E2 PROJECT – 'ARTICULATED GLOVE FOR HAND DISABILITIES'

FINAL REPORT

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Abstract

The purpose of the second-year EE Group Project entitled 'Articulated Glove' was to aid people with hand weakness caused by neurotrauma injuries through a physical solution that is cost-effective, portable, comfortable, and well-designed.

The team set about achieving a unique product through extensive market research into existing solutions which included the Eso Glove developed by NUS and Exo-Glove Poly by Seoul National University. It was observed that these products have downsides that our glove could avoid, while also offering avoid, as well as offer relatively improved performance as a rehabilitation device.

A thorough process of exploring concepts and design for the glove followed, both regarding the mechanical parts such as the exoskeleton and articulations, and the electronic system relying on a microcontroller regulating sensors and servo motors programmed via the Arduino IDE environment. Matrix methods were used by the team to choose concepts and models objectively, after which components were ordered and have been for the most part already integrated into the prototype. An additional feature in the form of the Myo Band was added, making the product applicable to a broader consumer base.

Project management was an important aspect and agreements on holding briefing meetings, recording points discussed, and tracking milestones through Gantt Charts were essential in ensuring group members could collaborate in a cohesive manner. The team has met its milestones but still needs to assemble the final product in time for the demonstration. With more time available, the team would have explored the use of the glove as an intelligent device capable of imitating movements made by another individual.

Introduction

Initially, the group's second-year group project aimed to address neurological disorders affecting the hands such as Arthritis, De Quervain's syndrome, and Carpal Tunnel Syndrome. The principal issue we saw was that while sufferers can still move their flanges to a small degree, their movements are not fluid due to a lack of strength or pain felt during the process. We also considered ALS, which would however require a complicated sensor mechanism to ignore the unintentional muscle twitches the disease triggers.

The goal of the cost-effective articulated glove was to help those affected to carry out essential tasks for daily life such as typing, grabbing light objects and even writing on paper, thus enabling them to recover confidence in themselves and re-enter the labour force.

Since then the team's focus has shifted to the more feasible aim of aiding people with hand weakness caused by neurotrauma injuries. Statistics from the National Health Interview Survey in the US show that 0.5% of the population aged 18-44 years, and 2.3% of people aged 45-64 find it "very difficult to handle small objects" (1), revealing a problem of significant scale we believe we are in a position to solve through the resources and timeframe we have at our disposal. The original intention to make the glove suited to neurological disorders was thus abandoned due to the pain the device would likely inflict on sufferers. Moreover, it was found that most patients affected by the serious aforementioned conditions undergo symptoms that include passive movements they cannot control, therefore making the need for further movement undesirable for them under many circumstances.

Market research revealed that at present, a number of supporting gloves that relieve discomfort and pain for patients are commercially available. However, we did not find a solution that was comfortable to wear and portable while concurrently being able to provide an automated movement mechanism. However, the team did not find a solution that was comfortable to wear and portable, while concurrently being able to provide an automated movement mechanism. Typically, the aforementioned solutions rely on soft soothing materials such as gel pads, while the Articulated Glove relies on a hard plastic exoskeleton. Therefore this solution would therefore be able to capture market share at least in the UK and European countries where demographics are favourable towards the elderly population most affected by the social problem, and awareness of difficulties faced by this subset high. If marketed correctly, the scope for making a positive impact on the community nationwide would be significant. Furthermore, given the shift in target market since the beginning of the project, the glove has applicable to a wider range of people of different ages since it is not reliant on a customer suffering from a degenerative disorder, but rather on a customer having a movement problem that can vary from minor to more debilitating.

The first solution proposed was a discrete, articulated glove consisting of a thin light exoskeleton fixed to a person's fingers through a glove cover. Whenever the user wishes to move a finger downwards, the device senses slight movement or pressure, unblocks itself, aids the finger in moving to the right position, and blocks itself when it no longer senses a pushing force. Upward and downward movements are permitted, with blocking points determined by a string system at a maximum of four stages between 0^o and 180^o. Between the materials proposed for the exoskeleton, PLA was chosen due to its feasibility, suitability and cost, while guitar strings would work best for their low elasticity and tensile strength. David's hand was used for taking measurements the final product will adhere to. By the time the interim report was finalised, an initial batch of components had been ordered.

This project has seen numerous developments since the last report on February 8th. By February 10th many components ordered arrived, leaving the team prepared to move onto a stage wherein the product is printed and assembled in its entirety. An existing technology suggested by our experienced supervisor, the Myo Band, was also integrated which allows an extension of the current design to allow even more accurate tracking of movements for the glove. The guitar strings were integrated into the exoskeleton, and testing of the different motors commenced. The microcontroller determining the sensors' behaviour will be the ATtiny, with the addition of a Bluetooth module to the design.

Market Research

Several similar products exist on the market, but all of them have specific drawbacks, one of which is shared by all. The product developed by the project team would aim to avoid these drawbacks as much as possible while not compromising a level of quality which could allow the product to be competitive against these other devices.

Exo-Glove Poly - SNU BioRobotics Lab (Seoul National University)

The Exo-Glove Poly (2) is an impressive piece of engineering, which restores functionality back to people who have experienced hand trauma in many of the ways the team would like to. There are several things which could be learnt from the Exo-Glove Poly, such as the material used for the glove and the way in which pulleys are used to convey the force from the actuator to the glove. Additionally, the actuator used can both pull and push the metal wire cables, allowing force to be applied in both directions.

However, the Exo-Glove Poly has the large disadvantage that the user must carry around a bulky and heavy actuator, which could be a problem if he/she is not in a wheelchair and experiences problems with balance, as well as not being very convenient. The user must also have the other arm free and functioning in order to operate a button which controls the glove's contraction.

Eso Glove - NUS (National University of Singapore)

The Eso Glove (3) has a slightly different aim to the group's original plan, and is more aligned with an idea that was developed later. The Eso glove is for rehabilitation of patients suffering from trauma to their hand. The most impressive aspects of the Eso Glove are that all the components in the glove are soft, and that it uses many independent soft actuators to control the different parts of each finger, allowing them to move independently. Another desirable characteristic is its use of electromyography and radio frequency identification to control the actuators, as well as the insertion of non-ferromagnetic material within the soft actuators making it suitable for use within an MRI machine.

However, the Eso Glove is mainly a table top device for use in hospitals, and while there is a waist belt version for mobile patients recovering at home, it once again bulky and not very portable.

Soft Robotic Glove - Harvard University

Through pumping water into a glove, the mechanism underlying this solution causes the glove to contract in a pre-programmed way (4). The advantage of using a hydraulic system to move the fingers is that it gives a very smooth and comfortable motion with uniform pressure applied across all sections of the finger.

The downsides of this device are both that it can only implement movement in one specific motion without being physically reprogrammed, and that it weighs around 3.5kg. This weight is partly due to having to carry water around, which denotes one of the main downsides to using a hydraulic system.

Comparison and Analysis of Objectives

As a stationary device for rehabilitation within hospitals, the Articulated Glove cannot compete with the Eso Glove since the team does not have the time, resources or experience to develop a glove which can work in an MRI machine. However, it could implement it's other features and functions while being more portable and convenient.

A common characteristic of all the above competitor devices is their weight and lack of portability. The Articulated Glove aims to be lighter, more portable and practical than its competitors, which may originally come at the expense of comfort to the user, but will aim to become competitive in all areas after the team have produced a working prototype. The portability combined with the extra flexibility of using EMG sensors and touch sensors to control the movement of the fingers results in a cheaper, more general purpose device than many of those already on the market, which could be used in both hospitals and homes.

Additionally, the majority of competitor devices on the market work purely as rehabilitation devices or aids to the user in everyday life. The articulated glove will have a stationary rig which can be used to exercise a hand and carry out rehabilitation exercises, however this is an additional function to a portable device as opposed to it being the main function. The team's decision to produce this rig was born after identifying the clear market for something of its type as demonstrated by the competitor products.

Additionally, the use of a separate EMG sensor unit such as a Myo Band, linked by Bluetooth technology, will allow doctors or helpers to demonstrate movements while wearing the EMG unit, which the glove worn by the user would then imitate. This would allow a more varied set of rehabilitation exercises which could also be easily tailored to specific patients.

Hence the unique selling points of the Articulated Glove are that it will be the only device which can be used both for rehabilitation and as an everyday convenience aid, and a device unique in using EMG sensors on a Myo Band linked by Bluetooth which allows EMG signals can be read from an arm other than the patient's. This will allow a doctor, nurse or friend to demonstrate any movement, and be imitated by the glove. The flexibility offered by this feature will also allow doctors to give better specific and more targeted care, with more ease than any other device on the market.

Design Criteria

The Design Criteria since the Interim report were largely unaltered. Factors such as cost, Design production, weight and space had been heavily discussed previously, and resulted in an accurate assessment of the constraints imposed on the design of the exoskeleton. The primary functions our design should satisfy thus remained ease-of-use, likeliness to a biological extension, the ability to grab objects safely, and portability, while comfort and compatibility with EMG sensor devices became new points of focus following the Interim report.

Cost

The project's budget is constrained to £100, an amount of money that undoubtedly limits the components we could acquire. However, it did present an opportunity for us to exercise our creativity in discovering how to develop a cost-effective solution. For instance, instead of choosing a sufficiently strong bipolar stepper motor, budget constraints led us to find a solution relying on a mechanism based on a unipolar servo motor and elastic strings.

Cost was also a primary factor influencing our choice of material between PLA and ABS, as well as a driver for developing a design early on showing its potential so that our team may gain more funding for the project. While we did not produce a prototype early enough and so were unsuccessful in gaining more funding, each member of the team agreed to contribute from our savings to the purchasing of new components and modules if needed.

Design Production

A vital consideration for this criterion is the function of the exoskeleton material, which the team originally theorised should take on characteristics similar to bone support prosthetics such as hip replacements. Therefore, a table was created in which materials such as Titanium 64 are benchmarked against a human bone. It was observed that most of these materials were stronger than necessary, and that the team lacked the knowledge and resources to machine them into the specified shapes. Since hiring someone at such an early stage is unfeasible given the small scale and budget of the project, 3D printing was the method chosen for creating a working prototype.

Weight

The articulated glove is a portable device, in that it should preferably be easy to carry and unnoticeable, this was accomplished by means of an appropriate selection of components. PLA Plastic was chosen due to its lightness, and since a servo motor's weight of 25 grams is only a fraction compared to the stepper motor of 280 grams, the former was chosen.

Space

Space is another primary consideration influencing the glove's usability. Fingers held close together require an exoskeleton design that is thin and concurrently durable, and whose individual parts should not be able to pull or rub against each other, which would compromise its functionality and safety. The individual 'half pipe' sections will be 3D printed to be non-hollow inside and thin enough to not interfere with each other. This may result in them being slightly heavier, but significantly more durable at such widths. The internal circumference is not reduced and not too tight on the finger, while the half pipes are significantly thinner yet sturdier.

Compatibility with EMG Sensors (the Myo Band)

This design criteria was established relatively late in the project, as the team acquired a Myo Band during late February. The Myo Band is not fully part of the project, but more of an investigation into possible future work, exploring an exciting aspect which could allow the glove to become competitive with devices such as the Eso Glove from NUS. The Myo Band communicates the data from the EMG sensors using Bluetooth, which required the team had to give the glove the capability to communicate using Bluetooth. Although not being fully part of the project, this criterion is still very important due to the opportunities it unlocks.

Comfort

The last design criteria are related to how the consumer would feel while using the device. It is a sum of all the previously explained design criteria and determines whether people are inclined to use it. One aspect of this criteria would be adding another material to the exoskeleton, such as gel pads, however this aspect is a second priority after having a working prototype. Particularly because the addition of comfort improving gel pads could decrease the effect of making the exoskeleton thinner.

Concept Designs

Compared to previously, the team started considering how the sensors would control the motor, and concluded that a microcontroller control circuit would be required. This would require a board design, which work was commenced on upon completion of the report. The introduction of these two aspects was therefore necessary.

Mechanical design

The finger movement mechanism design required the team to consider three options. The first option involved the use of 2 motors: one to bend and one to straighten. The second option used a bidirectional motor that could both bend and straighten the finger, but this would require hydraulics or two strings. In the end the team decided to use one motor and an elastic band. The first would pull the string and the second would straighten the finger, with no need for a second motor. These power devices would be placed along the forearm's length.

Control procedure

For the control mechanism two alternatives were considered. The first was to use two sensors per finger, one under the tip and one above the nail. When the bottom sensor recognises a higher output than the top, this signals that the finger would be "pushed in", and vice versa. If no sensor detects a touch, the finger will be held at its current position. The second implementation consists of one sensor per finger, which will be located under the fingertip so that when the sensor is touched, the motor inputs the necessary power to "push in" the finger until no more force is applied, and when the sensor is not touched an elastic band will pull the finger back to straight again. The circuit will be placed behind or on the other side of the forearm to reduce any noise that the motors may generate.

Motor Selection

Motors are an essential element of the device, as their role is to pull the fingers via a string system and let them go when needed. The characteristics of the motors model the rest of the design more closely than any other part. Furthermore, they are also the most expensive and taxing to the project's budget, and thus must be chosen carefully.

In order to obtain the torque needed, calculations were made to obtain a value for the strength a hand uses to grab an ordinary mug. A torque of 1.11 N/m was obtained as a good replication of human grip (refer to Appendix B for calculations). It has to be considered that the torque needed must be divided between the four motors. Table 1 illustrates their details, and Table 2 shows which components were considered:

DC motors	Stepper Motors	Servos
Single Direction	Bidirectional	Bidirectional
High RPM	Slow	Fast
No precision	Precise positional control	Accurate rotation control
Cheap	Expensive	Expensive
Light	Require more output pins	Angle of rotation is limited
	No built-in microcontroller	Built-in microcontroller
	High holding and rotational torque	Normal holding and rotational torque
	Very heavy	Light

Table 1: COMPARISON OF MOTORS

Motor	Price (£)	Size (mm^3)	Torque (oz./inch)	Type	Current (A)	Voltage (V)	Weight (g)	Deg/step
RB-Soy-02	17.00	42x42x42	36.00	Unipolar	0.80	6	280	1.8
Johnson Electric	10.59	30x12x15	7.08	Bipolar	0.20	12	25	18
Parallax Servo Motor - 1	9.37	46x56x19	38.00	Servo	0.14	4 - 6	44	-
Parallax Servo motor - 2	10.67	56x41x19	22.00	Servo	0.13	6 - 8.4	25	-

Table 2: MOTOR SPECIFICATIONS

Sensor selection

Capacitive Sensors were chosen due to having fewer analogue input pins compared to Force Resistive sensors (FSRs). Their cheaper cost and characteristics avoid the need of a microcontroller to read the voltage at 4 different pins simultaneously. However, the FSR comes with a built-in microcontroller and therefore needs less time to read each touchpad's state.

