Mechanical design of a biologically inspired prosthetic hand, The Touch hand 3

By

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the discipline of Mechanical Engineering, School of the College of Agriculture, Engineering and Science, university of KwaZulu-Natal, Howard College, South Africa.

The contents of this work have not been submitted in any form to another university and except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

____

Signed: Professor Riaan Stopforth

Date:_____________________

DECLARATION: PLAGARISM

I, Riaan Fourie, declare that:

1. The research reported in this dissertation, except where otherwise indicated, is my original research.
2. This dissertation has not been submitted for any degree or examination at any other university.
3. This dissertation does not contain any other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
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DECLARATION 2 – PUBLICATIONS

Details of contribution to publications that form part and/or include research presented in this dissertation:

Fourie, R; Stopforth, R; "The mechanical design of a biologically inspired prosthetic hand, the Touch hand 3." Published, presented at the IEEE 2017 Pattern Recognition Association of South Africa and Robotics and Mechatronics International Conference (PRASA-RobMech), 29 November to 1 December 2017, Central University of Technology, Free State, South Africa. ISBN: 978-1-5386-2313-8; IEEE Catalogue Number CFP1748U-USB.

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I would also like to dedicate this thesis to my lab partner and Masters Mechatronics graduate Andrew Mangezi, who has created a unique and brilliant control system for the hand. His tireless work has made the project the success that it is.

I would also like to thank my family and friends who gave me the strength and were able to encourage and stand by me through the project. I am also thankful for the School of Mechanical Engineering at UKZN for the privilege to study through them and for the enthusiasm they have for advancing Mechanical Engineering in KwaZulu-Natal, South Africa.

I would like to thank God for giving me the ability and strength to complete this dissertation.

ABSTRACT

The Touch hand 3 was developed to improve on the mechanical and mechatronic design of the Touch hand 2. A basic prototype hand was rapidly developed using 3D CAD software and 3D printing and tested on an amputee. The improvements in the final design included an improved finger actuation system utilizing mechanical linkages, an improved Electromyography (EMG) operated control system, four micro-linear servo-motors, modular fingers, hinges and chassis. The final design was designed such that the hand can be easily interchanged between a fully mechatronic system and full mechanically operated system using the same generic parts including the chassis, finger and wrist components. The hands were both tested with the Yale Open Hand test, a test used to assess robotic grippers. The Southampton Hand Assessment Procedure (SHAP), a test usually used to assess the effectiveness of upper limb prostheses, was also carried out on both versions of the hand. The hands were also tested with a hand dynamometer to assess their grip strength. The hand were compared to current hands on the market and their strength and weaknesses analysed.

DECLARATION

I hereby declare that this dissertation presents my own unaided work except where due acknowledgement has been given to others. This dissertation is being submitted to the University of KwaZulu-Natal for the Degree of Master of Science in Mechanical Engineering, and has not been submitted previously for any other degree or examination.

______________________________ Date _______________
Riaan Gerard Fourie

________________________________ Date _______________
Riaan Stopforth

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NOMLECLATURE

d	Diameter of material	mm
D_1	Inner diameter of a coil	mm
D_2	Outer diameter of a coil	mm
D	Coil mean diameter	mm
N_t	Total number of windings	number
N_a	Number of active windings	number
L	Free length (Length)	mm
Hs	Solid length	mm
P	Pitch	mm
P_i	Initial tension	N
c	Spring Index	c=D/d
G	Shear Modulus of Elasticity	N/mm^2
P	Load on spring	N
δ	Spring deflection	mm
k	Spring constant	N/mm
τ_0	Torsional stress	N/mm^2
τ	Corrected torsional stress	N/mm^2
τ_i	Initial stress	N/mm^2
X	Stress correction factor	number
f	Frequency	Hz
U	Spring-retained energy	N.mm
Ω	Per unit Volume material weight	kg/mm^3
W	Mass	kg
F	Newton's (Measurement of force)	N
g	Gravitational acceleration	mm/s^2
D	Outer diameter	mm
B	width of strip	mm
d	Inner diameter	mm
t	thickness of spring strip	mm
n	number of turns	number
k	spring rate	N/mm
E	Youngs Modulus	N/m^2
M	moment/torque on spring	N/m
L	length of strip	mm
G	Modulus of rigidity	N/m^2
I	second moment of Inertia	m^4
F	force to deflect spring	N
y	distance from neutral axis	mm
ϑ	deflection	radians
α	tensile/compressive stress resulting from deflection	N/m^2

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1 INTRODUCTION AND LITERATURE SURVEY

A prosthesis by definition is a device, either external or implanted that substitutes for or supplements a missing of defective part of the body (“Prosthesis”; 2017). A prosthetic limb is essentially a limb that is used by the patient to replace the limb that has been lost in the case of an amputee or person lacking limbs by birth. The loss of a finger or even a hand is a dramatic limitation of the humans ability to live and work, impairing a person’s life quality (Grebenstein; 2008)

Amputation or the surgical removal of all or part of a limb is a serious affair, the loss of hand function, touch feeling response, fine motor control and aesthetics are a great cause for concern and quite a serious condition to be faced with. A person is suddenly and for the rest of their lives faced with the condition of not having that limb which they used daily for functionality interacting with their surroundings and fellow human beings and objects, as well as affecting their ability to work. Therefore the design of prosthetic limbs becomes quite an important task to restore the person’s functionality and becomes key to the persons rehabilitation in the real world environment.

