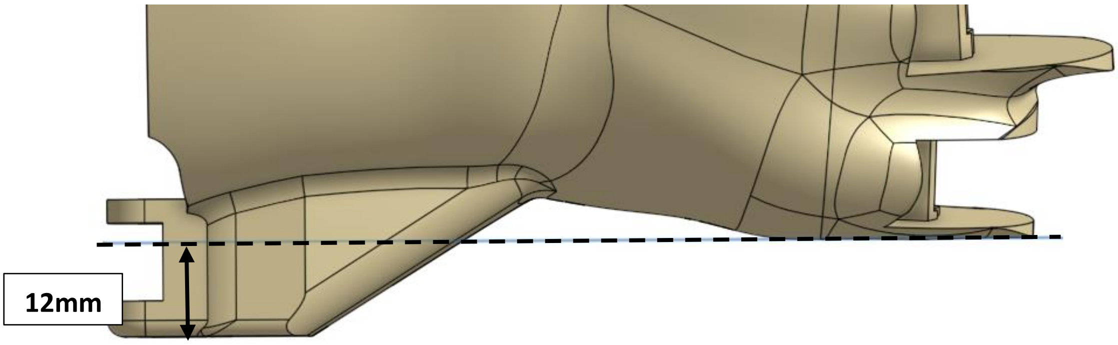


Figure 25-2: Wrist Joint Protrusion

A potential solution is to have all the fishing wires pass through one large PTFE tube when travelling through the wrist joint. As the joint's width is designed for three tubes in a row, having one would allow the width of the joint to be greatly reduced.

However, tests would have to be carried out to analyse what the effect of three fishing lines in one tube; will it increase friction, will they all be able to contract properly without being impeded by one another. It would therefore have to be assessed if this is a suitable change for the design.

25.4 Improve the Electronics Routing Through Palm (TE)

The routing developed on the inside cavity of the palm, even though it worked, was not an ideal solution for routing the electronics. The routes went through to sharp an angle for the fabric and wires to bend around. Additionally, it is difficult to assemble and make sure the conductive fabric does not touch and create a short circuit. Glue was also needed to keep the wires in place, which is not an effective way of assembling.

Better routing could therefore be developed which is potentially within the palm, like the fishing wires routes. However, the thickness in the palm is very constrained and there may not be possible routes for the number of wires.

As there is a 6mm tolerance between the user's hand and the palm there's a potential to extrude a cover over the existing routes to fix them in place throughout the palm. It would also be advised to alter the current routes to reduce the sharpness of the angle the wires currently travel through.

25.5 Fishing Wire Evaluation (TE)

Throughout the process of the project an evaluation of different types of fishing wire was never conducted. A strong, high Young's Modulus fishing wire was chosen off the basis that more energy provided from the motor will contract the fingers, as less was being lost to elastic potential, as discovered during the research phase in section 5.4.4.

However, the fishing line used is a fibrous wire not a solid plastic wire. The fatigue life and the amount of friction provided by both is unknown. Additionally, there are benefits to having a lower Young's Modulus fishing line, such as the adaptive grip, section 5.4.4. There may be a more suitable fishing line which will have high energy transfer efficiency but also give the prosthetic greater gripping capabilities by providing a more adaptive grip for the fingers.

Therefore, a thorough test into the difference into how different fishing lines effect; friction within the routings, fatigue life of the prosthetic and gripping capabilities of the product should be carried out to make an informed decision.

25.6 Conductive PLA (TE)

A potential technology that would be valuable to research and develop concepts with, is the 3D printable material conductive PLA, as discussed in section 5.4.3. This filament could be a cleaner and more suitable way to integrate electronics into the palm of the device. With the use of a dual extruder head printer, there is the possibility of embedding conductive routes to sensors in the fingertips or elsewhere in the palm. They would be robust as they are made of plastic and not an easily fatiguing material. This could allow for more electronics to be implemented, as many routes could be embedded into the design in more intricate ways with reduced assembly difficulty.

25.7 Flexibone Joint Thickness Test (TE)

Due to the testing carried out in section 16.2.2 only being preliminary, a more robust test could be carried out on the finger joints to find a concrete relationship between the thickness of the joints, the force taken to contract them and therefore their contraction order.

The thickness of joints that was used in the final prototype is not the most force efficient deign, with the thicknesses being chosen because they changed the contraction order only. Via the use of more thorough testing, the thickness of the joints, and the angle of the Flexibone hook, can be chosen so that drooping does not occur, and the contraction order is as desired, while also achieving a lower total contraction force than the current design.

25.8 Improved Thumb Position (JP)

Currently there is quite a narrow gap between the index finger and the thumb which makes it difficult to grasp larger objects, Figure 25-3. The thumb was modelled from the 3D scan on an actual human hand in a natural position. However, in this prosthesis that may not actually be ideal due to the limited range of movement in the thumb joint compared to an actual human hand. The current thumb position also makes it difficult to rest the hand flat on a flat surface as the thumb protrudes down from the face of the palm.

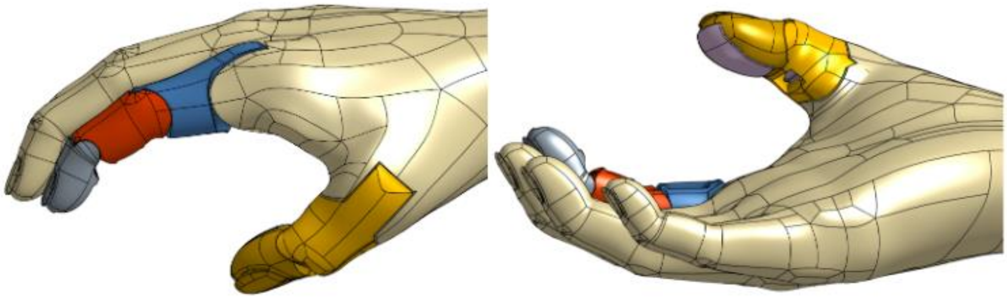


Figure 25-3: CAD Model of Prosthesis Design

To make it easier to grasp objects it may be beneficial to change the plane of rotation of the thumb knuckle joint to approximately that shown in Figure 25-4. This would increase the gap between the index finger and thumb and potentially make it easier to hold larger objects. The plane was rotated by 25° relative to the original plane. However, tests would have to be conducted to determine the optimum positioning of the thumb knuckle joint plane of rotation relative to the original plane.