Pressure Sensors	Switches	Capacitive Touch Sensors
Analogue output	Digital output	Digital output
1 sensor per pin	1 switch per pin	Up to 12 sensors with 1 I2C channel
Expensive ~£6 each	Cheap	£8.5 for all related components
Flat	Small mechanical parts	Flat

Table 3: COMPARISON OF SENSORS

Materials study

The first thing that was studied regarding materials was similarities with the human bone. It is because of this that using metals such as Titanium 64 or stainless steel were considered. However, it was quickly clear that these components were expensive. Designing the glove with 3D software and printing it using the Imperial Robotic Society facilities made the process of using PLA cost-effective and accessible. For further details, refer to Appendix E. Tables 3 and 4 compare the different material alternatives:

Material	Tensile Strength (MPa)	Density (g/cm^3)	Softens at (°C)	Fatigue Strength (MPa)	Price (£/kg)
Bone	150	3.90	400	<100	N/A
Titanium 64	862	4.50	680	500	10.00
Stainless Steel	860	7.80	650	240-270	1.50
Cobalt-Chromium Alloy	480-840	8.40	600	260-840	11.28
PLA	37-56.6	1.25	60	-	15.75
ABS	28.5	1.04	105	-	15.56

Table 4: COMPARISON OF MATERIALS

	PLA	ABS
Pros	Biodegradable plastic (more ecologically friendly)	Can be easily recycled
	More brittle, higher surface hardness	Weatherproof, more flexible
Cons	Prone to breaking while bent	Produces toxic gas while printing
	Higher density ($0.21g/cm^3$)	Not a very food-safe material
	Cost is almost identical	

Table 5: PLASTIC COMPARISON (5)

The main drawback of PLA, which makes it suited only to the prototype and not the final product, is its relatively low melting point which would not be safe in certain environments.

Articulation design

One of the design areas with largest amount of constraints is the articulation design, which is very closely related to the mechanical design. The development of an exoskeleton that is light, comfortable, and durable and of right size is very complicated. The process of construction of the articulation is steeper in that every new design builds on the last one with new improvements or adequate sizes.

Every time a new model is printed with the use of a 3D printer, it was cleaned up to eliminate any residues from the machine such as the rafts or supports. Then it was tested by introducing the pulling strings and the elastic strings through their respective holes. The following procedure involved introducing a finger into the articulation. Many times, the sizes were not adequate due to the difficulty in measuring finger lengths and correct positioning of the hinge, while not obstructing bending of the finger or obstructing adjacent fingers.

Final component selection

It was decided that the motor that best fits the constraints of the design was Parallax Inc. Servo motor 2 due to its rectangular dimensions that would fit properly into the arm and its torque. It is also cost-effective and very light.

Component Description	**Cost per each (£)**	**Quantity**	**Subtotal (£)**
Capacitive Touch Sensors	8.50	1	8.50
Servo Motors	10.67	4	42.68
Super Glue	0.98	1	0.98
Screw	0.05	5	0.25
Nuts	0.03	5	0.15
Microcontroller	2.50	1	2.50
Microcontroller Socket	0.102	4	0.41
Bluetooth Module	10.95	1	10.95
AA Batteries (Energiser)	0.24	5	1.20
Voltage Regulator	2.07	1	2.07
Crystal	0.218	1	0.22
3D printing	10.00	1	10.00
Stripboard	1.50	1	1.50
LED lights	0.074	2	0.15
Wires, resistors, capacitors...	1.00	1	1.00
		Total (£)	82.56

Table 6: COMPONENT COSTS

Throughout the development process, some components were purchased for testing the first physical prototype, though they did not perform as we expected or a better component was found to replace it. The components we ordered are shown in table 7:

Supplier	Component Description	Cost per item (£)	Quantity	Subtotal (£)
EBay	Bluetooth BLE module - HM-10	10.95	1	10.95
EEDSTORES	ADHESIVES CYANOACRYLATE ADHESIVE 3GR TUBE	0.98	1	0.98
EEDSTORES	Screw	0.05	3	0.15
EEDSTORES	Nut	0.03	3	0.09
EEDSTORES	Super Glue	0.98	1	0.98
EEDSTORES	Stripboard - Medium	1.50	1	1.50
OneCall	NANOTEC Stepper Motor DC 0.28Nm	17.85	1	17.85
Rapid Electronics	Adafruit 1602 8-Key Capacitive Touch Sensor Breakout	8.50	1	8.50
RS	Servo Motor	10.67	4	42.68
RS	Microcontroller Socket	0.10	17	1.74
RS	Atmel ATMEGA328-PU Microcontroller	2.50	1	2.50
RS	Crystal Oscillator 16MHz	1.89	1	1.89
RS	Crystal 16MHz	0.22	5	1.09
RS	Low Dropout Regulator	2.07	1	2.07
			Total (£)	92.97

Table 7: COMPONENT ORDER SUMMARY

Concept Selection

The group reasoned that in order to make the choice an objective and rational one, they could not rely on intuition or previous experiences, the latter being largely irrelevant for this project, or rely solely on our supervisor's or group leader's judgement.

The group therefore went about concept selection using one of the Decision Matrix methods learned in first year where selection criteria based on the design criteria are placed in the rows of the matrix, and the concepts or options inserted into each column.

The Controlled Convergence unweighted matrix was chosen, since all concepts had been developed to the same level of detail, and the criteria were all directly relevant to the key customer requirements outlined in the Design Criteria section.

Ratings were used that varied from:

++ = "best"	+ = "good"	o = "average"	- = "worse"	-- = "worst"

Ratings given to each criteria were agreed upon as a group even though some group members were inevitably more involved in the process for the concepts they were overseeing and developing. The concept chosen was the one in the column giving the highest result when all signs were added together.

The number of matrices was 6 for each of the concepts, and parts of the glove that had to be decide upon: Sensors, Motors, Materials, String, Microcontroller, Bluetooth module.

Sensors

	Sensors					
Type	Force Sensitive		Switches		Capacitive Touch	
Cost	£6 each	--	Cheap	++	£8.5 in total	+
Size	Flat	+	Small mechanical parts	-	Flat	+
Sensors per pin	1 sensor per pin	o	1 switch per pin	o	8 sensors with 2 - 4 pins	+
Output type	Analogue	+	Digital	o	Digital	o

Table 8: Decision Matrix - Sensors

The matrix method resulted in the following scores:

1. Force Sensitive = 0
2. Switches = +1
3. Capacitive Touch Sensors = +3

According to the method, capacitive touch sensors should be chosen. This was indeed the case.

Motors

	Motor					
Type	DC motors		Stepper Motors		Servos	
Cost	Cheap	+	Expensive	-	Expensive	-
Direction	Single Direction	--	Bidirectional	+	Bidirectional	+
Speed	Very fast	++	Slow	-	Fast	+
Weight	Light	+	Very heavy	--	Normal	o
Size	Small	+	Big	--	Normal	o
Torque	Normal	o	High	+	Normal	o
Control	N/A	--	Precise	+	Accurate	+

Table 9: Decision Matrix - Motors

The matrix method resulted in the following scores:

1. DC Motors = +1
2. Stepper Motors = -3
3. Servo Motors = +2

According to the method, servo motors should be chosen. This was indeed the case.

Materials

	3D Printing			
Material	PLA		ABS	
Ecology	Biodegradable	+	Recyclable	o
	/	/	Produce toxic gas while printing	-
Reliability	High surface hardness	+	Weatherproof	+
	Prone to break while bent	-	Flexible	+
Safety	/	/	Not food-safe	--

Table 10: Decision Matrix - 3D Printing

The matrix method resulted in the following scores:

1. PLA = +1
2. ABS = -1

According to the method, PLA should be chosen. This was indeed the case.

Strings

	Strings			
Type	Guitar		Nylon	
Durability	Prone to rust	-	Weatherproof	++
Cost	0.34p/cm	-	0.25p/cm	+
Width	0.009mm	++	1.3mm	--
Strength	450,000 psi	++	600psi	-

Table 11: Decision Matrix - Strings

The matrix method resulted in the following scores:

1. Guitar = +2
2. Nylon = 0

According to the method, Guitar Strings should be chosen. This was indeed the case.

This was because while durability is an important concern, the guitar strings could be sheathed in a protective cover and thus protected from the elements. Additionally, strength and width of the wire are essential criteria for ensuring that the glove can convey the power from the motors to the fingers, and the latter being especially important to tackle the main challenge of producing it small enough. This matters particularly as the wire will likely need to be wound around a wheel near the motor, and a thick cable could take up lots of space. The advantages of this concept overcame disadvantages such as cost because they have minimal impact to the budget being both very cheap in comparison to other modules such motors.

Microcontroller

The matrix method was not used for choosing the Microcontroller because this part of the product does not affect the customer directly. A different approach outlined in the Concept Development section whereby a suitable model was chosen by elimination given a set of detailed requirements, was considered most appropriate.

Bluetooth Module

This was a late selection as it was only needed after the Myo Band was introduced into the design. However, there are a wide range of Bluetooth BLE modules which could have been selected, requiring the use of the decision matrix below to select one.

	Bluetooth BLE					
Module	HM-10		HM-11		NRF8001	
Cost	£6.16	+	£10.60	-	£4.26	+
Breakout Board Cost	£4.49	+	Unavailable	--	£15.69	-
Firmware Available	Yes	++	Yes	++	No	--
Baud Rate Range (bps)	9600-115200	++	9600-230400	++	19200	--
Size (mm^3)	40x16x4	-	13.5x18.5x2.3	+	29x28x0.8	-
Supply Voltage	5V	+	3.3V	-	5V	+

Table 12: Decision Matrix - Bluetooth Module

The matrix method resulted in the following scores:

1. HM-10 = +6
2. HM-11 = +1
3. nNRF8001 = -4

Consequently, the team chose the HM-10 as it best fits the needs of the project, especially with greater weighting given to key aspects such as Firmware availability.

Concept Development

Circuitry

The development of the electronics of the device was constrained by the power and safety requirements of the previously chosen devices. It was because of this that the freedom of selection was severely reduced.

Microcontroller

The selection of the sensors and the motors established the criteria for the microcontroller. Each servo motor that was bought required a voltage from 6.0V to 8.4V DC, a current from 15mA to 180mA as its power supply (6). Therefore, for the 4 servo motors to function safely, 6.0-8.4 V will be the voltage across the power rail, and 720 mA the total current.

The PWM signal that controls each of the servo motors needs to have an amplitude of 3.3V or 5V, which consists of a 1.3 to 1.7ms control pulse followed by a 20ms refresh rate (7). If a microcontroller that operates with the aforementioned voltages is used, a 50Hz PWM output can be produced.

The advantage of the acquired capacitive sensors is that they have their own microcontroller, which is useful for speeding up the transducing process. However, this requires the use of either an SPI or I2C communication to the main microcontroller. Since the aim of the device is for it to be portable, the I2C communication system was preferred because it uses 2 pins rather than 4. Moreover, since there are a greater amount of online resources on connecting and programming capacitive sensors breakout boards to “Atmel” brand microcontrollers, it will be easier to use these microcontrollers compared to others. This reduced our microcontroller options from 7033 to 372 (8).

Moreover, due to budget limitations and repeated testing, ordering a PCB would be very expensive and its delivery time excessive. The alternative we chose was the use of stripboards, limiting the mounting type to through-holes components and narrowing down our choice to 63 microcontrollers.

Another characteristic pertinent to our choice of microcontrollers is the amount of pins in the chip. Available models offer 8, 20, 28 and 40 pins. Of these, 8 pins are not enough for the circuit to be implemented, while 40 pins would result in higher costs and more occupied space on the board that is unnecessary for our purposes and thus should be avoided.

Unfortunately, several microprocessors are only sold in pairs or are out of stock, leaving only 5 options to choose from. Finally, after taking into account the processor with the maximum clock frequency (20 MHz) for a faster processing speed and the cheapest microcontroller, the team decided to use the ATMEGA328-PU (9).

Power Supply

A 5V power supply for the microcontroller and a 6.0 to 8.4 V for the servos is required. It is then necessary to choose a 5V voltage regulator of fixed output type, with through-hole mounting and most importantly, of low dropout voltage. To achieve optimum efficiency, a switch mode power supply would be preferable, even though it utilises significantly more space than linear regulators. With low dropout voltage regulators, it is desirable for them to be relatively reliable in managing heat in case of high current drawn and less excessive power dissipation. The team finally decided to choose those with package type TO-220 instead of TO-92, which was a low drop-out voltage regulator as opposed to an SMPS.

MIC2940A-5.0WT was selected because of its good protection against reversed battery current that prevents components from being damaged when the battery pack is inserted in the wrong direction, and for the “load dump” protection provided from accidental voltage surges triggered by abrupt disconnections and motor noise (10). A much higher maximum output current due to a high chance that the 5V power supply is used for all the servos.

External Clock for Microcontroller

Initially, a crystal oscillator was bought, but it was then found that a 16MHz crystal could replace it. This reduced the number of pins to two, and allows functioning without a power supply.

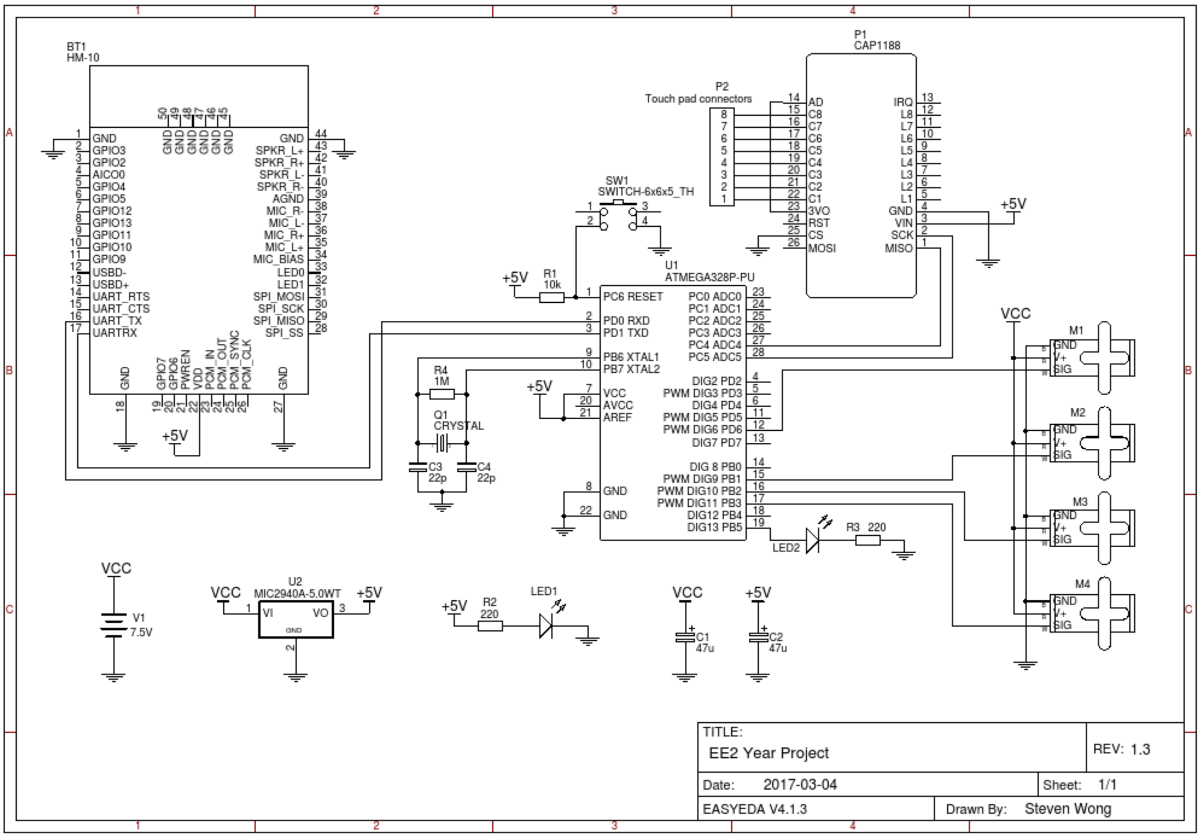


Figure 1:BOARD CIRCUIT

Software

Development Environment

As mentioned above, one of the reasons of selecting this specific microcontroller was because of the Arduino integrated development environment (IDE) supporting various ATMEGA microcontrollers. The IDE allows us to burn its bootloader to the microcontroller via Arduino as an ISP, thus opening access to several libraries provided by the manufacturer of the sensor breakout board: AdaFruit, and Arduino Libraries.