Prosthetics through the ages started in around 1500 B.C. where there are records of the Egyptians making limbs of fibre which were worn more for sense of ‘wholeness” they restored to the individual rather than the functional value. An Iron hand was written about by the Roman Scholar Pliny the Elder (23-79 A.D.) and worn by a Roman General who had to have his right arm amputated in the Second Punic War, the iron hand allowed him to hold his shield and return in battle. During the Dark Ages (476-1000 A.D.) the hook was introduced and prosthetics were reserved mainly for the wealthy and were more cosmetic.

The Renaissance (1400-1800’s) saw a time when new perspectives and discoveries were being made and different materials were used made of iron, steel, copper and wood. Advances were made in the mid to late 1500’s with hinged systems and harnesses and leather being introduced. Ambroise Pare, a French military doctor made advances in amputation and also made a hinged hand and made prosthetics more comfortable for the amputees shown in Figure 1-1 (Hernigou; 2013). Figure 1.1b shows Götz von Berlichingens hand of steel and springs (1500’s) (“War and Prosthetics”; 2012) .Figure 1.1 c shows a Victorian era detailed metalwork hand (1840-1940) (“In pictures: Prosthetics through time”; 2012). Thomas Openshaw, a surgeon designed this hand from 1916 (“War and Prosthetics”; 2012”).

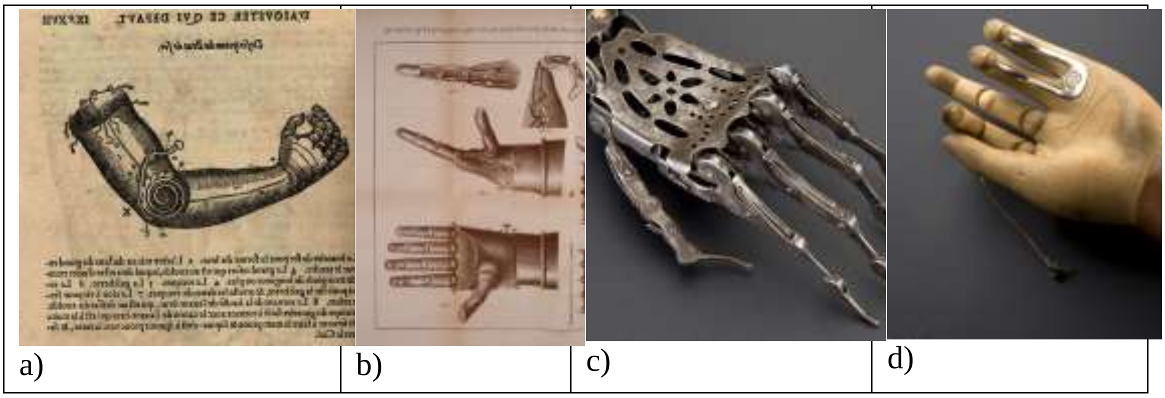


Figure 1-1.Prosthetics through the ages (from left to right) (a) Ambroise Pare early hand design (1579) (b) Götz von Berlichingen designed his own hand of steel and springs (1500's) c) Victorian era detailed metalwork hand (1840-1940) (d) Thomas Openshaw, a surgeon designed this hand from 1916.

Figure 1-2 shows an amputee using a prosthesis and being able to weld with it. ("War and Prosthetics"; 2012")

Figure 1-2. American army veteran using prosthetic adaption to weld at the Walter Reed memorial hospital (1919).

Modern times have seen great advances in prosthetics in the early 19th century. Many mechanical systems were introduced allowing amputees to regain a lot of their function with specialization taking place in the designs. With the advent of World War One in the 20th century mass production was introduced to cater for the large number of casualties experienced during the War and attachments allowed amputees to weld and even play basketball. The late 20th and early 21st century has seen advances in electronics, pneumatics, electric motors, microprocessors and robotics as well as materials and now allow the amputee much more choice in functionality and appearance. A limb can now be custom designed for the person and can even in some cases provide for restoration of sensory activity.

1.1 HAND ANATOMY AND CHARACTERISTICS

The human hand is a complex piece of biological equipment. The following headings are a study of the workings of the human hand.

1.1.1 The human hand

In order to obtain a good understanding about what a prosthetic hand needs to replace a thorough study of the human hand needs to be undertaken.

1.1.1.1 Anatomy of the hand and wrist

The human hand has twenty seven bones divided into three main groups: 8 carpal bones are found in the wrist, 5 metacarpal bones make up the palm, and fourteen phalanges make up the fingers. Figure 1-3 (“Hand and bone anatomy”; 2017) and figure 1-4 (Benjamin, Cummings; 1990) show the layout of the bones in the hand, Figure 1-4 details the phalanges in the fingers.