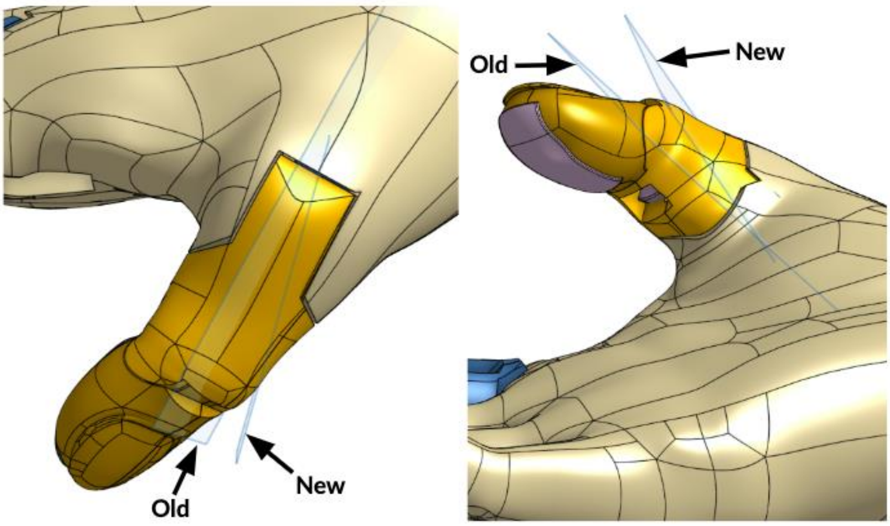


Figure 25-4: Old and New Thumb Plane of Rotation

Additionally, it would be beneficial to increase the range of motion of both thumb joints to allow for greater thumb articulation around an object.

25.9 Improved Finger design (JP)

Joint concealment

An ideal way of improving the finger design would be to create a finger that has completely concealed joints. This would prevent any dirt and debris entering the joints and prevent anything getting jammed in the joints that would stop the joints from contracting.

A rudimentary CAD model of a concealed knuckle joint can be seen in Figure 25-5 compared to the original knuckle joint of the index finger.

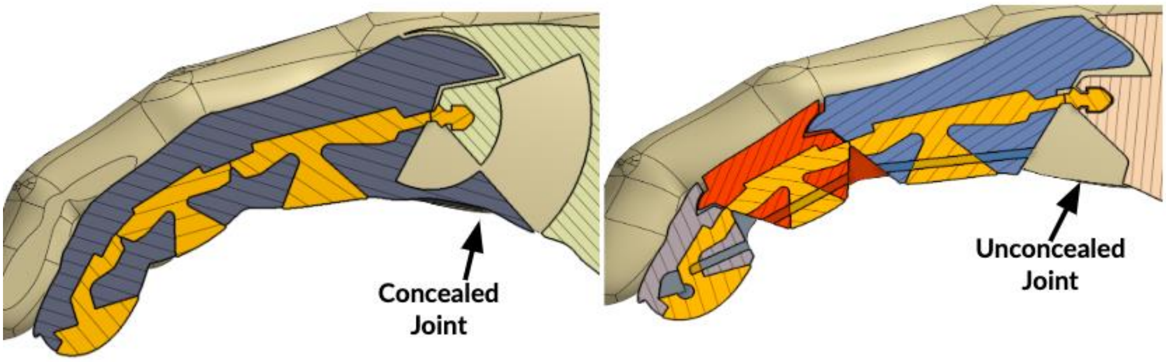


Figure 25-5: Joint Concealment

The downside to this new design is that it requires a lot of space internally in the palm and this may not allow enough room for the users stump to fit in or for the placement of electronics. Additionally, this is only a potential solution for the concealment of the knuckle joint, but the interim and distal joints will remain unconcealed and an innovation in design will have to be implemented there as well.

Finger Wire Routing

In Figure 25-6 you can see the finger wire routing. The distance the wire path is from the axis of rotation will affect both the force and length of wire required to contract the fingers, and unfortunately due to time constraints it was not possible to test this relationship. So, a future group of students could do a proper analysis of the relationship and determine the optimum distance between the wire routing path and the axis of rotation.