The Arduino IDE was also useful for flashing new firmware to the CC2541 chip upon the HM-10 Bluetooth module. This was done because the Arduino IDE offered access to a specific Myo-Bridge library, designed for communication between a Myo Band and an Arduino via a BLE module, which came with custom firmware for flashing to the chip. However, this was not as simple as first thought as the types of file required flashing and the type of file in which the firmware was provided did not match up. This meant a converted had to be downloaded and used.

See Appendix F for an example of how the firmware was flashed.

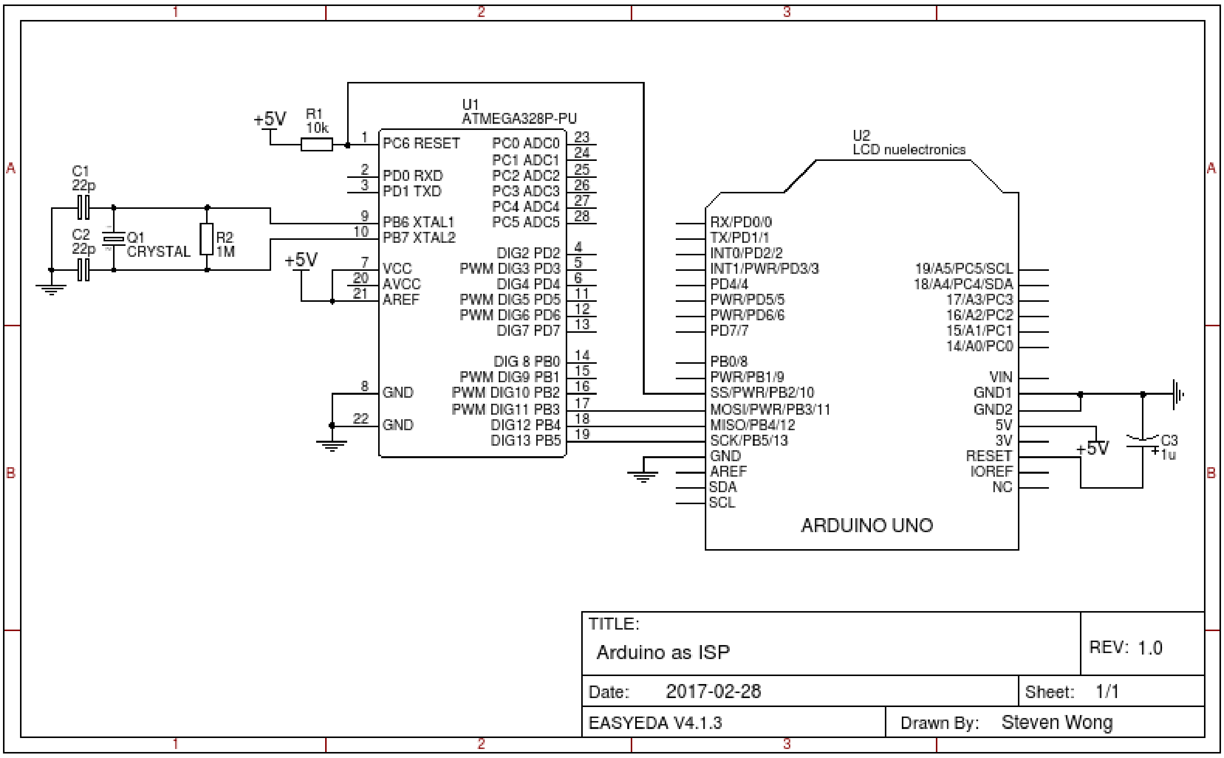


Figure 2: Circuit Diagram - Programming Microcontroller

Sensors

The I^2C communication was set up between the main microcontroller acting as the master, and the microcontroller on the capacitive touch breakout board acting as the slave. When the master sends out a request to the slave regarding its current status, the slave sends out 10 bits of data of which 8 bits indicate which pad has been touched. As the master receives this data, it determines in which direction each servo should move in order to approach its intended position from its current position.

	Communication Protocol			
Type	Serial Peripheral Interface Bus (SPI)		Inter-Integrated Circuit (I^2C)	
Minimum Connections	4	-	2	+
Speed	Microcontroller Clock Speed	+	400kHz	o

Table 13: Decision Matrix - Communication Protocol (11)

Bluetooth

The microcontroller also communicates with the Myo Band through the HM-10 BLE Bluetooth module. The Bluetooth module continuously remains in data mode, as the Myo band is only sending data, and hence requires no commands to be ever sent to it. While the HM-10 can act both as a master and a slave, in this application it acts as a slave to the main microcontroller.

The HM-10 can also act as both a central and a peripheral device, implying that it can initiate the connection with a peripheral device if need be. In this particular application, it acts as a peripheral device, with the Myo Band being the central device initiating the connection.

Looking to the future, the development team could fully utilise the capabilities of the HM-10 by using it to send AT commands to the Myo Band. This would be useful as the LED and vibrate functions of the Myo Band could be incorporated into the user interface.

Myo Band

In the run up to this report the team acquired a Myo Band which could potentially replace the sensors. A Myo Band uses EMG (electromyography) sensors to measure the electrical activity of the muscles in the user's forearm, including the muscles which move a person's fingers. It also has a 9 axis IMU (inertial measurement unit) sensor which gives the Myo Band a large amount of data which can be collected to control the articulated glove. This gives the glove greater flexibility in how it is controlled. For instance, one could set movements or rotations of the arm to cause the fingers to contract. This would make the glove much more flexible in terms of the scope of different diseases which could be treated, and helping solving one of the current theoretical problems with the glove. Namely, for the glove to be effective patients must be able to move their fingers a little, but with the Myo Band, as long as the patient's arm muscles are able to contract a little, even if they cannot convey this movement to their fingers, the assisted movement mechanism will be triggered.

Gaining the ability to observe a patient's intent using EMG would allow the Articulated Glove to compete with devices such as the Eso Glove produced by the NUS, while using a separate Myo Band device to achieve this results in a significantly less bulky system than that used by the Eso Glove.

The Myo Band communicates using Bluetooth BLE, a requirement that was met by the team through purchasing a HC-10 Bluetooth module. Receiving data from the Myo Band with the standard Texas Instruments firmware on the CC2541 chip would have meant a lot of low-level communication and processing of data. In a mission to avoid this, the team researched easier communication methods involving the Myo Band and found that an Arduino library called "Myo Bridge" (12) already existed with custom firmware. The team then went about flashing the firmware to the chip using an Arduino file called CCLoader.ino, before starting some low-level testing of communication with the Myo Band, using simple gestures to control LEDs. This firmware flasher required a .bin file but since the Myo Bridge firmware was a .hex file, the team used a program to convert the .hex file to .bin (13).

Given more time, the team could customise the Arduino library and firmware to make the glove responsive to a much wider range of movement, and possibly even able to identify specific muscles contracting to enable fingers to be controlled individually. Undoubtedly this would vastly increase the function of the Myo Band as it measures muscles contracting which move the finger in different directions without needing separate sensors for every axis of each finger.

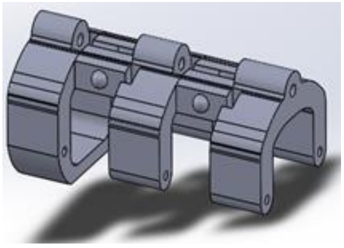
Lastly, the Myo Band and its Bluetooth link provide an exciting new way for doctors and nurses to aid and tailor rehabilitation for patients. Given more time to implement a glove imitating the movement of the human hand more closely, a doctor or therapist could wear the Myo Band and demonstrate the rehabilitating movements which could be reproduced accurately by the glove in real time. This would allow rehabilitation exercises to be much more portable and varied, as well as allowing the doctor to use specific exercises for specific patients conducive to a much more targeted and effective treatment of a patient's condition.

Mechanical Design

To design a new working model 3D design and simulation software Solidworks was used. This was a very slow process since for every new model the whole sketch had to be rebuilt. The introduction of parameters and relations was therefore necessary to describe the relationship between unknowns in mathematical form. Previously, if the new model needed a slightly larger finger thickness, the size of the sketch was modified from the interface. However, we found that this could interfere with the symmetry properties of the articulation or the layout itself, introducing problems such as incorrect extrusions and zero thickness geometry. We resolved this by using a text file whereby if one parameter is modified, everything changes accordingly.

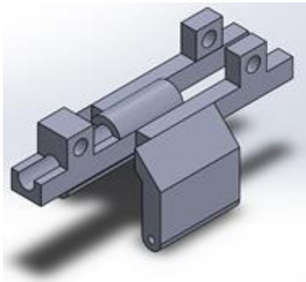
Throughout the project, 15 different models were developed, almost all of them printed. This led to an iterative and precise design procedure. During the week, a new model was tested, possible improvements uncovered and a new model subsequently printed during the weekend for it to be ready for the following week.

When the interim report was submitted, the latest design was the one shown in the figure below. It was very wide, and the articulation did not correctly attach itself to the user's hand. Moreover, the angle of movement was greatly limited by the hinges' freedom to turn.



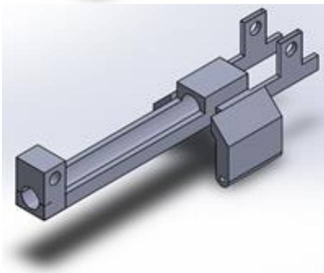
As part of the process each piece of the design was printed separately, but due to a mistake in the design the hinges were not connected to the main body. While three pieces should have been produced in total, the outcome was six instead. Despite its imperfections, as our first printed design it was very useful in giving the group an accurate picture of what the device would look like.

Figure 3: FIRST DESIGN FROM INTERIM REPORT SUBMISSION



Several of the problems arising from the first design were solved in the subsequently developed design shown in the figure 3. Showing only one of the pieces for clarity, this design was more functional but still problematic. A significant downside was that it did not allow enough space between the hinge pieces, meaning the assembled product would not fit.

Figure 4: SECOND DESIGN



The insufficiency of hinge space was resolved in the subsequent design iteration, in spite of other problems surfacing. Firstly, the hinges were very thin and therefore prone to being broken, especially when cleaning up the supports and raft. A large extension is present through which the elastic string goes through and leaves the hand through the lower side of the finger. The string is finally attached to an anchor connected to the board containing the remaining components.

Figure 5: THIRD DESIGN

The following figure illustrates the structure of the piece at the end of the articulation, where the sensor and the end of the elastic string would be allocated. It has a base structure where a conductive material would be connected to the two terminals crossing the holes in the main body. The row of holes seen in the main body is for attaching the articulation to the fabric of the glove, which in order to do so requires a needle to go through them. An additional improvement devised was that of increasing the thickness of the hinge extension so that the elements connected to the main body are thicker and less fragile.

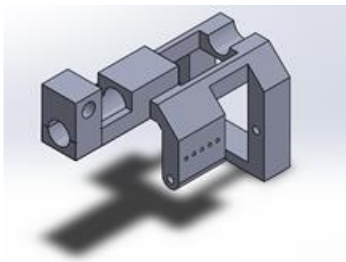
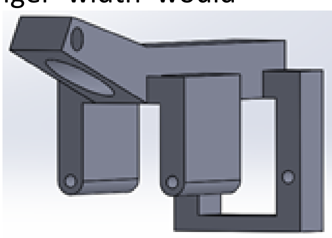


Figure 6: FOURTH DESIGN

The version that followed was very different. Firstly, most of the curved surfaces were erased from the parameters file for the sake of simplicity. For instance, increasing the finger width would diminish the body thickness within the diagonal area of the main body. After this change, a complete freedom for changing the variables as needed was achieved. During testing, it was observed that the finger would collide with the hinge after it bended the articulation to a certain degree. To avoid this a new hinge was developed which would move upwards to allow more space for the finger to bend. The outcome of this upgrade was the required creation of a new



path for the elastic band, which became the hole crossing the entire hinge structure.

Figure 7: FIFTH DESIGN

The latest design is illustrated in the figure below. A previously missed problem was that the tension of the elastic string would make the articulation move in a downwards rather than the intended upwards direction. A new path was designed for the model, whereby it would go above instead of under the screw, therefore changing the force to act in the desired direction. We also covered the path of the elastic string at the other end of the articulation to make sure the elastic string followed its path. A final feature was a small cut made to one of the main bodies so to amplify the angle of the exoskeleton movements.

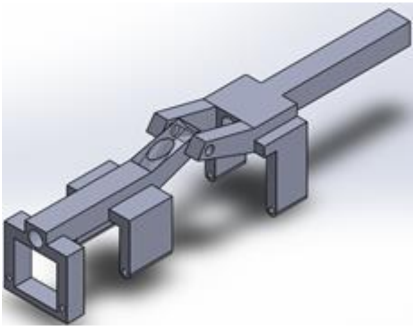


Figure 8: FINAL DESIGN

Project Management

By the time the group had reached this stage of the project, the development of the design had been split members between the different areas that had to be covered based on the different strengths and preferences of group.

A group consisting of Alex and Alistair was in charge of developing the mechanical part of the device, which included optimising the assembling of the motors into the glove to provide better torque and movement.

A second group comprising Steven, Patrick, Alistair and David was in charge of implementing the electronics and software of the glove, which involved the testing of the circuit that had already been designed, and approving any changes to it. Moreover, an additional objective the group aimed to achieve was that of making the sensors more efficient by ensuring suitable connections that would give the best result.

Another group comprised of Alex and Patrick was in charge of the design and the 3D printing of the exoskeleton, keeping track of any flaws in the design, and coming up with a better solution that would be more comfortable for the customer.

Sara and Erk were placed in control of the creation and design of the website, updating the content, and devising marketing strategies for capturing the market segment being targeted. The link to the website is: http://articulatedglove.weebly.com/

Alistair was assigned the task of understanding the function of the Myo Band, finding, purchasing and integrating a Bluetooth module which would allow the glove to communicate with the Myo Band. Lastly, he needed to integrate code on the Arduino software of the glove to allow it to communicate with the Bluetooth module without impeding the other functions.

Finally, David was considered responsible for creating a professional, comprehensive, structured and clearly written report.

Despite having honed a strong synergy between different group members and sub-groups, regular meetings were arranged twice a week. Their purpose was for the agreed upon sub-groups to update the rest of the group on any progress made, so all were aware of the latest updates on the product development to the same degree.

The team went about achieving this by making Group Study Room bookings in the library on a weekly basis scheduled for Wednesday afternoons for 30 minutes, with further shorter briefing meetings occurring in the EEE Computing Lab during Thursday or Friday lunchtimes.

During these meetings, Sara recorded meeting minutes including points discussed, and tasks were assigned to each group member and sub-group by Group Leader Alex as for the meetings earlier on in the spring term. As tasks were completed they were ticked off, and progress benchmarked against the Gantt Chart that represented a broader overview of the project.

By creating a Facebook group of which all group members were part of, it was ensured that each member was constantly updated on any progress made at different stages of the project. Social media collaboration was brought to a deeper level through uploading links to webpages of the products ordered from RS Components, as well as photographs of the hardware parts of the glove as soon as they were printed. Sub-groups comprising two or three people usually communicated by meeting when suited to members, and through one-to-one WhatsApp conversations.