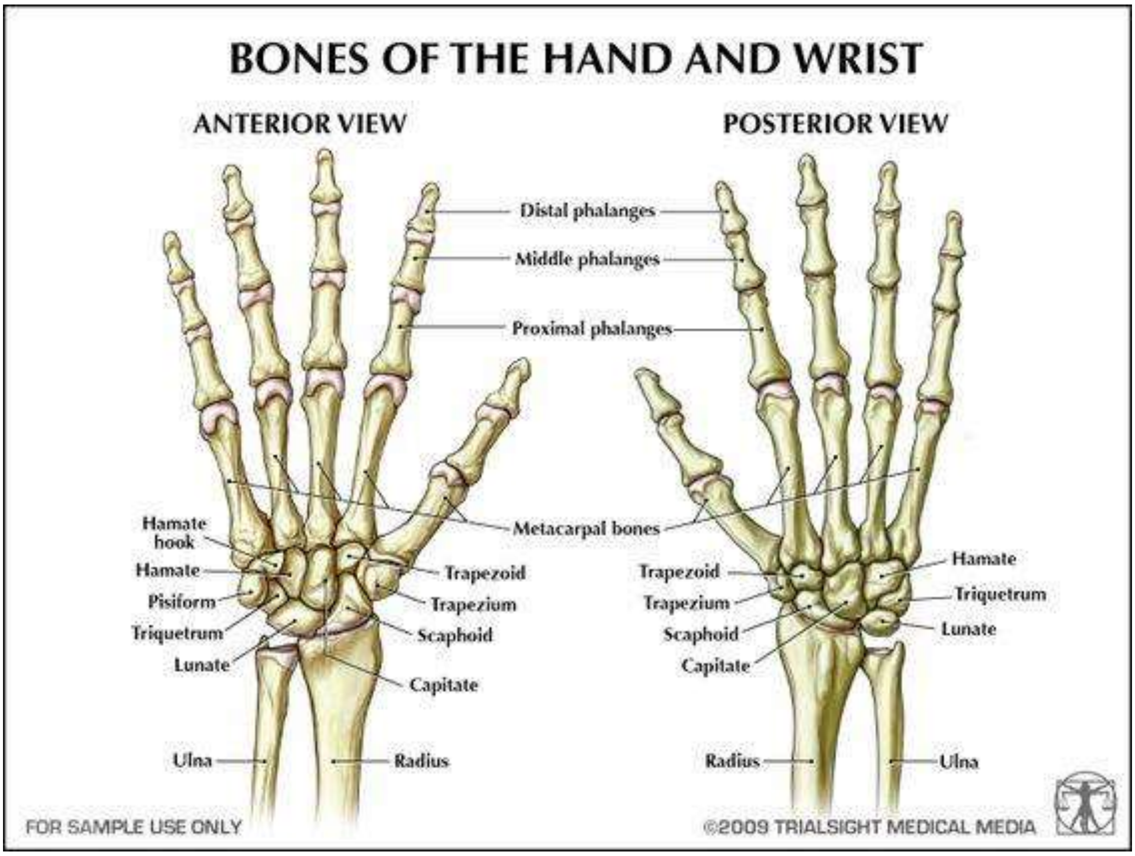


Figure 1-3. Bones of the hand and wrist.

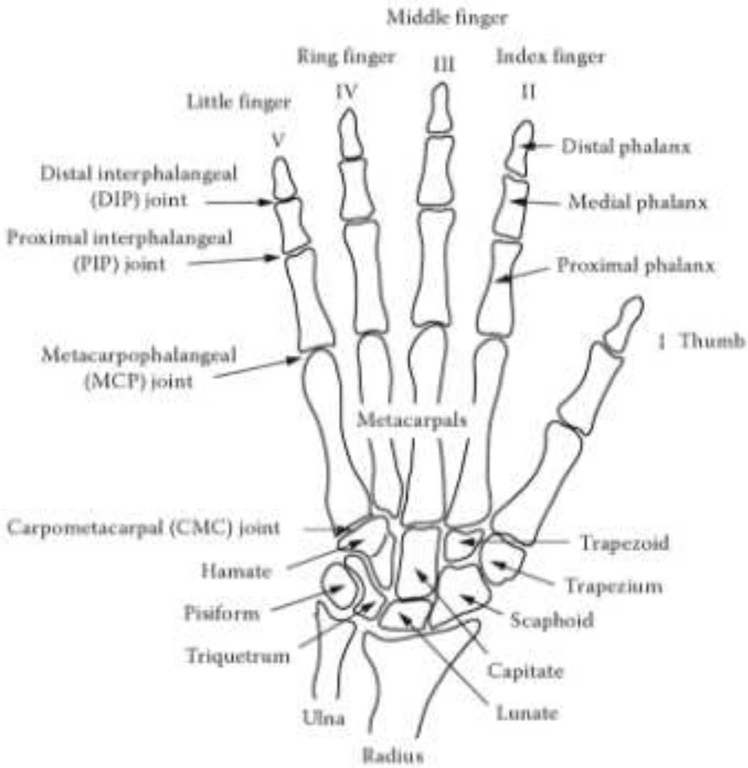


Figure 1-4. Bones and joints of the right hand.