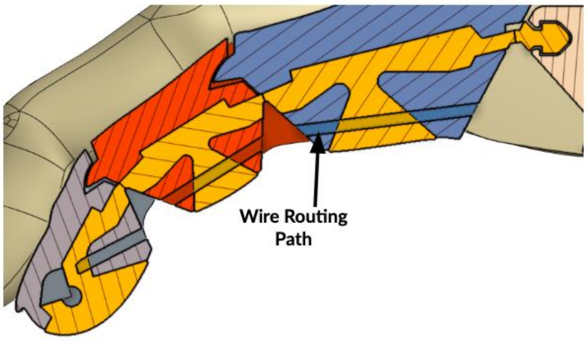


Figure 25-6: Wire Routing Path

25.10 Gauntlet support - motorised solution (SS)

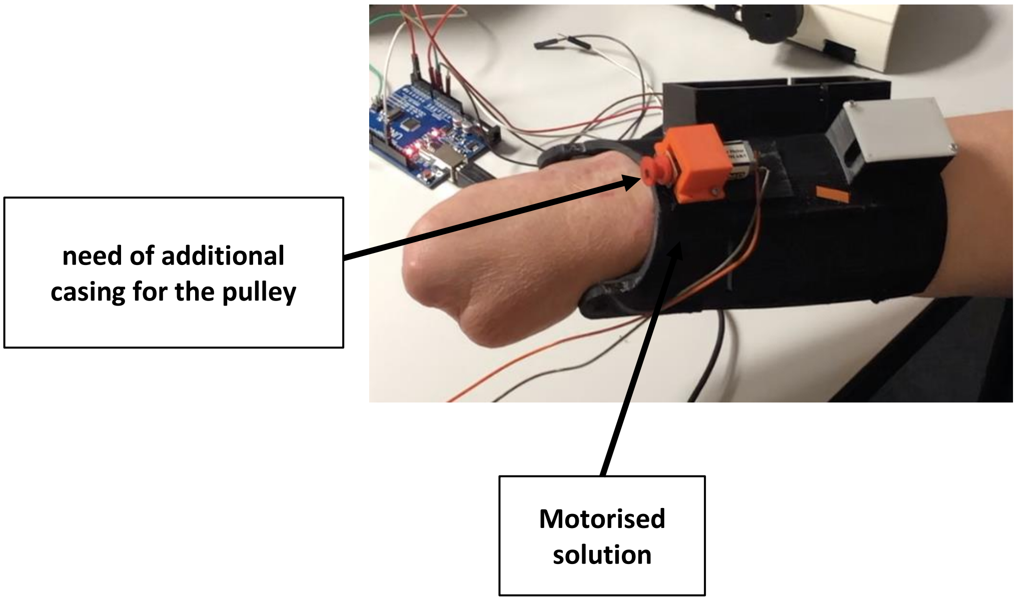


Figure 25-7: shows the place the extension in the casing is needed

The motorised solution was wanted to be improved according to the user's feedbacks for further applications in the. In the tests of the motorised solution on the gauntlet it was seen that the wires got out of the pulley and started coiling through the motor. For this problem, a casing was designed to put on top of the pulley like in the twistable locking mechanism's case part. The designed pulley case was connected to the motor casing. The wire could pass through the hole in the casing so that it could easily coil around the pulley.

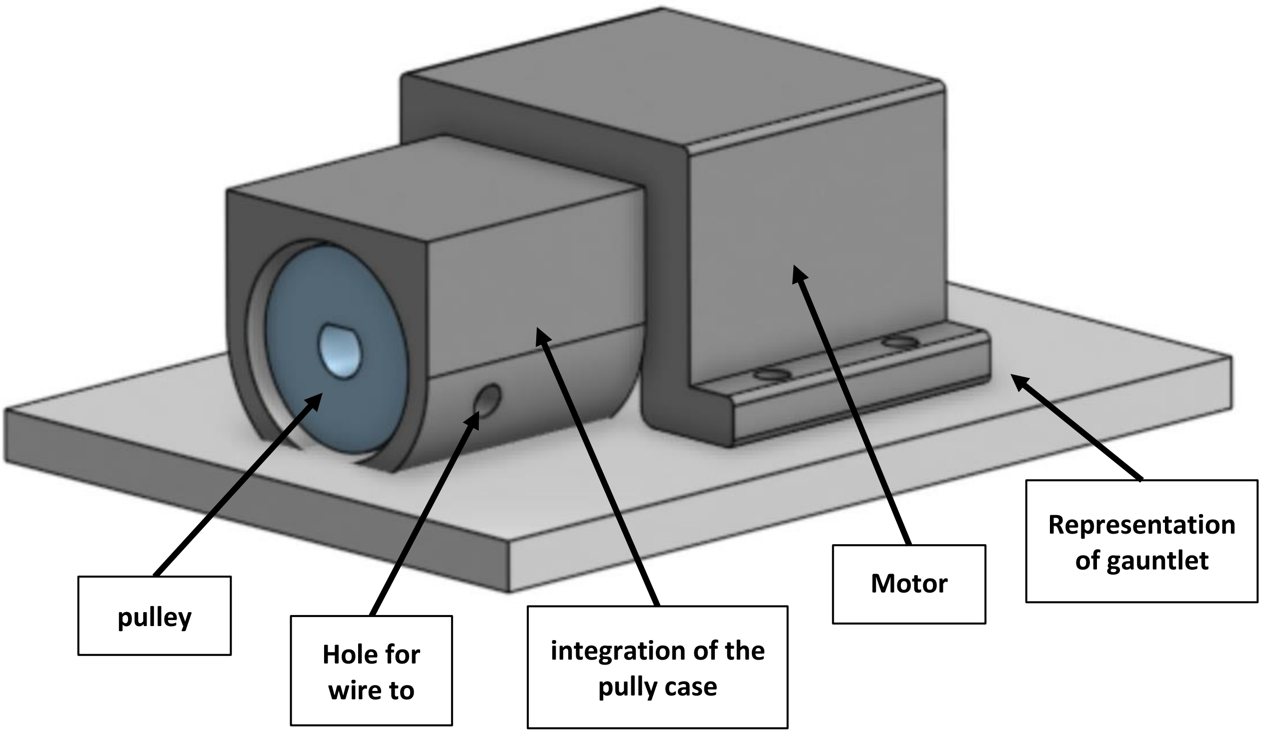


Figure 25-8 shows the extension of the motor casing to have a case for the pulley

To be able to make further improvements for safety according to the user's recommendations, same components were used for this improvement as in motorised pulley solution in section 13.1.6 and in addition to these components Arduino Uno was used for testing purposes. The circuit for this application can be found in Figure 25-9.