Furthermore, the Google Drive named “Articulated glove project” set up in November 2016 has been used heavily at all stages of the project, and includes all sketches, Charts, Report iterations, meeting minutes, and supplementary files relevant to the project. To ensure the report is in the ideal format by the time of submission, it was decided to bring the google doc file of the interim report over to Office 365 OneDrive where contributors to the online word document would be only a select few of the group including David, Alex and Steven.

The workload and timeframes for milestones and deliverables had already been spread throughout the available weeks and arranged using a Gantt chart. The main deliverables have been met on time and extra time was also made for implementing improvements to the product if this becomes a necessity. The Gantt chart for the project is shown in Appendix A, which represents an updated version from that included in the Interim Report.

Future Work Plans

During the next week, the team’s aim is to assemble the final product with all its constituents. While the chassis and the control circuit have been assembled, ensuring the sectors are well calibrated will be a challenge to tackle partially through trial and error. Moreover, at the moment only the exoskeleton of one out of five fingers has been printed and connected. The team aims to 3D print and connect all of the remaining fingers by 21st March, the date of the presentation, in order to show the final product as it would be available on the market. In order to accomplish that, more measurements will be taken to ensure the best fit possible. For the thumb, a new design might be required, but it will not be too far from the already provided one from the conceptual point of view. The development of these parts will be carried on by the sub-groups that have already been interested in the previous design and testing, benefitting from the rest of the team’s assistance.

One aspect that will be covered during the upcoming week is preparation for the presentation. A suitable PowerPoint presentation will be created, to make sure that the product is showcased at its best, which the whole group will be collaborating closely on to ensure that every section is covered fully and in detail.

A hypothetical integration of the glove with a Myo Band has already been considered and exploited. However, to fully exploit the exciting range of opportunities created by using the product, the team would need more time to gain an understanding of how the sensors and firmware work within the Myo Band. This could not be achieved by the group due to a lack of time and resources, and is unfortunate as some of the most exciting possibilities for the glove lie with integration with a Myo Band or similar EMG sensor network. The capabilities demonstrated by the team represent just the tip of the iceberg of the technology’s potential, and if more time had been available this area would have been thoroughly explored.

Another aspect which the team was unable to consider due to time, lack of experience in the fluid dynamics field, and monetary constraints was pneumatic artificial muscles (PAMs). These are often used in human emulating robotics as they give a much smoother and more natural movement through the gradual application of force. While our servo motors worked adequately, the movements induced were often jerky or too fast at some points and too slow at others. This could be uncomfortable for a user, leading the team consider the use of PAMs that could give a more comfortable end product, an idea that would require more research to be confirmed.

Conclusion

The articulated glove project for people with hand disabilities represents a mission to improve people's lives, being very much related to the recent advancements that the area of bioengineering has undergone in recent years. High quality prosthetics are being developed by academics and new companies focusing on these kinds of problems are surfacing. Some of these advances owe their merit to the great progress the field of signal processing has seen in the last few years. The remarkable technology the Myo Band is built upon demonstrates how electrical impulses to the muscles can be read, processed and interpreted, allowing devices to react to the intention to move body parts, even if the kinetic chain which would typically implement this movement fails.

So far, the project has advanced acceptably, but with more resources and time at our disposal much more could be accomplished. The main possible improvements depend on reducing the space used by the device, particularly the servo motors, while others are related to augmenting the robustness and intelligence of the system so that no accidental movements transpire.

One major obstacle that the product still faces before it could be commercialised and thus addressable to the actual market, would be the determination of testing equipment that could be used on real patients. Unfortunately to fulfil this goal, a large number of legal requirements would need to be dealt with since many safety concerns need to be considered. Due to the short time span of the project and the team members' lack of experience in these matters, testing on patients was not a feasible outcome for the project. So although the final design hasn't improved the world context, it has provided a valuable base, upon which further research and development could more easily improve the lives of patients across the world.

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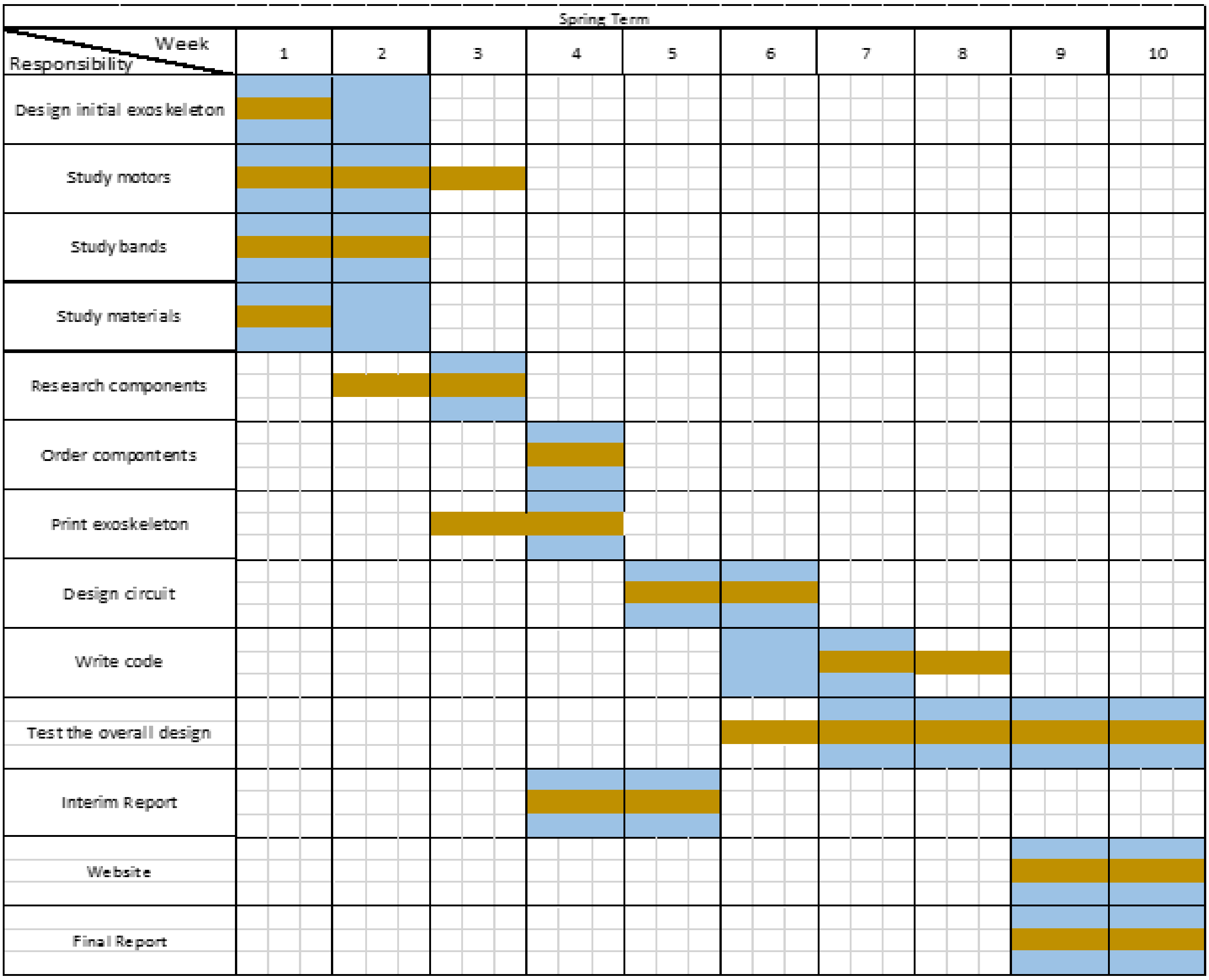
All circuit diagrams have been created using EasyEDA.

All design sheets in Appendix F have been created using Solidworks © software.

Appendix

Appendix A: Project Plan Gantt Chart



Appendix B: Torque Calculations

Below is a brief summary of the mechanics working used to model the system of a finger with a single tendon causing the bending of all three joints. This means that this finger would be unable to move joints of their finger independently, unlike a human finger.

The first calculation took a three-inch mug because the average grip strength of a US military pilot around a three-inch object is 444N, giving an upper bound reference point with which the required torque for our motors could be found.

It was assumed that the reaction force produced at the three contacts on each finger with the mug would has magnitude 111N.

The first diagram shows the finger approximated by a system of thin rigid rods, defining all the terms which would be used in the calculations.

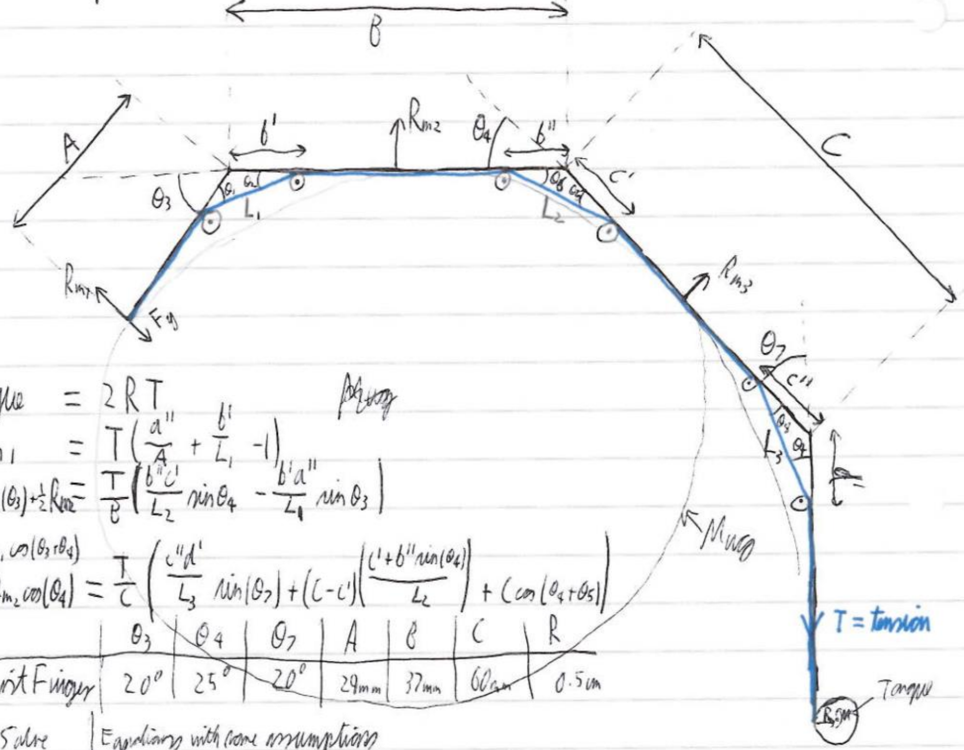
Next there are four equations, the first being the simple definition of torque as a pair of symmetrical moments around the same axis, and the second equation an effect of the tension of the tendon upon the force the end of the first finger section can apply, and therefore the effect upon the reaction force of the mug. The third equation is the effect of tension upon the reaction force produced at the end of the first finger section and the reaction force produced half way along the middle section. All these equations are in terms of lengths, tension and angles.

These equations were obtained by taking moments around each joint, and resolving vertically and horizontally from the point of view of each section; A, B and C. They were then linked together through their interactions, finally giving equation four linking the possible reaction forces. It is logical that these are all on the same side of the equation with the same sign, as the tension producing all three forces means one cannot increase one without decreasing the other. All derivations of these equations can be found on the pages following the summary.

Lastly, the measured angles and lengths were used to simplify the equations, after which they were solved using a series of assumptions and by differentiating with respect to tension in order to work out the right lengths to require minimum tension to produce 111N at each reaction force.

An example of one such assumption is: if you look at equations two, three and four, increasing b'' will increase the force produced by the tension in equations three and four, while having no effect upon equation two. Therefore, we would like this to be at a maximum, so sub in $b'' = B - b'$. This being the maximum value b'' can be. Using this process and by differentiating with respect to different variables, values for all the lengths were acquired, although a couple of variables required sensible seeming assumed values. Having gained these values a value of T was calculated, which was ≈ 110N. Assuming a winding of radius 5mm the required torque calculated was 1.1Nm.

Torque Calculations Summary



$$\text{Torque} = 2RT$$

$$R_{m_1} = T\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)$$

$$R_{m_1}\cos(\theta_3) + \tfrac{1}{2}R_{m_2} = \frac{T}{B}\left(\frac{b''c'}{L_2}\sin\theta_4 - \frac{b'a''}{L_1}\sin\theta_3\right)$$

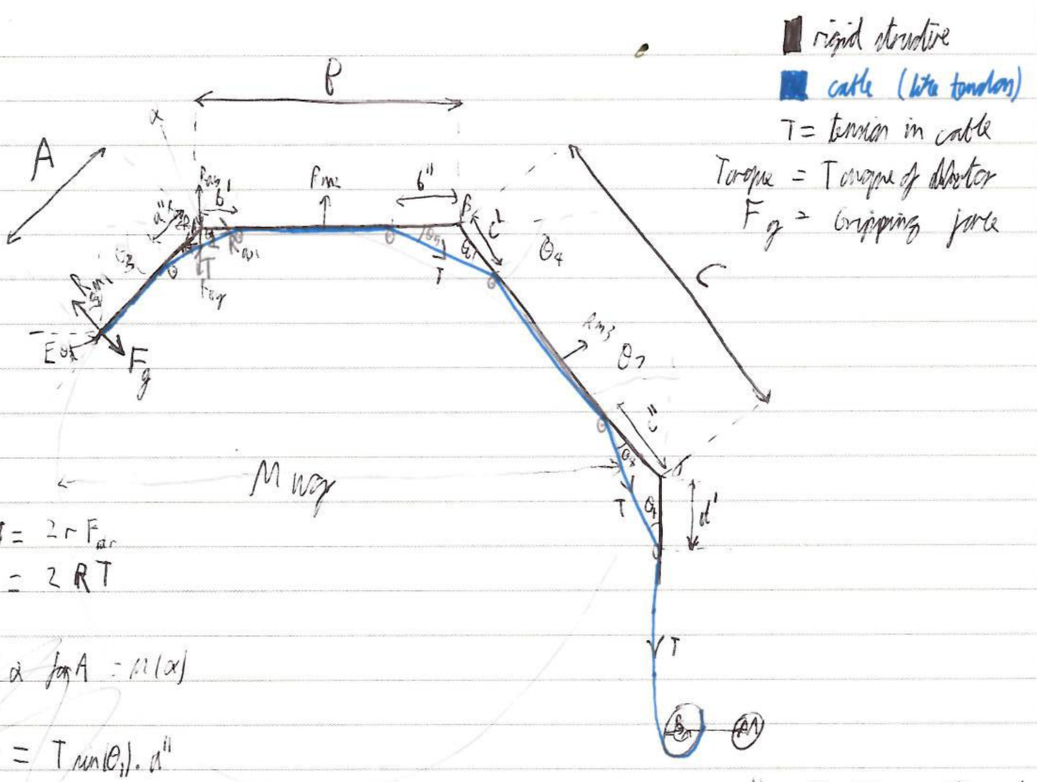
$$R_{m_1}\cos(\theta_3+\theta_4) + \tfrac{1}{2}R_{m_3} + R_{m_2}\cos(\theta_4) = \frac{T}{C}\left(\frac{c''d'}{L_3}\sin(\theta_7) + (C-c')\left(\frac{c'+b''\sin(\theta_4)}{L_2}\right) + C\cos(\theta_4+\theta_5)\right)$$