1.1.1.2 The fingers

The 5 metacarpal bones articulate proximally with the distal carpal bones as well as distally with the proximal phalanges of the digits. There are three phalanges for each digit and two for the thumb for a total of 14 bones. They are the proximal, middle and distal phalanges as can be seen in Figure 1-4. The thumb only contains the middle and distal phalanges. The heads of the proximal and middle phalanges are shaped in a bicondular fashion allowing flexion (bending), extension (straightening) and circumduction (circular movement) about their axes.

1.1.1.3 Finger joints

There are four joints in each finger going from proximal to distal: carpometacarpal joint (CMC), metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP). The carpometacarpal joint is relatively immobile and provides a hollow of the palm allowing the hand and digits to conform to the shape of the object being handled. Metacarpophalangeal joints are composed of the convex metacarpal head and concave base of the proximal phalanx and are held together by ligaments and a joint capsule. This joint allows flexion of 90 degrees and extension of 20 to 30 degrees from neutral in the sagittal plane left and right. Flexion range differs among individual fingers with the index finger having the smallest flexion angle of 70 degrees and the little finger having the largest angle of 95 degrees.

The interphalangeal joints (IP) are hinge joints that only allow for flexion and extension. Each finger has only two interphalangeal joints, the proximal interphalangeal joint (PIP) and distal interphalangeal joint (DIP). The thumb has only one such interphalangeal joint. Volar and collateral ligaments that are connected to extensor tendons prevent any side-to-side movement. Flexion range is 100 to 110 degrees approximately in the PIP joints while a smaller range of 60 to 70 degrees is found in the DIP joints.

1.1.1.4 The wrist

The bones of the wrist including the trapezium, trapezoid, capitate and hamate are bound together by interosseous ligaments to form a relatively immobile joint known as the carpometacarpal joint (CMC).The bones of the proximal row are the scaphoid, lunate, triquetrum and psitiform. Their proximal surfaces form a biconvex surface which articulates with the distal extremity of the radius.

1.1.1.5 Muscles of the forearm, wrist and hand

The muscles that allow the fingers to move are divided into two groups: extrinsic and intrinsic. Extrinsic muscles originate in the forearm and are large providing strength while intrinsic muscles originate in the hand and are smaller providing co-ordination for the fingers. Extrinsic muscles are divided into flexors on the front end of the forearm and extensors on the posterior forearm. Most flexors begin from the medial epicondyle of the humerus while extensors originate from the lateral epicondyle of the humerus. They can be divided into superficial and deep groups of muscles. Intrinsic muscles of the hand are divided into the thenar, hypothenar and midpalmar muscle groups. The thenar group acts on the thumb, hypothenar acts on the little finger while midpalmar muscles act on all the phalanges except the thumb. These intrinsic muscles allow for independent flexion/extension and abduction/adduction of each of the phalanges allowing for precise finger movements. Muscles controlling finger movement in the forearm or wrist are the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) are main finger flexor muscles involved in the most repetitive work, Long et al. (1970) identified the flexor digitorum profundus (FDP) as the muscle performing most unloaded finger flexion whereas the flexor digitorum superficialis (FDS) comes into play when more strength is required, this was found out using electromyography (EMG) studies of which will be described later in this dissertation. The FDP the main muscle involved in hand strength originates from the proximal anterior and medial surface of the ulna and inserts into the base of the distal phalanx. In the mid-forearm the muscle divides into the radial and the ulnar with the radial part inserting into the index finger while the ulnar muscle inserts into the middle, ring and little fingers which consequently move together, while the index finger can function independently from the others.

1.1.1.6 Flexor tendon pulley systems

The FDP tendon goes through the finger through a series of pulleys which maintain the moment arm required for flexing or extending the finger. Before inserting into the distal phalanx in each case the FDP passes through a split in the FDS tendon. Figure 1-5 shows the tendon pulley system as in the fingers – there are two tendons – one runs along the bottom of the finger allowing for flexion and the other along the top for extension. (Grabowski, S.R.; 2002)

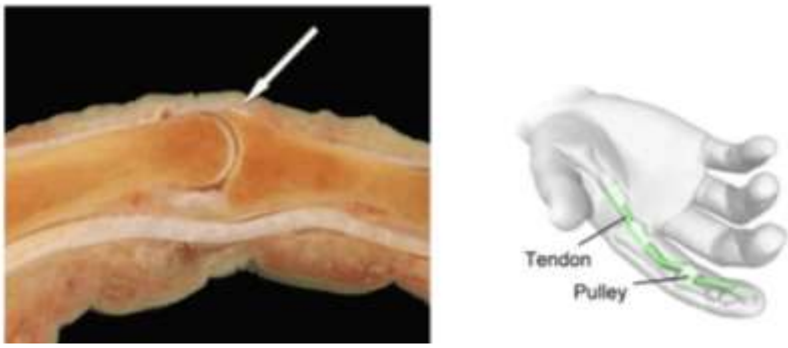


Figure 1-5. Tendon- pulley system: as found in the fingers.