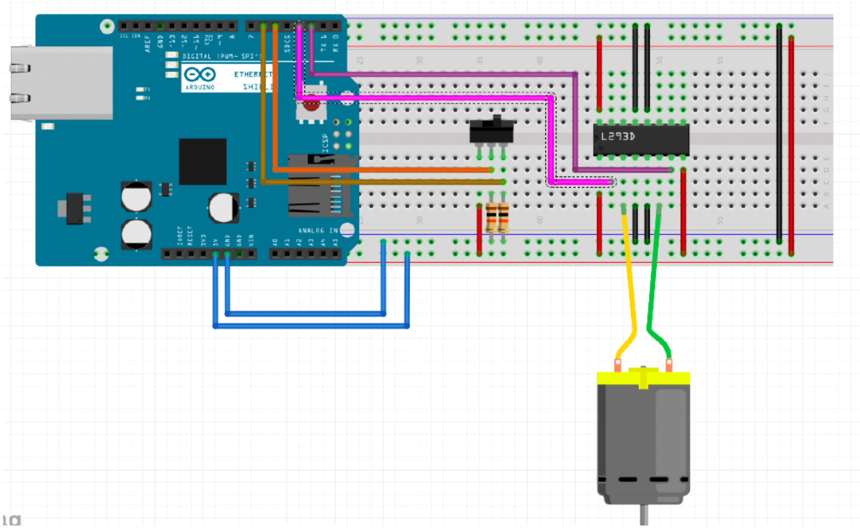


Figure 25-9 shows the circuit for the improved motorised solution

As in the motorized solution, the user needed to stop the motor manually and there wasn't any safety stop. In this improved solution, even the user doesn't stop the motor, the safety stop will automatically stop coiling. In this way even, the user forgets or couldn't stop the motor, the motor will be automatically stop itself. And by still using a 3-way toggle switch, the option would be given to the user rather to stop the winding in the preferable position. By giving a time constrain by using a delay() function, this solution was achieved. An adjustment can be done for different users just by changing the time in the delay() function. This solution could not be fully tested on the forearm or by the user as she was preferred to continue with the mechanical solution for her prosthesis. The code for this improved application can be seen in Appendix V.

Another way to improve this solution can be made by using two-way toggle switch just to run the motor backwards and forwards. By using the delay() function the time it supposed to coil the wires to tighten or loosen can be given. By this way the wires will be automatically tighten or loosen by toggle switch without needing to stop manually. For this solution the coiled wire length when the gauntlet is comfortably fixed on the forearm needs to be measured to further find the time it takes to tighten the wires. The time can be put into the delay function. To achieve this solution with a two-way toggle switch, the last 'else' function's loop needs to be taken out and the other parts of the code can be used.

To find the time for both solutions certain steps can be followed:

1. Measure the difference (x) between the wire length in when the wire is loosened (L_{loosen}) and tightened ($L_{tighten}$)

$$x = L_{loosen} - L_{tighten}$$

2. Calculate the designed pulley's inner circumference in this way how many millimetres of wire would be coil in one revelation can be find

$$c = \pi d$$

Where c is circumference and d is diameter

3. By looking at the total wire length calculate how many revolutions are needed to tighten the wire

$$revolution\ needed\ (R) = \frac{x}{c}$$

4. As the motor has a certain revolution per minute as in this JSumo DC motor the speed (S) is 400 rpm. To finf the time (t in minutes) it is needed for tightening or loosening it the below equation should be applied;

$$t = \frac{S}{R}$$

25.11 Gauntlet (PB)

- The gauntlet throughout prototyping was used as a way of rapid prototyping ideas, and therefore many of the features and thicknesses on the gauntlet are not needed, or thicker than necessary. The design could therefore be optimised or redesigned to reduce the amount of material used.
- If the circuit and battery are shrunk, the overall size/length of the gauntlet could be reduced, and thus weight.

25.12 Casing (PB)

The casing was designed quite rapidly and therefore suffers from a few issues.

- Not fixed securely – for example the back-casing lifts at the front. Can be improved by fixing it onto the gauntlet better, as currently it requires glue. More bolts could be a better alternative.
- Battery difficult to get in and out of back casing – increase length of the inside battery casing by a few millimetres.
- If the circuit and battery are changed, the casing could be reduced in size. Particularly the back casing, whereby it extends the length of the gauntlet. This feature could be removed.

25.13 Control (PB)

- Although the user was able to effectively control the prosthesis using the joystick design, further testing should be undertaken with her to improve its functionality. The control of the open/close function was deemed successful; however, the team were not able to discern whether flexion/extension of the thumb was also feasible for control in conjunction with this. It's suspected that the user needs more time to get used to the control mechanism.
- Remove twisting of the joystick – as mentioned in section 13.1.1, the joystick rotates slightly, and this can limit movement in flexion. This rotation should either be stopped, or the inside of the palm / joystick attachment edited to avoid collision.
- The thresholds chosen for the joystick control could be edited to the user's preference to make it easier for her to control.

- Removing the grip pattern toggle from the joystick and replacing it with a switch on the gauntlet could be a simpler and more useful solution for the user, particularly as she likes to use her other hand to assist the prosthesis.
- The team were unable to effectively test extension of the thumb as a means of control, so this should also be investigated.
- Once the user has become fully accustomed to using the joystick controller. It could be possible to add variable speed control, wherein the user can control the speed of the finger contraction by how far the joystick is moved, much like a throttle. It is not known if this would be beneficial, but it could increase functionality of the prosthesis, allowing very slow movements for precision tasks and fast movements where precision is not required.

25.14 Force Feedback (PB)

In section 7.3 it was stated that tactile feedback offers limited practicality should the controller be predictable. In the final design, the controller developed is deemed predictable enough that tactile feedback is not a requirement. However, it is still an important consideration in terms of embodiment of the prosthesis and its inclusion in the design should not be overlooked. With little testing on the User, however, it is difficult to conclude its benefit in this sense and it may also aid the controller in some way. The designers would argue, that for a user with a myoelectric sensor as a controller, the force feedback mechanism employed would be of greater use, as myoelectric sensors by nature can be unreliable controllers.

- The implementation of force feedback is an optional addition to the design. The force feedback and index finger designs are a proof of concept. With a pressure sensor already successfully implemented in the index finger, it would not be a difficult task to implement further sensors to other fingers or the thumb using the same method. These could be additional pressure sensors, temperature sensors, or piezoelectric sensors, for example.
- Little testing was done on the exact forces associated with the fingertip sensor due to time constraints, however they would likely be useful for future development. For example:
  - What force is required on the fingertip to trigger the sensor?
  - How does this force vary across the fingertip?
  - At what points on the fingertip does it not sense force at all?
  - How does the thickness of the NinjaFlex affect the force required to trigger the sensor?
- Although little testing has been done on this, the designers would suggest that implementing a slip sensor in the thumb would be a good next step in terms of feedback. The thumb would be a good candidate as it is involved in almost all gripping tasks. The slip would not need to be relayed to the user, but instead, using the Arduino, the system could automatically compensate and increase the grasping force when an object begins to slip. A piezoelectric sensor would be a good candidate in this sense and would easily fit on the thumb.
- The conductive fabric could also be replaced with conductive thread, provided it can be prevented from short circuiting. The routing of the thread/fabric should also be improved to be completely concealed inside the palm, in the same way as the fishing wire, for durability.
- Force derivative feedback (section 5.3) could be added to the code to allow the device to automatically respond depending on the force reading in the fingertip, acting as a closed loop controller. One problem with this, however, is determining the thresholds required. As a method of limiting the force being applied, for example, a force too high for one object may be too low for another. This could be resolved by having different ‘modes’, i.e. delicate mode, where the prosthesis does not apply above 5N to an object as an example.