	θ_3	θ_4	θ_7	A	B	C	R
4th and First Finger	20°	25°	20°	29mm	37mm	60mm	0.5cm

Solve ↓ Equations with some assumptions

$$T \approx 110\,N$$

$$\text{Torque}_{\text{per finger}} \approx 1.1\,Nm$$



$\text{Torque} = 2rF_{ar}$

$\text{Torque} = 2RT$

Moment about α for A : M(α)

$$F_g A = T\sin(\theta_1) \cdot a''$$

M(E)

$$A(R_{b_y} + R_{ax}) + (A-a'')T\sin(\theta_1) = A(R_{ay} + R_{bx})$$

Result for A

$$R_{m_1} = T\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin\theta_3$$

$$\text{Torque} = 2R\,\frac{R_{m_1}}{\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin\theta_3}$$

- Human Max Grip = 444N around 3'' object like a mug.
- ∴ $4 \times R_{m_1\,max} = 444N$

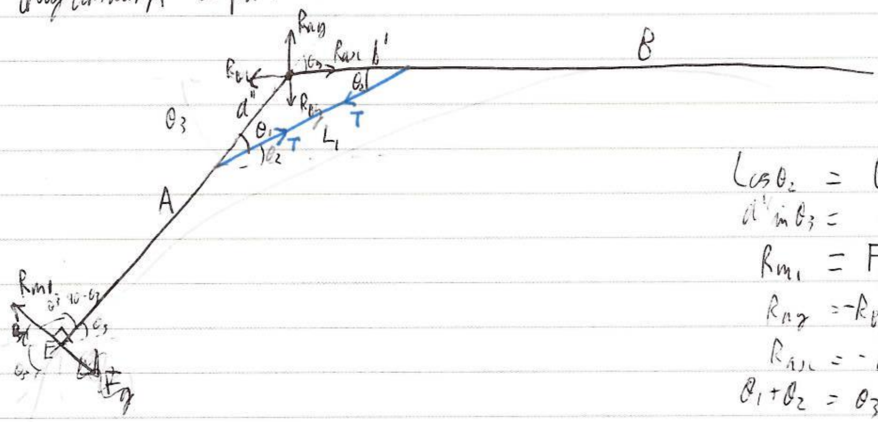
Result for B

$$R_{m_1}\cos\theta_3 + \tfrac{1}{2}R_{m2} = \frac{T}{B}\left(\frac{b''c'}{L_2}\sin\theta_4 - \frac{b'a''}{L_1}\sin\theta_3\right)$$

Result from C

$$\tfrac{1}{2}R_{m3} + R_{m2}\cos\theta_4 + R_{m1}\cos(\theta_3+\theta_4) = \frac{T}{C}\left(\frac{c''d'}{L_3}\sin\theta_5 + (C-c')\left(\frac{c'+b''\sin\theta_4}{L_2}\right) + C\cos(\theta_4+\theta_5)\right)$$

First only consider A - Part 1



$L\cos\theta_2 = b' + a''\cos\theta_3$

$a''\sin\theta_3 = L\sin\theta_2$

$R_{m_1} = F_g = 444N$

$R_{ay} = -R_{By_1}$

$R_{ax} = -R_{Bx_1}$

$\theta_1 + \theta_2 = \theta_3$

$180 = 90 + \theta_3 + \theta$

$\theta = -\theta_3 + 90$

M(x)

$AC \neq AC \quad AC = C$

$+ T\sin(\theta_1)(d'') = R_m \cdot A$

$$\boxed{R_m = T\sin(\theta_1)\frac{d''}{A}} = T\sin(\theta_1)\left(1 \pm \frac{d''}{A}\right)$$

M(E)

$AC = C$

$T\sin(\theta_1)(A-a'') + A(R_{ax}\sin(\theta_3)) = A R_{ay} \cancel{\sin(\theta_3)} \sin(90-\theta_3)$

$T\sin(\theta_1)(A-a'') + AR_{ax}\sin\theta_3 = A R_{ay}\cos(\theta_3)$

$$\boxed{T(A-a'') + AR_{ax} = \frac{AR_{ay}}{\tan(\theta_3)}}$$

R(→)

right = left

$R_{ax} + T\cos(\theta_2) = R_{m_1}\sin\theta_3$

$$\boxed{R_{ax} = R_{m_1}\sin\theta_3 - T\cos\theta_2}$$

R(↑)

up = down

$R_{ay} + R_{m_1}\cos(\theta_3) + T\sin(\theta_2) = 0$

$$\boxed{R_{ay} = -R_{m_1}\cos(\theta_3) - T\sin(\theta_2)}$$

$$T(A-a'') + AR_{ax} = \frac{A(-R_{m_1}\cos(\theta_3) - T\sin(\theta_2))}{\tan(\theta_3)} = -A\left(\frac{R_{m_1}\cos^2(\theta_3)}{\sin(\theta_3)} + \frac{T\sin\theta_2}{\tan\theta_3}\right)$$

$$T(A-a'') + A(R_{m_1}\sin\theta_3 - T\cos\theta_2) = -A\left(\frac{R_{m_1}\cos\theta_3 + T\sin\theta_2}{\tan(\theta_3)}\right)$$

$$T\left((A-a'') - A\cos\theta_2 + A\frac{\sin\theta_2}{\tan\theta_3}\right) = R_{m_1}\left(-A\frac{\cos\theta_3}{\tan\theta_3} - A\sin\theta_3\right) = -R_{m_1}\left(\frac{\cos^2\theta_3 + \sin^2\theta_3}{\sin\theta_3}\right) = \frac{-R_{m_1}}{\sin\theta_3}$$

$$T\left(1 - \frac{a''}{A} - \cos(\theta_2) + \frac{\sin\theta_2}{\tan\theta_3}\right) = R_{m_1}\left(-\frac{\cos\theta_3}{\tan\theta_3} - \sin\theta_3\right)$$

...nsidering A - continued

Equation about bar A

$$R_{m_1} = T \sin(\theta_1) \frac{a''}{A}$$

$$\frac{\sin\theta_1}{b'} = \frac{\sin\theta_2}{a''} = \frac{\sin(180-\theta_3)}{\theta_2}$$

$$T(A-a'') + A R_{ax} = \frac{A R_{ay}}{\tan\theta_3}$$

$$R_{ax} = R_{m_1}\sin\theta_3 - T\cos\theta_2$$

$$R_{ay} = -R_{m_1}\cos(\theta_3) - T\sin(\theta_2)$$

$$R_{m_1} = T\sin\theta_2\left(\frac{a''}{A} + \frac{b'}{a''} - 1 - 2\cos\theta_1\cos\theta_2\right)$$

$\theta_3 = \theta_1 + \theta_2$

$$\tan\theta_3 = \frac{\tan\theta_1 + \tan\theta_2}{1 - \tan\theta_1\tan\theta_2} = \frac{\frac{\sin\theta_1}{\cos\theta_1} + \frac{\sin\theta_2}{\cos\theta_2}}{1 - \frac{\sin\theta_1\sin\theta_2}{\cos\theta_1\cos\theta_2}} = \frac{\frac{\sin\theta_1}{\cos\theta_1} + \frac{\sin\theta_2}{\cos\theta_2}}{\frac{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}{\cos\theta_1\cos\theta_2}} = \frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}$$

$$T\left(1 - \frac{a''}{A} - \cos(\theta_2) + \frac{\sin\theta_2}{\tan\theta_3}\right) = \frac{-R_{m_1}}{\sin\theta_3}$$

$$T\left(1 - \frac{a''}{A} - \cos\theta_2 + \frac{\sin\theta_2}{\frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}}\right) = \frac{-R_{m_1}}{\sin\theta_1\cos\theta_2 + \cos\theta_1\sin\theta_2}$$

$$T\left(1 - \frac{a''}{A} + \frac{\sin\theta_2 - \cos\theta_2\frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}}{\frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}}\right) = \frac{-R_{m_1}}{\sin\theta_1\cos\theta_2 + \cos\theta_1\sin\theta_2}$$

$$T\left(1 - \frac{a''}{A} + \frac{\sin\theta_2(\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2) - \cos\theta_2(\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1)}{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}\right) =$$

$$T\left(1 - \frac{a''}{A} \quad \frac{\sin\theta_2\cos\theta_1\cos\theta_2 - \sin\theta_1\sin^2\theta_2 - \sin\theta_1\cos^2\theta_2 + \sin\theta_2\cos\theta_1\cos\theta_2}{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}\right) =$$

$$T\left(1 - \frac{a''}{A} + \frac{\cos\theta_1\sin(2\theta_2) \cancel{+ \frac{1}{2}\cos\theta_1\sin(2\theta_2)} - \sin\theta_1(\sin^2\theta_2 + \cos^2\theta_2)}{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}\right) = \frac{-R_{m_1}}{\sin\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2}$$

$$T\left(\left(1 - \frac{a''}{A}\right)\sin\theta_2 + \cos\theta_1\sin(2\theta_2) - \sin\theta_1\right) = -R_{m_1}$$

Considering A - continued

Equation stat for A

$$\frac{\sin\theta_1}{b'} = \frac{\sin\theta_2}{a''} = \frac{\sin(180-\theta_3)}{L}$$

$$R_{m_1} = T\sin(\theta_1)\frac{a''}{A}$$

$$T(A-a'') + AR_{ax} = \frac{AR_{ay}}{\tan\theta_3}$$

$$R_{ax} = R_{m_1}\sin\theta_3 - T\cos\theta_2$$

$$R_{ay} = -R_{m_1}\cos(\theta_3) - T\sin(\theta_2)$$

$$R_{m_1} = T\sin\theta_2\left(\frac{a''}{A} + \frac{b'}{a''} - 1 - 2\cos\theta_1\cos\theta_2\right)$$

$$\theta_3 = \theta_1 + \theta_2$$

$$\tan\theta_3 = \frac{\tan\theta_1 + \tan\theta_2}{1 - \tan\theta_1\tan\theta_2} = \frac{\frac{\sin\theta_1}{\cos\theta_1} + \frac{\sin\theta_2}{\cos\theta_2}}{1 - \frac{\sin\theta_1\sin\theta_2}{\cos\theta_1\cos\theta_2}} = \frac{\frac{\sin\theta_1}{\cos\theta_1} + \frac{\sin\theta_2}{\cos\theta_2}}{\frac{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}{\cos\theta_1\cos\theta_2}} = \frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}$$

$$T\left(1 - \frac{a''}{A} - \cos(\theta_2) + \frac{\sin\theta_2}{\tan\theta_3}\right) = \frac{-R_{m_1}}{\sin\theta_3}$$

$$T\left(1 - \frac{a''}{A} - \cos\theta_2 + \frac{\sin\theta_2}{\frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}}\right) = \frac{-R_{m_1}}{\sin\theta_1\cos\theta_2 + \cos\theta_1\sin\theta_2}$$

$$T\left(1 - \frac{a''}{A} + \frac{\sin\theta_2 - \cos\theta_2\frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}}{\frac{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2}}\right) = \frac{-R_{m_1}}{\sin\theta_1\cos\theta_2 + \cos\theta_1\sin\theta_2}$$

$$\sin(2\theta_2) = 2\sin\theta_2\cos\theta_2$$

$$T\left(1 - \frac{a''}{A} + \frac{T\left(\left(1 - \frac{a''}{A}\right)\sin\theta_2(\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2) - \frac{b'}{L}\ldots\right)}{T\left(\left(1 - \frac{a''}{A} - \frac{b'}{a''}\right)\sin\theta_2 + \cos\theta_1\sin(2\theta_2)\ldots\right)}\right) = -R_{m_1}$$

$$T\left(1 - \frac{a''}{A}\frac{T\sin\theta_2\left(\sin\theta_2\frac{a''}{A}\cos\theta_1\cos\theta_2 \frac{b'}{a''} + \sin\theta_1\sin^2\theta_2\right) - \sin\theta_1\sin^2\theta_2 + \sin\theta_2\cos\theta_1\cos\theta_2}{\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}\right) =$$

$$\cancel{T\sin\theta_2\left(\frac{A-a''}{A} - \frac{b'}{a''} + 2\cos\theta_1\cos\theta_2\right) = -R_{m_1}}$$

$$T\left(1 - \frac{a''}{A} + \frac{T\sin\theta_2\left(\frac{Aa'' \ldots (A-a'') - Ab'}{Aa''}\cos\theta_1\sin(2\theta_2) \ldots - R\sin\theta_1(\sin^2\theta_2 + \sin^2\theta_2)\right)}{T\sin\theta_2\left(\frac{a''^2 (A \ldots)\sin\theta_1\cos\theta_2 + \sin\theta_2\cos\theta_1}{Aa''}\right)}\right) = \frac{-R_{m_1}}{\sin\theta_1\cos\theta_2 + \sin\theta_1\cos\theta_2}$$

$$=$$

$$\sin\theta_2\left(\frac{a''T}{A}\left(\left(b' - \frac{a''}{A}\right)\sin\theta_2 + \cos\theta_1\sin(2\theta_2) - \sin\theta_1\right)\right) = -R_{m_1}$$

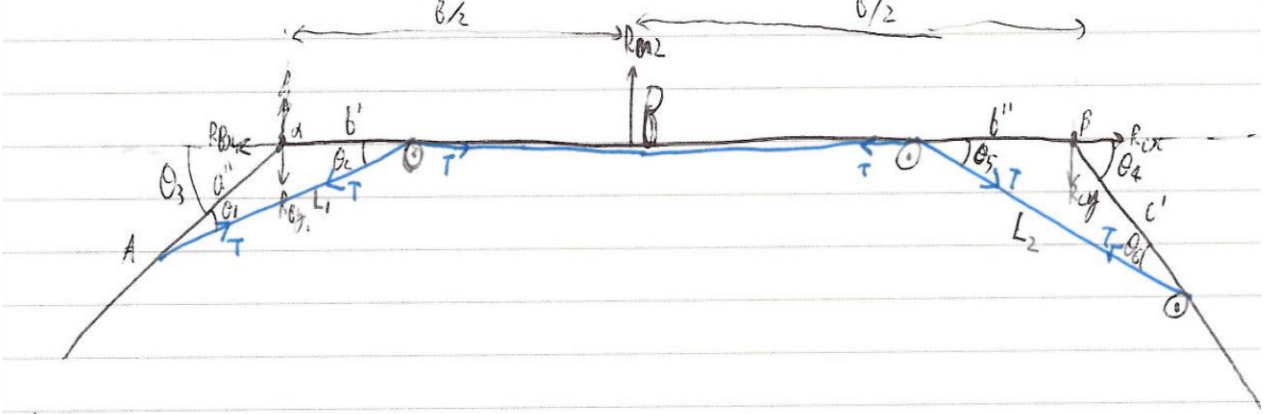
$$\frac{b'}{a''} - 1 - 2\cos\theta_1\cos\theta_2 = R_{m_1}$$

$$\sin\theta_2 = \frac{a''}{L}\sin\theta_3$$

$$\cos\theta_2 = \frac{b'}{L} + \frac{a''}{L}\cos\theta_3$$

Part 2 - Only considering B

R_{cx} is what is felt by B - reverse when doing for C



$M(\alpha)$ $\quad$ AC = C

$$\underline{\tfrac{1}{2} B \cdot R_{m2} = T b' \sin(\theta_2) + T(B-b'')\sin\theta_5 + B R_{cy}} \quad ✓$$

$M(\beta)$ $\quad$ AC = C

$$\underline{\tfrac{1}{2} B R_{m2} = T\left(b''\sin\theta_5 + (B-b')\sin\theta_2\right) + B R_{by}}$$