In each finger is a tendon sheath which is a double-walled tube surrounding the tendons containing synovial fluid and provides a low friction gliding surface as well as nutrition for the flexor tendon. The tendon sheath begins at the neck of the metacarpal phalanx and ending at the distal phalangeal joint held against the phalanges by pulleys. The pulleys act to prevent tendons bowstringing or moving across the joints during flexion and also maintain a constant moment arm on the finger. Pulleys can be divided into three types based on their locations – palmar aponeurosis pulley, five off annular ring shaped pulleys (A1,A2, A3, A4 and A5). Three off cruciate (cross-like) pulleys (C1,C2 and C3). A2 and A4 pulleys are found on the proximal and middle phalanges, while A1, A3 and A5 pulleys are located at the palmar surface of the MCP,PIP and DIP joints. The A2 and A4 pulleys are important for normal function and for a stable joint. Damage to pulleys can occur during extreme activities when the body weight is supported by the fingers, the A3 pulley which is more flexible and other pulleys come into play after the A2 and A4 pulleys fail.

1.1.1.7 How muscles work – hand and wrist muscles

There are seven main muscles involved in hand and wrist mechanics and are the flexor carpi radialis (FCR), flexor carpi ulnaris (FCU) flexor digitorum profundus (FDP) , flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), extensor carpi radialis longus (ECRL) and extensor carpi radialis ulnaris (ECU). The main function of FCR, FCU, ECRB, ECRL and ECU are to move the wrist while FDP and FDS are secondary wrist movers responsible for flexing and extending the fingers and rotating the wrist. Muscle length determines the mechanical potential for tendon movement. When moving the wrist for example each tendon slides across the wrist joint to execute the movement. The FCR, FCU, ECRB provide larger tendon movement during flexion and extension than ECRL and ECU while ECRL and ECU have greater tendon movement during radial and ulnar deviation movement. FCR and FCU can be seen as prime muscles for flexion with ECRB for extension and ECRL for radial deviation, ECU for ulnar deviation.

1.1.1.8 Finger and hand anthropometry data

Anthropometry is the scientific study of the measurements of the human body and is necessary for the biomechanical modelling of the hand. Anthropometric data looked at here includes segment link lengths, segment weights, centre of gravity, centre of joint rotation location, joint range of motion, and muscle insertion points. Table 1-1 contains most of the information derived from studies of adult's for male and female hands of the length of the various finger bones (Garrett, J.W; 1970). Table 1-2 is a simplified table of the lengths of bones of the human hand which was adapted from Table 1.1(Garrett, 1970).

Table 1-1. Interphalangeal dimensions Note: I – thumb, II – index finger, III- middle finger, IV – ring finger, V –pinkie finger.

	Breadth		**Thickness**	
Joint	**Male**	**Female**	**Male**	**Female**
IP(I)	22,9(3,8)	19,1(1,3)	20,1(1,5)	16,8(1,0)
PIP(II)	21,3(1,3)	18,3(10)	19,6(1,3)	16,3(1,0)
DIP(II)	8,3(1,3)	15,5(1,0)	155(1,3)	13,0(1,0)
PIP(III)	21,8(13)	18,3(1,0)	20,1(1,5)	16,8(1,0)
DIP(III)	18,3(13)	15,2(1,0)	16,0(1,3)	13,2(1,0)
PIP(III)	20,1(1,3)	18,3(1,0)	18,8(1,3)	15,8(1,0)
DIP(IV)	17,3(1,0)	14,5(0,8)	15,2(1,3)	12,5(0,8)
PIP(V)	17,8(1,5)	14,5(0,8)	16,8(1,3)	14,0(1,0)
DIP(V)	15,8(1,3)	132(0,8)	13,7(1,3)	11,4(0,8)

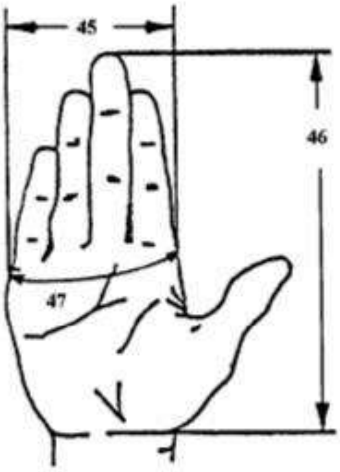
Table 1-1. Finger bone measurements.

	Distal	**Medial**	**Proximal**	**Metacarpal**
I(Thumb)	22		34	45
II(Index)	16	24	45	
III(Middle)	18	26	45	
IV(Ring)	18	26	42	
V(Pinkie)	16	18	35	

Figure 1-6 ("Human Factors"; 2010) shows samples of measurements of the human hand from male and female subjects with hand height from the base of the palm to finger tips being 193 mm and hand breadth from side to side being for the 90 mm for men in the 50th percentile. This is the mid-range and give a good guideline of hand geometry in general.