25.15 Haptic Array (PB)

- The haptic array itself was not highly developed, as it was already deemed a successful proof of concept and therefore time was spent developing other aspects of the design. For it to be implemented fully and effectively, testing should be done to find the optimal arrangement and material for the vibration motors to make it as perceptible to the user as possible. As it was not effectively tested on the user, its application for providing feedback on the state of the device was also unevaluated.
- Other types of vibration motors could also be investigated to increase perceptibility.

25.16 Battery (PB)

- Due to the overall low weight of the prosthesis, the team do not deem it necessary to have an external battery due to the inconvenience and weakness provided by routing wiring across the body.
- The battery could be changed for one that can be easily replaced. In its current arrangement, it is difficult to replace the battery when it runs out and therefore the user would not be able to use it until it has been plugged in and recharged.
- Once a locking mechanism has been successfully implemented, the size of the battery should be re-evaluated as this would increase the battery life greatly, meaning a battery with a lower amp hour rating could be used, thus reducing weight and price.

25.17 Actuation (PB)

- Metal geared servos are recommended over plastic to avoid teeth shear. In the current design, the Hitec HS-85BB Servo Motor. Upon reflection, this was a poor choice as the plastic gears broke on multiple occasions. It is therefore not deemed durable enough for the purposes of this design. The team would instead recommend the Hi-tec HS-5087MH HV Digital Micro Servo, which has the same dimensions but has metal gears. These are far superior in strength and unlikely to break. It is greater in cost (Appendix M), but this is worth it for greater reliability and a smaller chance of having to replace it.
- If wanted, it is likely that a third actuator could be added that could be used to increase the number of grip patterns available, for example to actuate the middle finger separately. This would allow the tripod grip, for example. This is a stable pinch grip that is used for writing, eating with cutlery etc. As the user likes to paint, this could be useful for her. Alternatively, a mechanism could be implemented to remove the ring and little from the right pulley, like a clutch, to allow this.
- More powerful servo motors could be investigated, should the user require a greater torque for their daily activites.

25.18 Circuit (PB)

- The circuit could be easily shrunk to a smaller scale. This could be done by designing a PCB or using smaller versions of components.
- Alternative microcontrollers could be used that offer the same functionality provided by an Arduino Micro. These may be cheaper and smaller but were not investigated by the team.

25.19 General (PB)

- Testing of the prosthesis is needed to determine what objects it can hold. Due to time constrains there was little time for testing. It would also be very beneficial to do continue testing with the user to continuously make improvements to the design and determine its strengths and weaknesses.
- It would also be good to test the prosthesis on other users to obtain a different perspective. Something that is good for one, might not be for another, and this would help to improve the design.

26 Business Process

26.1 Introduction to e-Nable/Gre-Nable

e-Nable is a global network of passionate volunteers using 3D printing to create free 3D printed hands and arms for those in need of an upper limb assistive device.

The premise of their business model, which is a non-profit organisation, is to match builders (who are individuals with access to 3D printing and are willing to invest their time in making a prosthetic device) with users (those who need a prosthetic device). As the builders are the ones incurring the cost of producing the devices, this reduces e-Nables costs as they do not need to have capital tied up in material and machinery.

e-Nable relies mostly on the donations of benefactors and several sponsor companies who, over the lifetime of the organisation, have given them financial assistance in the form of funds or a service. The company uses the same business model as a charity and asks for donations which are used to maintain the website and keep the open source information, stories, resources and helpful links created by the e-Nable Community, in an accessible location to all people involved. The help of generous patrons helps to ensure that the 3D printable hands, tool files, resources, stories, educational materials, tutorials and support to those reaching out to e-Nable for help [120]

The entirety of the designs made by the e-Nable community are open source and free from patents. This encourages the continuous development of the devices by community members in the hope of innovating on the designs and producing the best prostheses possible [121].

Throughout this project the design team has worked alongside the Gre-Nable community, a Grenoble based team of the e-Nable community, who put the design team in contact with the user.
Regular correspondence with e-Nable France and the Gre-Nable community through their social media pages provided the design team with advice and assistance on certain design problems and queries from various knowledgeable individuals willing to help.

26.2 Development Criteria

Assumptions

As this is a university project within an institution and not a business, it is difficult to calculate the exact cost of what has been spent over the course of the project.

The institution, Grenoble INP, have funded and provided the facilities for the project team, with each of the four members of the team pay £4,500 to attend for the semester. The Universities direct cost is unknown as they receive funding from the French government and external investors. Additionally, age of machines and costs of the tools used from the workshop are unknown, hence the costs such as floor space and workshop costs, except 3D printing, have not been calculated and assumed to be paid for by the student fee.

Business Criteria

Three criteria were instigated by the supervisors at the beginning of the project, being:

- A development budget of €400.
- Unlimited use of the polymer 3D printers.
- Final product cost of €200.

These criteria were interpreted as, a maximum of €400 can be spent on ordering external arts for testing and use throughout the duration of the project. Therefore, as the second criteria allows unlimited use of the 3D printers, this cost would not be included in the €400. Additionally, any components that are already within the department or provided by the supervisors were not part of the €400 development cost. Finally, the €200 product cost would be the total price for all the components and materials that makes up one product.

26.3 Development Costs

The cost of the whole project has been broken up into 3D printed parts, ordered parts and all used/tested components.

26.3.1 3D Printed Parts

The two main 3D printers used during this project were the Zortrax M200 and the P3Steel. A cost for using, powering and the material used by the machines has therefore been calculated based off the specifications for both machines. The details for the M200 are from the official Zortrax website [66], and the P3Steels data has is from the Prusa website [122], due to it being the Prusa i3 machine with a structural upgrade kit.