$R(\rightarrow)$ $\quad$ left = right

$$R_{bx} + T\cos(\theta_2) + \cancel{T} = T\cos\theta_5 + \cancel{T} + R_{cx}$$

$$\underline{R_{cx} = R_{bx} + T(\cos\theta_2 - \cos\theta_5)}$$

$R(\uparrow)$ $\quad$ up = down

$$\underline{R_{m2} = R_{by} + R_{cy} + T\sin\theta_2 + T\sin\theta_5}$$

$$\boxed{\begin{aligned} L_2\sin\theta_5 &= c'\sin\theta_4 \\ L_2\cos\theta_5 &= b'' + c'\cos\theta_4 \end{aligned}}$$

$$\underline{R_{cy} = R_{m2} - R_{by} - T(\sin\theta_2 + \sin\theta_5)} \quad ✓$$

$$\tfrac{1}{2} B R_{m2} = T b'\sin\theta_2 + T(B-b'')\sin\theta_5 + B\left(R_{m2} - R_{by} - T(\sin\theta_2 + \sin\theta_5)\right)$$

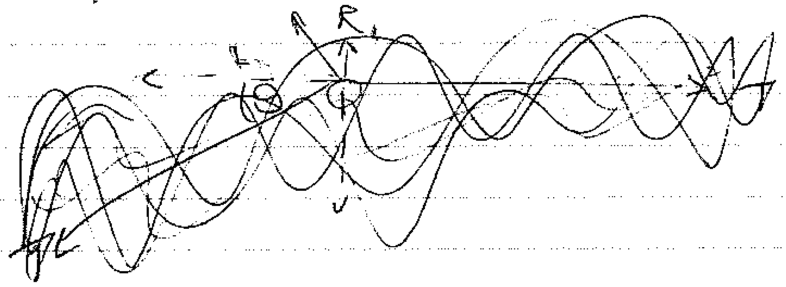
$$-\tfrac{1}{2} B R_{m2} = -B R_{by} + T\left(b'\sin\theta_2 + (B-b'')\sin\theta_5 - B\sin\theta_2 - B\sin\theta_5\right)$$

$$-\tfrac{1}{2} B R_{m2} = -B R_{by} + T\left((b'-B)\sin\theta_2 - b''\sin\theta_5\right)$$

$$-\tfrac{1}{2} B R_{m2} = +B\left(+R_{m1}\cos\theta_3 + T\sin\theta_2\right) + T\left((b'-B)\sin\theta_2 - b''\sin\theta_5\right)$$

$$-B R_{m1}\cos\theta_3 - \tfrac{1}{2} B R_{m2} = T\left(b'\sin\theta_2 - b''\sin\theta_5\right)$$

Considering C - continued



$$L_1 \sin\theta_2 = a'' \sin\theta_3$$

$$\sin\theta_2 = \frac{a''}{L_1} \sin\theta_3$$

$$\sin\theta_5 = \frac{c'}{L_2} \sin\theta_4$$

$$B\left(R_{m1}\cos\theta_3 + \tfrac{1}{2}R_{m2}\right) = T\left(b''\sin\theta_5 - b'\sin\theta_2\right)$$

$$R_{m1}\cos\theta_3 + \tfrac{1}{2}R_{m2} = \frac{T}{B}\left(b''\sin\theta_5 - b'\sin\theta_2\right)$$

$$\underline{R_{m1}\cos\theta_3 + R_{m2}\tfrac{1}{2} = \frac{T}{B}\left(b''\frac{c'}{L_2}\sin\theta_4 - b'\frac{a''}{L_1}\sin\theta_3\right)}$$

$$R_{m1} = \frac{-R_{m2}}{\cos\theta_3} + \frac{T}{B}\left(\frac{b''c'}{L_2}\frac{\sin\theta_4}{\cos\theta_3} - \frac{b'a''}{L_1}\tan\theta_3\right)$$

$$R_{cx} = R_{cx} + T(\cos\theta_2 - \cos\theta_5) = R_{m1}\sin\theta_3 - T\cos\theta_2 + T\cos\theta_2 - T\cos\theta_5$$

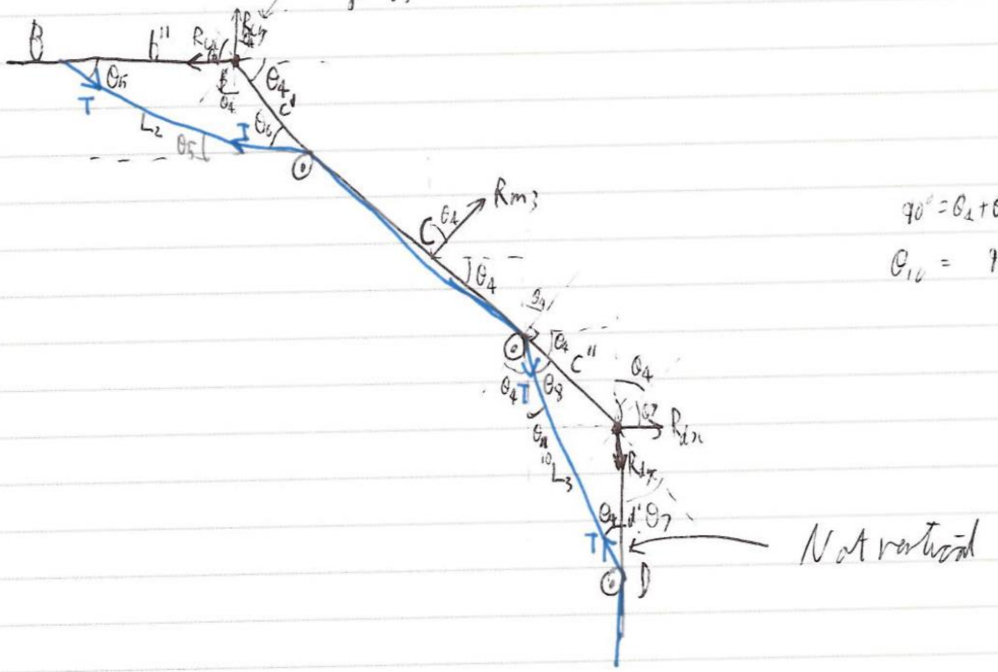
$$\underline{R_{cx} = R_{m1}\sin\theta_3 - T\cos\theta_5}$$

Part 3 - Only considering C

$\theta_4 = \theta_5 + \theta_6$

$\theta_7 = \theta_8 + \theta_4$

As seen by C. Not opposite direction to when calculating for B.



$90^\circ = \theta_4 + \theta_{10} + \theta_8$

$\theta_{10} = 90 - \theta_4 - \theta_8$

Not vertical

$M(F)$ AC = C

$\frac{1}{2} C . R_{m3} + C R_{dx} \cos\theta_7 = T(c' \sin\theta_6 + (C - c'')\sin\theta_8) + C R_{dy} \sin\theta_7$

$M(\delta)$ ~~A~~C = AC

$\frac{1}{2} C R_{m3} + C R_{cy} \cos\theta_4 = T(c'' \sin\theta_8 + (C - c')\sin\theta_6) + C R_{cx} \sin\theta_4$

$R(\uparrow)$ up = down

$R_{m3} \cos\theta_4 + R_{cy} + T\sin\theta_5 = \cancel{T\cos\theta}\ R_{dy} + \cancel{T\cos}\ T\cos\theta_{10}$

$R_{m3} \cos\theta_4 + R_{cy} + T\sin\theta_5 = R_{dy} + T\sin(\theta_4 + \theta_8)$

$R(\rightarrow)$ left = right

$R_{dx} + T\cos(\theta_4 + \theta_8) + R_{m3}\sin\theta_4 = R_{cx} + T\cos\theta_5$

$R_{dx} = R_{cx} - R_{m3}\sin\theta_4 + T(\cos\theta_5 - \cos(\theta_4 + \theta_8))$

$R_{dy} = R_{m3}\cos\theta_4 + R_{cy} + T\sin\theta_5 - T\sin(\theta_4 + \theta_8)$

$$R_{cx} = R_{m1}\sin\theta_3 - T\cos\theta_5$$
$$R_{cy} = R_{m2} - R_{by} - T(\sin\theta_2 + \sin\theta_5)$$
$$R_{by} = -R_{m1}\cos\theta_3 - T\sin\theta_2$$
$$R_{cy} = R_{m2} - T(\cancel{\sin\theta_2} + \sin\theta_5) + R_{m1}\cos\theta_3 + \cancel{T\sin\theta_2}$$

$$\frac{1}{2}c\,R_{m3} + cR_{cy}\cos\theta_4 = T\left(c''\sin\theta_8 + (c-c')\sin\theta_6\right) + c\,R_{cx}\sin\theta_4$$

$$\frac{1}{2}R_{m3} + R_{cy}\cos\theta_4 = \frac{T}{c}\left(c''\sin\theta_8 + (c-c')\sin\theta_6\right) + \left(R_{m1}\sin\theta_3 - T\cos\theta_5\right)\sin\theta_4$$

$$\frac{1}{2}R_{m3} - R_{m1}\sin\theta_3\sin\theta_4 = \frac{T}{c}\left(c''\sin\theta_8 + (c-c')\sin\theta_6\right) - R_{cy}\cos\theta_4 - T\cos\theta_5\sin\theta_4$$

$$\frac{1}{2}R_{m3} - R_{m1}\sin\theta_3\sin\theta_4 = \frac{T}{c}\left(c''\sin\theta_8 + (c-c')\sin\theta_6 - c\cos\theta_5\sin\theta_4\right) - R_{cy}\cos\theta_4$$

$$\frac{1}{2}R_{m3} - R_{m1}\sin\theta_3\sin\theta_4 = \frac{T}{c}\left(c''\sin\theta_8\right. \qquad - \left(R_{m2} - T\sin\theta_5 + R_{m1}\cos\theta_3\right)\cos\theta_4$$

$$\frac{1}{2}R_{m3} + R_{m2}\cos\theta_4 + R_{m1}\left(\cos\theta_3\cos\theta_4 - \sin\theta_3\sin\theta_4\right) = \frac{T}{c}\left(c''\sin\theta_8 + (c-c')\sin\theta_6 - c\cos\theta_5\sin\theta_4 + c\sin\theta_5\cos\theta_4\right)$$

$$\frac{1}{2}R_{m3} + R_{m2}\cos\theta_4 + R_{m1}\cos(\theta_3+\theta_4) = \frac{T}{c}\left(c''\sin\theta_8 + (c-c')\sin\theta_6 - c\cos(\theta_4+\theta_5)\right)$$

$$\frac{1}{2}R_{m3} + R_{m2}\cos\theta_4 + R_{m1}\cos(\theta_3+\theta_4) = \frac{T}{c}\left(c''\frac{d'}{L_3}\sin\theta_7 + (c-c')\left(\frac{c'}{L_2} + \frac{b''}{L_2}\sin\theta_4\right) - c\cos(\theta_4+\theta_5)\right)$$

$$L_2\cos\theta_5 = b'' + c'\cos\theta_4$$
$$L_3\sin\theta_8 = d'\sin\theta_7$$
$$L_2\sin\theta_6 = c' + b''\sin\theta_4$$

Putting R_{m2} in term of T

$$R_{m1} = T\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin\theta_3$$

$$\frac{1}{2}R_{m2} = \frac{T}{B}\left(\frac{b''c'}{L_2}\sin\theta_4 - \frac{b'a''}{L_1}\sin\theta_3\right) - R_{m1}\cos\theta_3$$

$$\frac{1}{2}R_{m2} = \frac{T}{B}\left(\frac{b''c'}{L_2}\sin\theta_4 - \frac{b'a''}{L_1}\sin\theta_3\right) - T\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin\theta_3\cos\theta_3$$

$$\frac{1}{2}R_{m2} = \frac{T}{B}\left(\frac{b''c'}{L_2}\sin\theta_4 - \frac{b'a''}{L_1}\sin\theta_3 - \left(\frac{Ba''}{A} + \frac{Bb'}{L_1} - B\right)\sin\theta_3\cos\theta_3\right)$$

$$\frac{1}{2}R_{m2} = \frac{T}{B}\left(\frac{b''c'}{L_2}\sin\theta_4 - \frac{b'a''}{L_1}\sin\theta_3 - \frac{B}{2}\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin(2\theta_3)\right)$$

$$\boxed{R_{m2} = \frac{T}{B}\left(\frac{2b''c'}{L_2}\sin\theta_4 - \frac{2b'a''}{L_1}\sin\theta_3 - B\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin(2\theta_3)\right)}$$

Putting R_{m3} in term of T

$$\frac{1}{2}R_{m3} = \frac{T}{C}\left(\frac{c''d'}{L_3}\sin\theta_5 + (c-c')\left(\frac{c'+b''\sin\theta_4}{L_2}\right) + C\cos(\theta_4+\theta_5)\right) - R_{m2}\cos\theta_4 - R_{m1}\cos(\theta_3+\theta_4)$$

$$= \frac{T}{C}\left(\frac{c''d'}{L_3}\sin\theta_5 + (c-c')\left(\frac{c'+b''\sin\theta_4}{L_2}\right) + C\cos(\theta_4+\theta_5)\right) - T\left(\frac{2b''c'}{BL_2}\sin\theta_4\cos\theta_4 - \frac{2b'a''}{L_1B}\sin\theta_3\cos\theta_4 - \left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin(2\theta_3)\cos\theta_4\right)$$

$$- T\left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin\theta_3\cos(\theta_3+\theta_4)$$

$$\boxed{\begin{aligned} R_{m3} = 2T\Bigg(&\frac{c''d'}{CL_3}\sin\theta_5 + \frac{(c-c')}{C}\left(\frac{c'+b''\sin\theta_4}{L_2}\right) + \cos(\theta_4+\theta_5) - \frac{\cancel{2}b''c'}{BL_2}\sin(2\theta_4) - \frac{2b'a''}{L_1B}\sin\theta_3\cos\theta_4 - \left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\sin(2\theta_3)\cos\theta_4 \\ &- \left(\frac{a''}{A} + \frac{b'}{L_1} - 1\right)\overset{\sin\theta_3\cos(\theta_3+\theta_4)}{\cancel{\sin(2\theta_3)\cos\theta_4}}\Bigg)\end{aligned}}$$

For first Finger

	First+4th	Pinky	Middle
θ_3	$20°$	$30°$	
θ_4	$25°$	$10°$	
θ_7	$20°$	$20°$	
A	29mm	27mm	31mm
B	37mm	~~45mm~~ 28mm	42mm
C	60mm	~~65mm~~ 51mm	65mm

$f_{m1} = 111 N$

$\theta_3 = 20°$

$\theta_4 = 25°$

$$324 = T\left(\frac{a''}{29\times10^{-3}} + \frac{b'}{L_1} - 1\right)$$

$$96.1 + \tfrac{1}{2} f_{m2} = \frac{T}{0.037}\left(\frac{b''c'}{L_2}\,0.42 - \frac{b'a''}{L_1}\,0.34\right)$$

$$\tfrac{1}{2} f_{m3} + 0.41 f_{m2} + 78.5 = \frac{T}{C}\left(\frac{c''d'}{L_3}\,0.34 + (0.06-c')\left(\frac{c'+0.42b''}{L_2}\right) + 0.048\right)$$