45 Hand breadth. The breadth of the hand, measured across the ends of the metacarpal bones (metacarpal-phalangeal joints).

	Sample		Percentiles 1st	5th	50th	95th	99th
A	Men	cm	8.1	8.4	9.0	9.8	10.0
		(in)	(3.2)	(3.3)	(3.5)	(3.9)	(3.9)
B	Women	cm	7.1	7.3	7.9	8.6	8.9
		(in)	(2.8)	(2.9)	(3.1)	(3.4)	(3.5)



46 Hand length. The distance from the base of the hand at the wrist crease to the tip of the middle finger.

	Sample		Percentiles 1st	5th	50th	95th	99th
A	Men	cm	17.3	17.9	19.3	21.1	21.9
		(in)	(6.8)	(7.1)	(7.6)	(8.3)	(8.6)
B	Women	cm	15.9	16.5	18.0	19.7	20.5
		(in)	(6.3)	(6.5)	(7.1)	(7.8)	(8.1)

47 Hand circumference. The circumference of the hand, measured around the knuckles (metacarpal-phalangeal joints).

	Sample		Percentiles 1st	5th	50th	95th	99th
A	Men	cm	19.2	19.9	21.3	23.0	23.7
		(in)	(7.6)	(7.8)	(8.4)	(9.1)	(9.3)
B	Women	cm	16.7	17.3	18.6	20.0	20.7
		(in)	(6.6)	(6.8)	(7.3)	(7.9)	(8.2)

Figure 1-6. Hand anthropometry.

1.1.1.9 Grasping:

There are a large variety of grasps that the hand can perform (Grebenstein, 2008), some of the main types are described here below. It is important that the prosthetic hand is able to perform most of these for it to be effective in daily use. A grasp is every static hand posture with which an object can be held securely with one hand, irrespective of the hand orientation.

Grip types can be broken down into two main types based on function; power grip (for strength) and prehension grip (pinch- for precision).

The power grip is the most powerful grip wherein the fingers flex around an object. The main types being Cylindrical, spherical and hook grips:

Grasping of cylindrical objects in different sizes (Power grip): during this grip the entire palmar surface of the hand grasps around a cylindrical object. For example grasping a hammer.

Grasping of spherical objects of different sizes: cupping using the finger flexors and palm around an object, for example holding a ball.

Hook grasp: Gripping an object like a hook formed by flexing the fingers without thumb involvement, for example holding a suitcase.

Precision grips are grips wherein the object is held between the tips of the finger and thumb, the thumb is abducted, these grips are used for fine motion and accuracy. There are four types: pad to pad - pinch), tip to tip (pincer grip), lateral prehension and lumbrical grip.

Pinch grip: 2 or 3 jaw chuck: the pad of the thumb opposes the object against one digit or both index and middle finger, for example picking up an object from the side.

Pinch grasp: tip to tip pinch, where the tip of the thumb comes up against the tip of the other digits, this is the most precise grip.

Lateral prehension: Key grasp: eg. Holding a key, thumb and index finger motion toward one another without much inclination and twist.

Lumbrical grip; referred to as the plate grip, holing a plate, holding an object horizontal.
Grip examples are described below using Neumann's classification: (Neumann, 2002)

Table 1-2. Neumann's classification: based on the number of digits involved in the purpose of the task.

Neumann's Classification			Conventional classification
by digits involved	by purpose of task	examples	
grip	power grip	holding a hammer	power grip
(all digits are used)	precision grip	holding an egg	
pinch	power grip (key pinch)	holding a key	prehension grip
(primarily use thumb and index)	precision pinch	holding a pin	
hook grip		holding a suitcase	power grip
(grip without thumb)			

Figure 1-7 (Schlesinger, 1919) shows the various types of grasp :power grips – cylindrical, hook, spherical grasp; precision grips; tip,palmar and lateral.