26.3.1.1 Electricity Cost

The price of a kWh was found to be €0.067 from the official French government database [123], based off the price for a commercial business for the last half of 2018, due to the first half of 2019 statistic not being available.

<u>M200</u>

The maximum power consumption of the M200 is given as 200W. Therefore, the electricity cost per hour is:

$$€0.067 * 0.2 = €0.0134/hr$$

<u>P3Steel</u>

The average power consumption of the P3Steel is 120W. Therefore, the electricity cost per hour is:

$$€0.067 * 0.12 = €0.008$$

26.3.1.2 Machine Cost

To find the cost per hour of each machine the maximum possible amount of time that these machines can be used for printing had to be calculated. This was done by considering how many days they are accessible for, with the workshop being open for 251 days in a year [124], excluding weekends and public holidays. The workshop is then only open from the hours of 8am to 6pm giving a value of 10 hours of accessibility a day for use. Even though long prints can continue past 6pm and through the night, the value of 10 hours, averages this factor with the fact that the printers will not be in constant use during the workshops opening hours. Finally, both printers have a minimal lifespan of 2 years due to both machines having this time scale for their warranties [125]. Even though these printers will be used past this warranty time limit, this conservative estimate will factor for the maintenance and replacement of parts over the machines warranty period. The maximum possible working hours for both these machines are therefore:

$$251 * 2 * 10 = 5020hrs$$

<u>M200</u>

The current retail price of this printer from 3DPrima [126] is €1,395. Therefore, the machine cost per hour is:

$$\frac{€1,395}{5020} = €0.2779/hr$$

P3Steel

The current retail price of this printer from Prusa [122] is €769. Therefore, the machine cost per hour is:

$$\frac{€769}{5020} = €0.1532$$

26.3.1.3 Combined Running Cost

The costs to run each machine based on their primary cost and electricity cost are:

M200	€0.291
P3Steel	€0.161

Table 26-1: Electricity and Machine Cost

26.3.1.4 Filament Cost

Three different types of filament were used during development of the protect. The materials and their price per kg were:

Material	**Printer**	**Price per kg (€)**
Zortrax ABS	M200	41.20
Zortrax Semi-Flex	M200	96.78
Ninjaflex	P3Steel	82.50

Table 26-2: 3D Filament Prices

26.3.1.5 Total 3D Printing Cost

Using the machine and material costs calculated above, the overall costs for the 3D printed parts over the course of the development period were calculated. This is done by using the weight of each material printed and the time spent printing all the material using the equations below.

$$Material\ Cost = Total\ Weight\ (g) * \ Price\ per\ g$$

$$Machine\ Cost = Total\ Time\ (hours) * Price\ per\ hour$$

Therefore, the cost for all items 3D printed during the project is given in Table 26-3 below. A full breakdown of the 3D parts printed is given in Appendix W.

Material	**ABS**	**Ninjaflex**	**Semi-Flex**	
Total Weight (kg)	2.134	0.443	0.034	
Total Print Time (hours)	367.38	79.6	6.8	
Material Cost (€)	95.42	42.86	2.81	
Machine Cost (€)	107.64	12.58	1.99	**Total Cost (€)**
Combined Cost (€)	203.06	55.44	4.80	263.3

Table 26-3: Cost Spent on 3D Printing Showing a Breakdown for each Material and the Overall Cost

26.3.2 Additional Components Cost

This section breaks down the cost of all additional parts that were not 3D printed, but instead either ordered for the project, supplied by the department, or tested during the project's development. A full component list can be found in Appendix W, with the relevant suppliers contact information provided. A summary is given in Table 26-4.

	Cost (€)
Ordered Parts	313.98
Supplied Parts	615.69
Total	929.67

Table 26-4: Cost of Ordered and Parts Supplied from the Department

It is to be noted that ordered parts cost does not include shipping cost as that information was not available. Therefore, the ordered parts cost would be greater than given in Table 26-4.

26.3.3 Development Time

The labour hours spent by the four team members have been estimated and the total is therefore the amount of time that has been spent conceptualising, testing and developing the final prototype.

The dates for the beginning and final deadline were as follows; 05/02/2019 to the 05/06/2019, giving exactly 4 months for the total development process of the project. During this time there were 17 weekends in which work was not carried out. Additionally, there were two university holidays during the 4 months, in which there was no access to the project. The dates of these two weeks of holiday were; 25/02/2019 to the 01/03/2019 and 22/04/2019 to the 26/04/2019. A breakdown of how many days the project has been worked on is given below.

	Days
Project Duration	121
Weekends	34
Holidays	10
Total on Project	77

Table 26-5: Breakdown of the Number of Days Worked on the Project

For the duration of the project a schedule was put in place to make sure everyone was working from at least 9am until 5pm, with a one-hour lunch break from 12pm to 1pm. This structure was established up until the end of the second break on the 29/04/2019. After this point the working times grew to 9am until 7pm due to impending deadlines. Therefore, a breakdown of the number of hours spent on this project has been given below.

Number of Days	Working Times	Number of Hours
05/02/2019 – 18/04/2019 (49 Days)	9am – 5pm (7 hours)	343
29/04/2019 – 05/02/2019	9am – 7pm (9 hours)	252
Average Individual Hours		595
Average Team Hours		2380

Table 26-6: Breakdown of the Number of Hours each Team Member has Worked and as a Group

Therefore, a minimum of 2380 hours was spent on research, development and prototyping of this product.

26.3.4 Labour Cost

As this project has been conducted by university students for a volunteer community there are no Labours costs associated with the final product. However, if this project had been developed by a company then the number of hours spent by each member of the team would be an additional cost. Therefore, an estimate of the labour costs of this project have been calculated based on the calculated average development hours.

Firstly, the minimum wage for an intern in France is €554 [127] a month, with a working week of 35 hours. The salary per student per hour was therefore found to be €3.65/hr from the calculation below.

$$\frac{€554 * 12}{52 * 35} = €3.65$$

Using the calculated average number of hours of 595 hours per student a labour cost breakdown is shown for each student and for the project.