Assume $f_{m2} = f_{m3} = f_{m1}$ - uniform force across the ring

$L_1 = \sqrt{a''^2 + b'^2 - 2a''b'\cos(180)}$

$L_1 = 0.021$

$L_2 = \sqrt{18.5^2 + c'^2 - 18.5\cdot c'\cos(155)}$

$b''\phi = f_{m2}\phi$ and $f_{m3}\phi$

Assume $b'' = \frac{B}{2}$

$\therefore c''\phi = f_{m3}\phi \qquad c'' = \frac{C}{2}$

$d'\phi = f_{m3}\phi \qquad d' = \frac{C}{2}$

$L_3 = \sqrt{2\cdot 0.03^2 - 0.03^2\cos(160)}$

$= 0.03\sqrt{2 - \cos(160)}$

$L_3 = 0.051$

$$5.61 = T\left(\frac{c'}{L_2}\cdot 7.8\times10^{-3} - \frac{b'a''}{L_1}\cdot 0.34\right)$$

$$14.1 = T\left(\frac{3.06\times10^{-4}}{L_3} + (0.06-c')\left(\frac{c'+7.8\times10^{-3}}{L_2}\right) + 0.048\right)$$

$$14.1 = T\left(\cancel{5.75\times10^{-3}}\ 0.054 + (0.06-c')\left(\frac{c'+7.8\times10^{-3}}{L_2}\right)\right)$$

→ by observation, max at about $c' = 0.025$

$\therefore L_2 = 0.037$

$$14.1 = T(0.054 + 0.031)$$

$$\boxed{T_3 = 166.2N}$$

$$5.61 = T\left(0.053 - \frac{b'a''}{L_1}\cdot 0.34\right)$$

$$\boxed{T_2 = 110N}$$

Assume $a'' = \frac{A}{2}$

$b' = \frac{B}{4}$

$$324 = T\left(\frac{a''}{29\times10^{-3}} + \frac{b'}{L_1} - 1\right)$$

$$\boxed{T_1 = -4530 N}$$

Appendix C: Meeting Minutes

Wednesday - 30/11/16 - Alex, David, Steven, Erk, Sara

Points Discussed

- The tasks proposed by the Project leader, Alex, were assigned to different people

Tasks Assigned

David

- Find out the dimensions of an average hand

Wednesday - 14/12/16 - Alex, Ali, Dave, Steven, Patrick

Points Discussed

- How to convey power from the stepper motors to fingers. Came to conclusion to use one motor per finger with an elastic band pulling the finger outwards and the motor opposing movement
- Decided to use analogue pressure sensors as opposed to digital capacitive touch sensors.
- Perhaps using hydraulics cables, much like bike brakes, to relay the force from the stepper motors to the glove
- Using Arduino or ARM assembler for the microcontroller, didn't decide which one
- Using more sensors to differentiate between pressure from finger on the glove internally and external pressure on the glove, but decided this would be too complicated
- Agreed to try and complete assigned tasks over Christmas break

Tasks Assigned

Ali

- Look into hydraulics
- Work out the torque we needed the stepper motors to produce
- Look further into what materials to use and where we were going to 3D print the design

Patrick

- Design the solid and elastic parts of the glove, basically the glove minus the electronics, but mainly the hard pieces around the fingers. After he had finished this he would send the design to Alex or Ali who would implement it in Solidworks.

Alex

- Look into which stepper motor to use and he also needed to check whether a unipolar stepper motor could run passively in reverse

Steven

- Look into pressure sensors and capacitive touch sensors

Wednesday - 11/01/17 Alex, Patrick, David, Steven, Sara, (Alistair)

Points discussed

- Design of the hinges for the exoskeleton, which will be made out of two forks that attached through a screw. The structure will be a half tube that will be attached to the glove instead of straps, helping the user in putting it on
- Perhaps using a special glove since the exoskeleton will be relatively thick and the glove thin, which should be elastic and it would be great for it to be waterproof
- Decided which motor to buy: Torque of 2.5 Kg/cm at 12 pounds per unit
- Different Materials, with PLA chosen as the most suitable option
- Found out that there is a neurotraumatology department at college which could make use of

Tasks Assigned

Ali

- Take a further look into 3D printing in the department

Patrick

- Research on possible tendons and choose

Alex

- Finish the design of the exoskeleton

Steven

- Program an Arduino based driver for the stepper motors

Thursday - 26/01/17 Alex, Patrick, Erk, Steven, Sara, Alistair

Points discussed

- First contact with our first components: 3 screws, 3 nuts, 1 stepper motor, superglue
- Analysed the motor and came to the conclusion that it was good for testing but that it would be very difficult to implement into the design because it was too big and too heavy
- Basic layout for the interim report due the 8h of February

Tasks Assigned

Ali

- Print the first batch of components

Patrick

- Write interim report

Alex

- Make second design of exoskeleton and write interim report

Steven

- Order components

Erk

- Write interim report

Sara

- Write interim report

Thursday - 02/02/2017 (Alex, Alistair, David, Erk, Patrick, Sara, Steven)

Points discussed

- Analysis of the printed components: components are quite accurate for a first draft, but can be improved by printing the hinges with the armours themselves and not separately
- Discussion about the report and the parts that have already been written
- Planning of parts that still have to be written or corrected

Tasks Assigned

Alex

- Create new model for 3D printing and forward it to Alistair in the evening

Alistair

- Print the new design in the morning

David

- Write interim report

Erk

- Write interim report

Patrick

- Write interim report

Sara

- Format the design files

Steven

- Create a hypothetical PCB design

Friday - 03/02/2017 (Alex, Alistair, Erk, Patrick, Sara) - Meeting with the Supervisor

Points discussed

- Presentation of the project and the design to Dr Demeris
- Discussion of the design with Dr Demeris: the supervisor approves our design, but he raises some doubts on the feasibility of a light exoskeleton able to sustain a powerful motor like the one required. However, he proposes to create a static device, useful for rehabilitation training when at rest
- Supervisor offers us help by putting us in contact with his associated researchers and by lending us some of his research tools if needed
- Components with the new design not available because 3D printers were broken

Tasks assigned

No tasks assigned

Tuesday - 07/02/2017 (Alex, Sara, Steven)
<u>Points discussed</u>

- Discussion on interim report issues
- Polishing imperfections in interim report
- Adding content to the report

<u>Tasks assigned</u>
No tasks assigned

Wednesday - 08/02/2017 (Alex, Alistair, David, Erk, Patrick, Sara, Steven)
<u>Points discussed</u>

- Finalization of the interim report
- Submission of interim report

Wednesday - 15/02/2017 (Alex, Alistair, David, Erk, Patrick, Sara, Steven)
<u>Points discussed:</u>

- Sum up of all the work done up to interim report;
- Decision to divide the group into sub-groups that would work independently and brief the rest of the group about what had been;
- Split of the work load.

<u>Tasks:</u>
Alex and Alistair:

- Develop mechanical part;
- 3D printing and design issues.

Steven, Patrick and David:

- Write a suitable software;
- Implementation and testing of the electronic part.

Sara and Erk:

- Build the website.

David:

- Responsible for the report.

Sara:

- Write meeting minutes;
- Arrange meetings.

Wednesday - 22/02/2017 (Alex, Alistair, David, Erk, Patrick, Sara, Steven)
<u>Points discussed:</u>

- Update on the work of the various sub-groups.

<u>Tasks:</u>

- Keep on working in the various sub-areas.

Friday - 03/03/2017 (Alex, Alistair, David, Erk, Patrick, Sara, Steven)
<u>Points discussed:</u>

- Update on the work of the various sub-groups;
- Need to start writing the report.

<u>Tasks:</u>

- Keep on working in the various sub-areas;
- Start writing the parts of report concerning one’s expertise.

Wednesday - 08/03/2017 (Alex, Alistair, David, Erk, Patrick, Sara, Steven)

Points discussed:

- Update on the process of report writing.

Tasks:

- Keep on working on the report and writing about each other’s expertise.

Appendix D: Complete Materials Study (early stages of development)

A few materials are needed for this project. The first material is the hard part of the exoskeleton needed to give the glove rigidity. The second is the softer, more flexible, glove-like material for the joints and covering of the exoskeleton. The third material is the string type material with high tensile strength and low elasticity for replicating the tendons between the stepper motors and joints.

Specifications for Material 1

- Weight
- Strength
- Does not rust (Durability/Non-reactiveness)
- Plate form as opposed to in rod form if the exoskeleton is on the outside of the hand, so that if the glove is pressing in to allow the user to grip something it does not dig into the hand.
- Possible to make hinges out of
- Ideally 3D printed but not necessarily a priority.

Discussion

Originally materials used in hip replacements etc. were considered, as the glove's exoskeleton is replicating a bone. This is why the table includes materials such as Titanium 64, and human bone for reference. However most of these materials a stronger than required, and more importantly require skills the team does not have to be machined into the shapes we need. 3D printing will be more useful for creating a working prototype.

Three main methods were identified for 3D printing: FDM, SLA and SLS.
SLS seems to be the least common of these methods, as it is better for very complex structures with lots of overhangs, however parts can be created out of a wide range of materials, which could be useful. However, parts can be porous or have a rough surface depending on what material is used, and it is also vulnerable to thermal distortion, mainly for polymer parts.
SLA can make very hard and durable parts, but is more expensive (roughly $150 per kilo) and slower. It also produces higher resolution, smoother and more accurate parts, but less durable as the resin can suffer when exposed to sunlight for extended periods.
FDM is much cheaper, starting at $25 per kilo. It typically uses PLA (Polyactic Acid) or ABS (Acrylonitrile) filament, and some can use PLA blends where it is mixed with wood, ceramics, metals, carbon fibre etc. However, FDM does not give as much precision or a smooth surface finish.

After further research was carried out FDM seems like it should be strong enough, which can be confirmed by **producing some test parts** with a couple of materials and **do some strength tests.** Michigan State University did a study on it and concluded that "It is clear from these results that parts printed from tuned, low-cost, open-source RepRap 3-D printers can be considered as mechanically functional in tensile applications as those from commercial vendors."
Using FDM **both PLA and ABS should be considered** (both types of plastic), as although PLA has a larger tensile strength and elastic moduli, it has a lower melting point. This is important as the exoskeleton must be strong, and rigid, yet we usable in a domestic environment. They are both also relatively un-dense, so should not be too heavy, however this again have to be tested as it is difficult to estimate the volume of plastic used before it is designed.
The Imperial College Robotics Society is currently assisting the team in finding out if one of their printers could be used, and if so what type and at what cost.

PLA melts at only 50 ℃, which could be problematic if the product is to be used around the house, for instance washing dishes. The best solution is to take parts out of both ABS and PLA and then test both; if ABS seems to be strong enough then it should be used due to its higher melting point. Both are relatively cheap and so tests are possible, leaving most of the budget to the purchasing of motors.

Specifications for Material 2

- Comfortable
- Not conductive

Discussion

It will probably be the same material as a glove but still in progress.

Specifications for Material 3

- A high enough tensile strength for the glove to be able to grip things properly
- Low elasticity so the glove can react quickly and the force at the stepper motor is transferred to the exoskeleton quickly