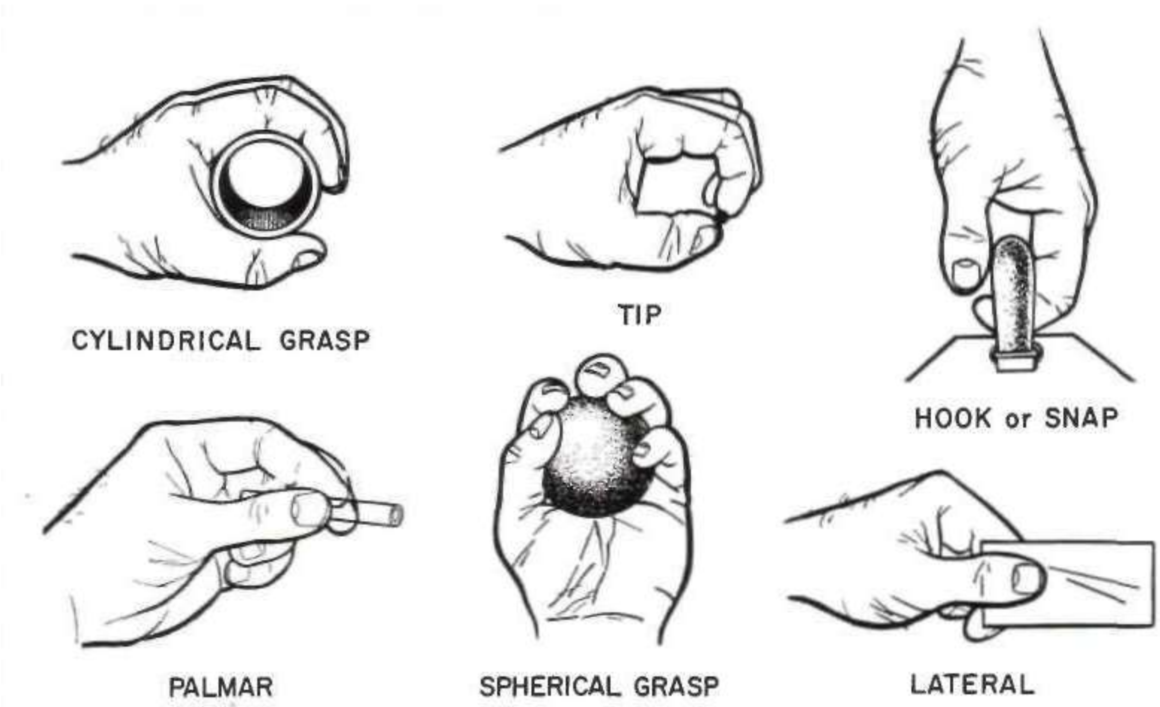


Figure 1-7. Six types of hand grasp or prehension.

1.1.1.10 Hand grip strength

Hand grip strength is a measure of the maximum isometric strength of hand and forearm muscles it can exert when closing. This gives an indication of the weight that can be held in the hand. Hand grip strength is measured in kilograms (kg) and is measured using a device called a dynamometer. Pictured in Figure 1-8 ("Handgrip Strength Test"; 2011) is a digital dynamometer that gives a digital readout of the kilograms exerted by the hand. This digital dynamometer uses a high precision strain gauge graduated in 0.1 kg increments to get an accurate readout of the kilograms exerted.

Figure 1-8. Electronic hand dynamometer used to measure grip strength.

Table 1.4 shows normative results of normative hand grip strength showing standard deviation for males and females (Mathiowetz, *et al*, 1986). From this table one is able to work out an average grip strength for a prosthetic hand that would compare favourably for most users. – the yellow highlighted part shows the average range of the grip strength used for this project -55 N.

Table 1-3. Normative hand grip strength data measured in Newton's.

Age	Hand	Males (N) Mean	SD	Females (N) Mean	SD
6 to 7	R	14,70	2,20	13,00	1,90
	L	13,90	2,40	12,30	1,90
8 to 9	R	19,00	3,30	16,00	3,80
	L	17,70	4,20	15,00	3,10
10 to 11	R	24,40	4,40	22,50	3,70
	L	22,00	4,90	20,50	3,10
12 to 13	R	26,60	7,00	27,10	4,80
	L	25,10	7,70	23,10	5,40
14 to 15	R	35,10	7,00	26,40	56,00
	L	29,20	6,80	22,40	5,40
16 to 17	R	42,60	8,80	30,50	7,50
	L	35,60	18,70	25,80	6,40
18 to 19	R	49,00	11,20	32,50	5,60
	L	42,20	12,60	28,00	5,70
20 to 24	R	54,90	9,30	31,90	6,60
	L	47,40	9,90	27,70	5,90
25 to 29	R	54,70	10,40	33,80	6,30
	L	50,10	7,30	28,80	5,50
30 to 34	R	55,20	10,10	35,70	8,70
	L	50,00	9,80	30,80	8,00
35 to 39	R	54,30	10,90	33,60	4,90
	L	51,20	9,80	30,10	5,30
40 to 44	R	53,10	9,40	31,90	61,00
	L	51,20	8,50	28,30	6,30
45 to 49	R	49,80	10,40	28,20	6,80
	L	45,70	10,30	25,40	5,80
50 to 54	R	51,50	8,20	29,80	5,30
	L	46,20	7,70	26,00	4,90
55 to 59	R	45,90	12,10	26,00	5,70
	L	37,70	10,60	21,50	5,40
60 to 64	R	40,70	9,30	25,00	4,60
	L	34,80	9,20	20,70	4,60
65 to 69	R	41,30	9,30	22,50	4,40
	L	34,80	9,00	18,60	3,70
70 to74	R	34,20	9,80	22,50	5,30
	L	29,30	8,20	18,80	4,60
75+	R	29,80	9,50	19,30	5,00
	L	24,90	7,70	17,10	4,00

1.2 A REVIEW OF MODERN PROSTHETIC HANDS

There are an ever growing list of actuator driven and non-driven prosthetic hands on the market today, many highly advanced mechanical and mechatronic systems. Below is a summary of some of the hands commercially available on the market.