Student Salary	€2,173
Project Labour Cost	€8,694

Table 26-7: Labour Cost per Student and for a Group of 4

The figure of €8,694 would have to be considered in the development costs if the circumstance of project were based within a business and not a university.

26.3.5 Total Development Cost

	Cost (€)
Ordered	313.98
Development (Ordered + 3D Printed)	577.28
Total Development (Ordered + Supplied +3D Printed)	1192.97

Table 26-8: Combined Costs for Project

As can be seen in Table 26-8, the €400 development budget was met as only €313.98 was spent on additional orders over the project period. However, if the initial specification was interpreted differently to include the 3D printing costs as part of the development then the budget was exceeded by €177.28.

From the aspect of an individual within the e-Nable community carrying out the project in the same fashion, the total cost for them would be €1192.97, assuming they already own a 3D printer. This would allow them to test, design and prototype every item and aspect of the design mentioned throughout the document.

26.4 Product Cost

For a member of the e-Nable community to recreate the final prototype for a new user there would be a cost for them to print and assemble the entire product. Firstly, they would have to obtain the materials needed to produce the product. Therefore, assuming the developer already has a 3D printer, the cost is given in Table 26-9 below.

	Cost (€)
Material	343.07
Minimum for One Product	201.11

Table 26-9: Cost to make One Prototype with all the Materials and the Exact Materials

The difference between the two costs above is due to the €201.11 being the cost for the exact amount of materials to produce one product, and the €343.07 is the price of buying all the materials to make the product, e.g. the price of the whole reel of fishing wire, an entire spool of ABS filament, etc. Therefore, if a community member wanted to make a one-off replicate of the prototype, the cost would be €343.07. However, this cost includes a large amount of left-over material, which could make multiple of the prototype. Furthermore, if the developer is producing multiple versions of the product the cost to make one will reduce, and the more that are made the closer the products cost will be to the minimum price of €201.11. Therefore, the criteria for a product cost of a €200 product can be met if multiple are made.

26.5 Developer Time

In addition to the cost for the developer, there would also be the cost of their time to print and assemble the full product. These two times are given below in Table 26-10.

	Time (hours)
3D Printing	65.37
Assembly	16
Total	81.37

Table 26-10: Time for a Developer to Produce a Prototype

The assembly time starts once all items have been printed off. It includes the time taken to solder the circuit and integrate the electronics into the mechanical model. Therefore, to be able to produce the product the developer will need 65.37 hours to have all the parts printed, and then spend 16 hours assembling until completion. The overall time for a complete model from the first print is 81.37 hours, assuming the developer only has one 3D printer.

26.6 Potential Business Model

As e-Nable is a volunteer community, where each developer must fund the device they are making themselves, there is a potential business model that could be implemented to help reduce the cost of the product and remove the difficulty of sourcing the individual parts. This could be achieved by developing a 3rd party, non-profit, supply chain specifically for the prototype. The model is shown below in Figure 26-1.

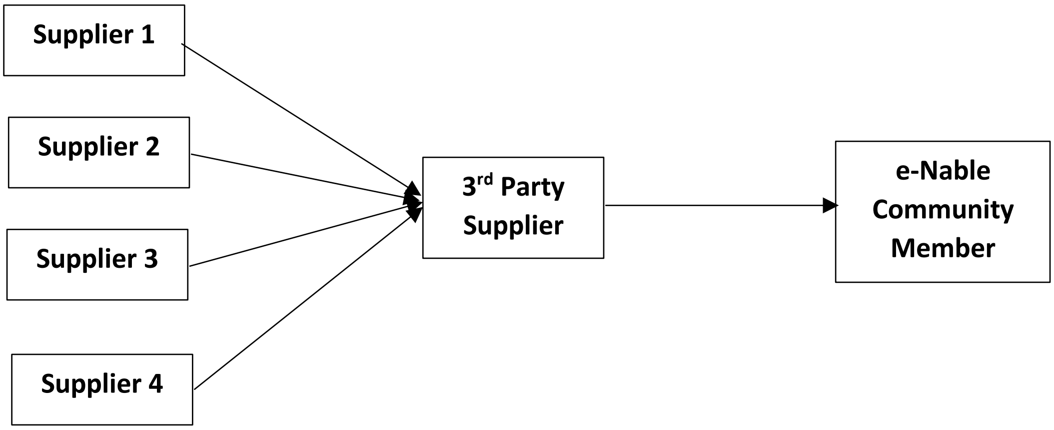


Figure 26-1: Business Model Diagram

This model will reduce the cost of producing the product using batch buying by the 3rd party supplier. This will reduce costs in three ways:

1. Shipping Costs.
2. Batch Buying Discount.
3. Exact Material Amount.

Firstly, the shipping cost is reduced when batch purchasing. Currently the community member would have to pay a shipping fee to each of the suppliers to acquire all the components. The 3rd party supplier would order multiple components from each of the suppliers to create numerous kits. This would cost the same amount in shipping from each supplier but for more products, therefore this cost would be split across the number of kits made, hence reducing the cost.

Secondly, suppliers apply a discount to components when bought in batches. Batch cost calculations were made based on building 5, 10, 25 and 100 of the product (Table 26-11). Buying components and materials in bulk often reduces the price per unit, and this is shown. It also greatly reduces shipping costs, as over a certain value many suppliers offer free shipping. Therefore, this business model could be scaled to reduce the price of the kits further. Starting with a batch of 5 reduces the cost of each kit by €15. As the demand for the product kits increases, the 3rd party supplier can increase the size of the batch order and therefore bring the price of the kit down further.