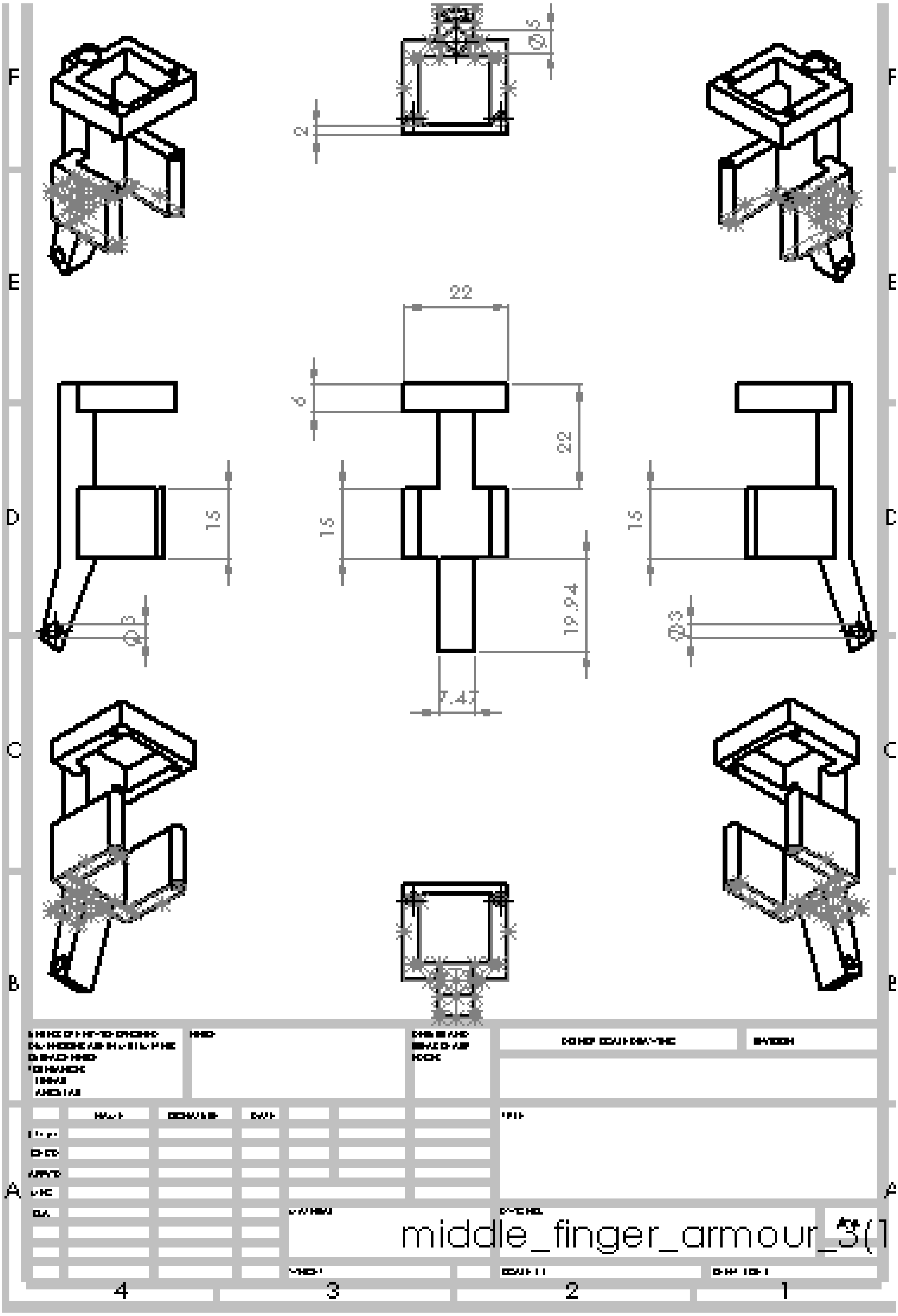
Discussion

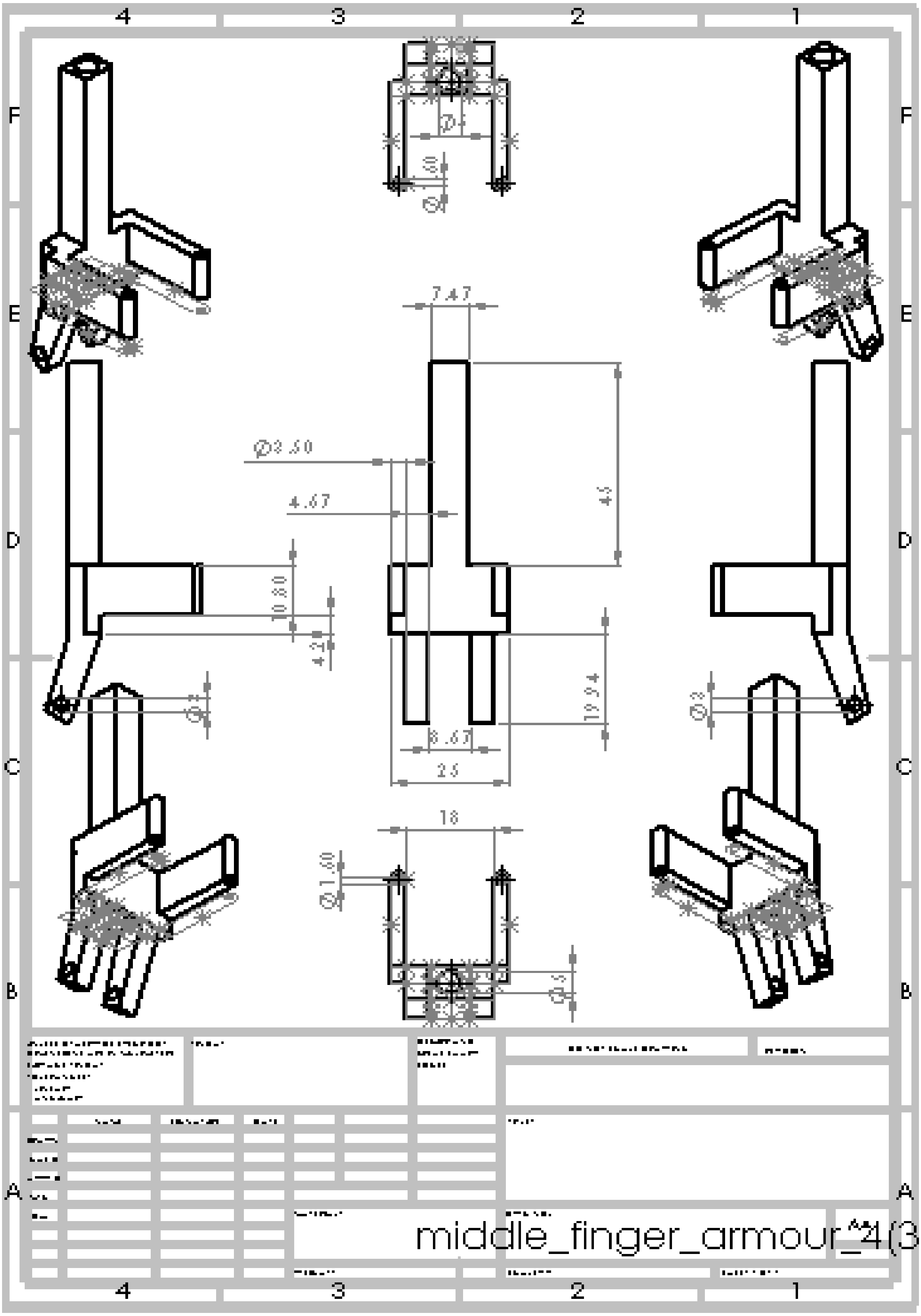
Hydraulics could be used instead of strings. This would have the advantage of only needing one tendon for both directions as opposed to a string for each direction.

Using 0.009 guitar strings could be a good idea, they are strong enough cheap and readily available. With a diameter of 0.2286mm, they should be thin enough not to weigh too much and get in the way when wound.

Appendix E: Component design sheets

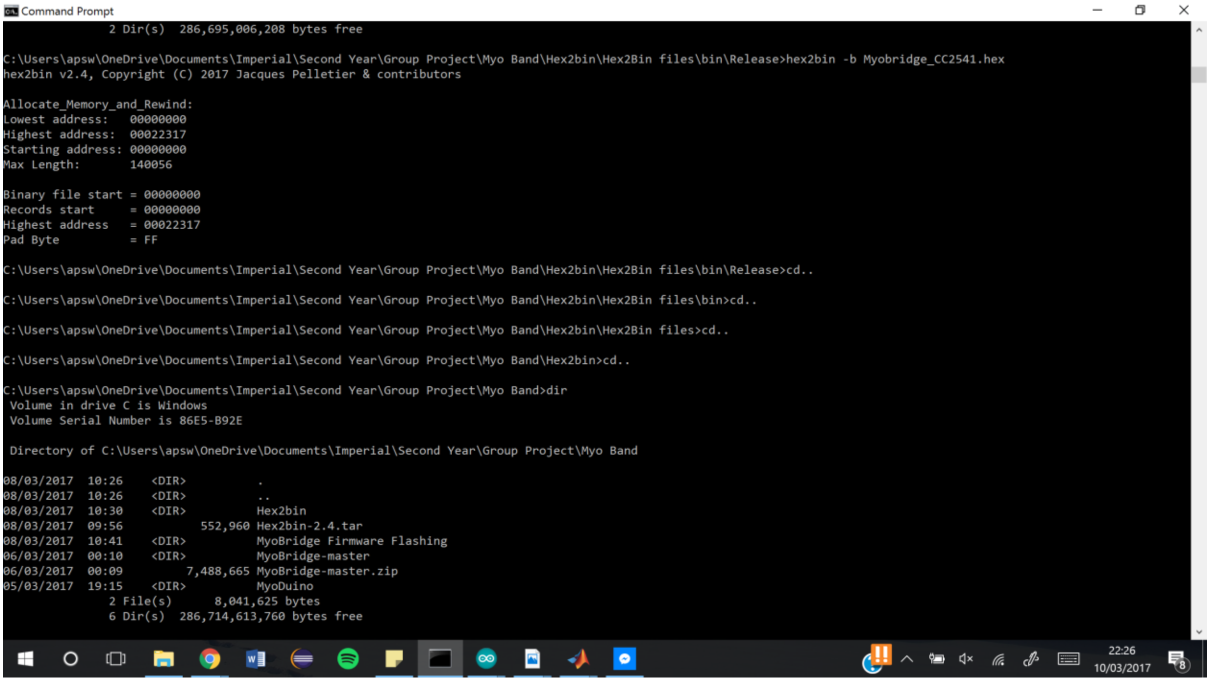
All sheets have been created using Solidworks © software:



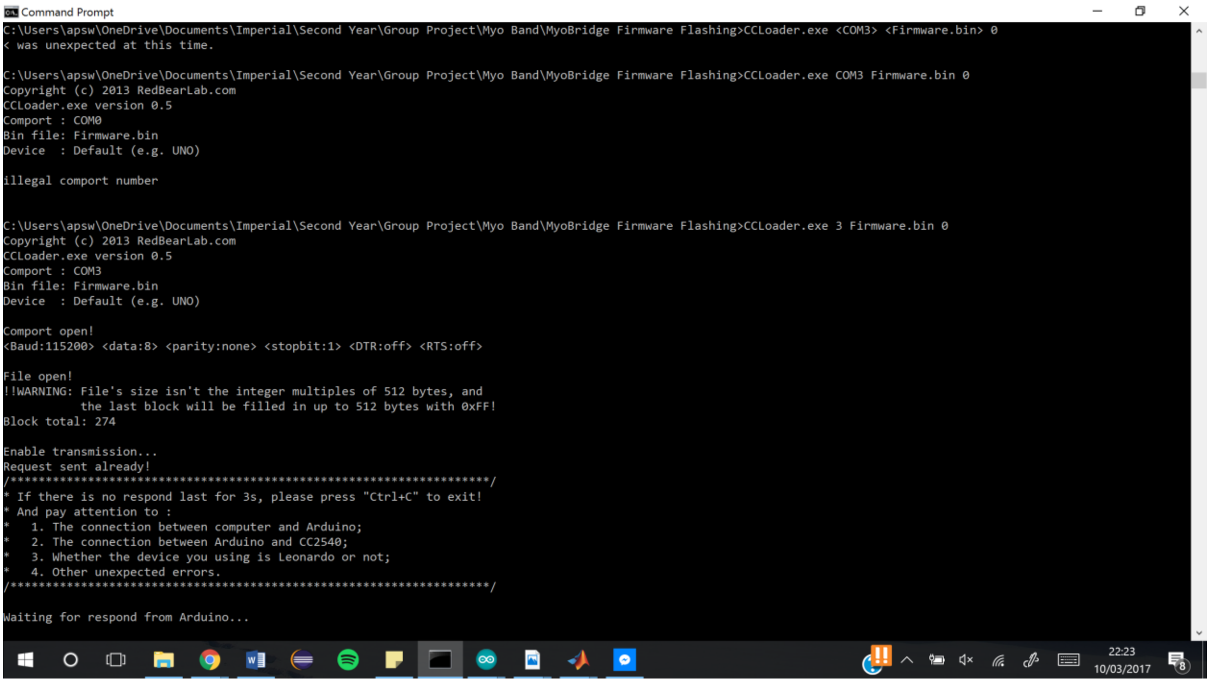

7.47
∅3.50
4.67
45
10.80
4.20
∅2
19.94
8.67
25
18
∅1.80
∅3
middle_finger_armour^4(3

Appendix F: Software

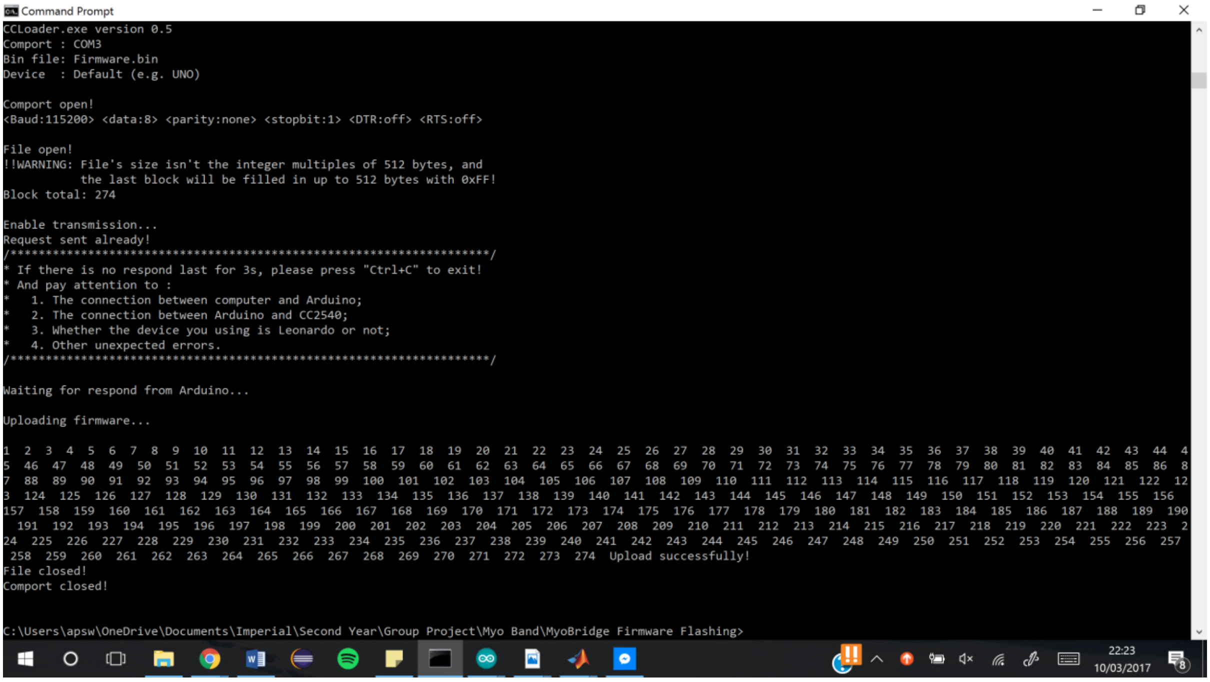
Command Line from Flashing firmware



```
Command Prompt
               2 Dir(s)  286,695,006,208 bytes free

C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\Hex2bin\Hex2Bin files\bin\Release>hex2bin -b Myobridge_CC2541.hex
hex2bin v2.4, Copyright (C) 2017 Jacques Pelletier & contributors

Allocate_Memory_and_Rewind:
Lowest address:   00000000
Highest address:  00022317
Starting address: 00000000
Max Length:       140056

Binary file start = 00000000
Records start     = 00000000
Highest address   = 00022317
Pad Byte          = FF

C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\Hex2bin\Hex2Bin files\bin\Release>cd..

C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\Hex2bin\Hex2Bin files\bin>cd..

C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\Hex2bin\Hex2Bin files>cd..

C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\Hex2bin>cd..

C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band>dir
 Volume in drive C is Windows
 Volume Serial Number is 86E5-B92E

 Directory of C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band

08/03/2017  10:26    <DIR>          .
08/03/2017  10:26    <DIR>          ..
08/03/2017  10:30    <DIR>          Hex2bin
08/03/2017  09:56           552,960 Hex2bin-2.4.tar
08/03/2017  10:41    <DIR>          MyoBridge Firmware Flashing
06/03/2017  00:10    <DIR>          MyoBridge-master
06/03/2017  00:09         7,488,665 MyoBridge-master.zip
05/03/2017  19:15    <DIR>          MyoDuino
               2 File(s)      8,041,625 bytes
               6 Dir(s)  286,714,613,760 bytes free
```

```
Command Prompt
C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\MyoBridge Firmware Flashing>CCLoader.exe <COM3> <Firmware.bin> 0
< was unexpected at this time.

C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\MyoBridge Firmware Flashing>CCLoader.exe COM3 Firmware.bin 0
Copyright (c) 2013 RedBearLab.com
CCLoader.exe version 0.5
Comport : COM0
Bin file: Firmware.bin
Device  : Default (e.g. UNO)

illegal comport number


C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\MyoBridge Firmware Flashing>CCLoader.exe 3 Firmware.bin 0
Copyright (c) 2013 RedBearLab.com
CCLoader.exe version 0.5
Comport : COM3
Bin file: Firmware.bin
Device  : Default (e.g. UNO)

Comport open!
<Baud:115200> <data:8> <parity:none> <stopbit:1> <DTR:off> <RTS:off>

File open!
!!WARNING: File's size isn't the integer multiples of 512 bytes, and
           the last block will be filled in up to 512 bytes with 0xFF!
Block total: 274

Enable transmission...
Request sent already!
/********************************************************************/
* If there is no respond last for 3s, please press "Ctrl+C" to exit!
* And pay attention to :
*   1. The connection between computer and Arduino;
*   2. The connection between Arduino and CC2540;
*   3. Whether the device you using is Leonardo or not;
*   4. Other unexpected errors.
/********************************************************************/

Waiting for respond from Arduino...
```



Command Prompt
CCLoader.exe version 0.5
Comport : COM3
Bin file: Firmware.bin
Device : Default (e.g. UNO)
Comport open!
<Baud:115200> <data:8> <parity:none> <stopbit:1> <DTR:off> <RTS:off>
File open!
!!WARNING: File's size isn't the integer multiples of 512 bytes, and
the last block will be filled in up to 512 bytes with 0xFF!
Block total: 274
Enable transmission...
Request sent already!
/**/
* If there is no respond last for 3s, please press "Ctrl+C" to exit!
* And pay attention to :
* 1. The connection between computer and Arduino;
* 2. The connection between Arduino and CC2540;
* 3. Whether the device you using is Leonardo or not;
* 4. Other unexpected errors.
/**/
Waiting for respond from Arduino...
Uploading firmware...
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 4
5 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 8
7 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 12
3 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156
157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190
191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 2
24 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257
258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 Upload successfully!
File closed!
Comport closed!
C:\Users\apsw\OneDrive\Documents\Imperial\Second Year\Group Project\Myo Band\MyoBridge Firmware Flashing>
22:23
10/03/2017