		Price Per Component				
Component	**Supplier**	**1 Unit**	**5 Units**	**10 Units**	**25 Units**	**100 Units**
Vibration Motor	Sparkfun	€7.60	€1.90	€1.90	€1.90	€1.90
Sparkfun DRV2605L Haptic Driver	Sparkfun	€7.02	€7.02	€6.95	€6.96	€6.58
BC337 NPN Transistor	Sparkfun	€1.76	€0.44	€0.44	€0.44	€0.44
Thumb Slide Joystick	Sparkfun	€3.07	€3.07	€3.07	€3.07	€3.07
Interlink Electronics 0.2" Circular Force Sensitive Resistor	Robotshop	€6.73	€6.73	€6.4	€6.47	€6.08
Hitec HS-85BB Servo Motor	Robotshop	€35.28	€34.58	€34.58	€33.88	€33.88
Li-ion Battery, 7.4V 2,200 mAh (2S2P) with PCM	Gen Robots	€22.90	€22.90	€22.90	€22.90	€22.90
8.4V 1000mAh, lithium ion charger	Amazon	€8.99	€8.99	€8.99	€8.99	€8.99
Arduino Micro	Arduino	€18.00	€18.00	€18.00	€18.00	€18.00
2.5-9V Fine-Adjust Step-Up/Step-Down Voltage Regulator S9V11MA	Polulu	€7.90	€7.37	€7.37	€7.75	€7.75
Toggle Switch	Sparkfun	€1.73	€1.73	€1.73	€1.73	€1.73
Conductive Nylon Fabric Tape - 8mm Wide x 10 meters long	Ebay	€2.61	€0.52	€0.26	€0.10	€0.05
Amphenol Clincher Connector, 2 position male	Sparkfun	€3.90	€3.9	€3.9	€3.9	€3.9
1.2k resistor (20pk)	Sparkfun	€0.95	€0.19	€0.19	€0.19	€0.19
10k resistor (20pk)	Sparkfun	€0.95	€0.19	€0.095	€0.095	€0.095
Female headers (40pk)	Robotshop	€0.36	€0.36	€0.32	€0.32	€0.3
Male headers (80pk)	Robotshop	€0.36	€0.36	€0.36	€0.36	€0.36
Prototyping board (58x78mm)	Robotshop	€1.09	€1.09	€1.04	€1.04	€1.01
10 pins ribbon cable (15')	Sparkfun	€4.34	€0.868	€0.434	€0.1736	€0.0434
Total Cost		€135.54	€120.21	€118.93	€118.27	€117.27

Table 26-11: Cost of Components when Batch Buying

Finally, the 3rd party supplier would put the exact number of components and length of material needed to produce one product in one kit. For example, to purchase the ASSO 130m fishing line costs €36.20 for the whole reel. However, the product only needs 3.8m of the fishing line to assemble the product, worth €1.06. The 3rd party supplier would therefore be able to distribute the fishing line cost across the number of kits, therefore creating a potential reduction of €35.14 for the community member.

The target market would be for e-Nable community members, who already own a 3D printer, wanting to reproduce the Flexibone V2 electrically assisted prosthetic. There would be two kit options available:

1. All Flexibone V2 components + 3D filament
2. All Felxibone V2 components

These two options will allow members who either do or do not have the correct filament for their 3D printers to reproduce the device. The member would pay the kit price and the postage fee which will give them the exact amount of material and number of components needed for the product. This kit would therefore bring the product down to at least it’s minimum price of €201.11.

27 Conclusion

Throughout the project period, the methodology of testing and iteration of ideas drove the project and its members into producing a functioning electronically assisted prosthesis prototype. This device was made bespoke for a user through the means of interviews throughout the project period. However, it also has the potential to be made adaptable for other users with a similar disability. All files were created on the CAD software Onshape, making it open source for the e-Nable community. All mechanical parts of the product were 3D printed, with all additional electronics and parts being easily sourced. This ensures that the product is reproducible for a minimum price of €201.11, keeping in line with target price of €200 set out by the initial criteria. It is a compact design, with all components located within the palm and gauntlet, with an overall weight of 561g. Although this is greater than the 500g criteria, it is still within the comfortable weight range for long term prosthesis use.

The Flexibone V2 mechanical model was chosen through the means of thorough testing of common palm models, where the finger contraction force and their gripping capabilities were compared along with other criteria. The traditional method of using fishing line to contract the fingers was chosen in conjunction with 2 servo motors. This allowed for the compact designs of pulleys to be used, where pre-tensioning mechanisms and whippletrees could be implemented to create a reliable gripping force. The development of new fishing line routing incorporated the use of PTFE tubing throughout the device, reducing friction and creating a more efficient system. This routing also gave the user back the functionality of their wrist joint, allowing them to grasp objects while freely moving their wrist. Finally, a new method of attaching the device to the user was developed. Drawing inspiration from the tightening of a snowboard boot, the turning of a knob on the gauntlet tightens fabric to the users arm until secure.

After the investigation of many input sensors, such as flex, pressure and Myoelectric sensors, a bespoke control system was developed for the user, allowing them to communicate easily with the device. By integrating the use of their residual thumb with a cross directional micro joystick, a control method was created giving the user 4 input commands within the palm. This control method in conjunction with 2 servo motors allowed the implementation of multiple grips, the main being the power grasp and the pinch.

To increase the acceptance of the prosthesis by the user, a haptic vibration feedback loop was implemented into the device. The implementation of a pressure sensor in the index finger's distal bone allowed the user to receive feedback in the form of multiple vibrating haptic motors when contact was made with an object. Depending on the contact strength, a different motor position will vibrate in the array that is placed along their forearm. This indicates to the user how much force they are applying to an object.

The performance of the prototype allowed the grip of multiple sized objects, ranging from small pieces of foam, using the pinch grip, to lifting 400ml bottles of water, using the power grip. During the final meeting, good dexterity was witnessed by the user with the device. They could easily pick up and manipulate objects, with the input controls being quickly understood. The user's feedback was positive, with the design being aesthetically pleasing for them, with the input control being simple and intuitive. The new attachment method was also seen as a great improvement over their current devices Velcro, providing greater comfort.

However, as the device is a prototype, it is prone to malfunctions. One occurred during the final meeting with the user, where both servo motors proceeded to go wrong, therefore ending the demonstration. This malfunction was due to the motors having plastic gears whose teeth broke while holding a high torque. These errors highlighted potential areas for further development of the device.

Overall, the final device developed was a functioning proof of concept, with numerous new aspects developed and others investigated heavily. It has provided a large amount of research and development for the rest of the e-Nable community to use and implement into their own devices. Additionally, it has laid a large foundation for a future finalised design of an electronically assisted prosthesis for the user.

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