1.2.1 Bebionic hand

Bebionic hand: the Bebionic hand offered at a price of $ 11000, is controlled using myoelectric sensors and is widely considered the best prosthetic hand on the market. It fingers are driven individually by gears and leadscrews with full actuation, with the thumb also having its own actuator with 2 manual selection positions opposed or non-opposed to the fingers. The bebionic can provide 14 selectable grip settings or hand positions. The hand is programmed using Bebalance software wherein information is transmitted wirelessly between the hand and receiver and the software allows for control parameters such as hand speed, grip force and grip selection optimisation. (Medynski, 2011) The Bebionic can handle up to 45 kg and is made of highly durable thermoplastic. Figure 1-9 shows the Bebionic hand ("Bebionic"; 2017).

Figure 1-9. Bebionic hand: RSL Steeper.

1.2.2 Michelangelo hand

The Michelangelo hand is a prosthetic hand developed by German company OttoBock and its American partner Advanced Arm Dynamics. It is constructed of metal and plastic and is driven by electromyography, using the users remaining arm muscles to provide motion control. The hand is capable of opening a toothpaste tube lid as well as performing other daily tasks such ironing and cooking. The hands thumb, index and middle fingers are actively driven when the ring and pinkie passively follow the other fingers. It has two motors to position the thumb. The hand offers seven grip types and is available for approximately $100,000. An Axo wrist is available which allows rotation of the hand to 160 degrees inside and out. Weight is approximately 420 g and maximum grip force is approximately 70 N. AxonSoft software is provided for adjustment of the electrodes and configuration via Bluetooth. Figure 1-10 shows the Michelangelo hand with socket. ("Otto bock"; 2017)

Figure 1-10. The Michelangelo hand (Otto Bock).

1.2.3 I-Limb hand

The i-Limb hand is manufactured by Touch Bionics and is controlled using myoelectric sensors with electrodes placed at to predetermined muscle sites. It utilises a Vari-grip system which allows the user to increase the strength of their grip around an object. It works with cell phone application software which allows up to 24 different grips. The cost of the I-limb is anywhere from $38000 to $120,000 depending on the arm fit. Figure 1-11 shows the I-Limb hand grasping a stress ball. ("Touch bionics"; 2017)

Figure 1-11. I-Limb prosthetic, Touch Bionics.

1.2.4 Mechanical hands

The mechanical prosthetic hand is the oldest form of the prosthetic. Mechanical hands are usually body powered usually using a strap that goes over the shoulder of the amputee. Two types of main body powered systems exist – voluntary opening and voluntary closing. Voluntary opening devices rely on the force exerted by the amputee to open, while voluntary closing devices use the pull force to close. Voluntary closing devices rely on body power to close giving more control where voluntary opening systems usually have a system of springs or elastic bands which keep them in the closed position. Some examples of mechanical prosthetic hands are hooks and prehensors. Hooks or the split-hook device allows amputees to hold and squeeze objects between the split hooks. Split hooks are preferred due to their functionality, ability to grasp small objects, durability and weight. A split hook can grasp a weight of approximately 11 kg.

Prehensors are not as cosmetically pleasing but allow some advantages such as much larger grip strengths and more control than hooks. The Grip 5 prehensor in Figure 1-14 is an example of a prehensor type of prosthetic hand.

1.2.5 Open source 3D printed hands

Since the advent of 3D printing growing in its popularity and availability for home users a number of open source 3D printed hands are available online. There are a number of initiatives driven by communities to make these open source hands freely available to the public. One such initiative is the Enable hand which can be seen in Figure 1-12 (“e-Nable”; 2017), and has a unique system whereby it operates. This hand is fully body powered and works by the amputee flexing his muscles on the remaining stump where the hand is attached via the 3D printed socket. The enable hand is not a usual body powered hand and is an example of a voluntary closing hand.

Figure 1-12. Enable open source 3D printed hand.

1.2.6 Grip 5 Prehensor

Another completely mechanical hand that is worth mention in this thesis is the Grip 5 Prehensor body powered mechanical hand available from TRS prosthetics. This hand designed by Bob Radocy who is himself an engineer and became an amputee in the 1971 due to a car accident. This has worthy note as it is the hand that enabled Bob to win the 2016 Cybathlon, an Olympic games designed for amputees using prosthetic devices. This body powered hand with Bob as its pilot came first ahead of the Michelangelo and I-limb hands mentioned here previously in the competition. Figure 1-13 Shows Bob Radocy with his Grip 5 Prehensor hand competing in the 216 Cybathlon and Figure 1-14 (“TRS Prosthetics”; 2017) is a close up of the hand from the competition.

Figure 1-13. Bob Radocy and the Grip 5 Prehensor at 2016 Cybathlon.

Figure 1-14. Close up of the Grip 5 Prehensor.

A comparison of some of the modern commercially available prosthetic hands can be seen in Table 1-5 (Jones, G; 2015):

Table 1-4. General characteristics of commercially available prosthetic hands.

Hand	Developer	Weight (g)	Overall size	Number of joints	Degrees of Freedom	Number of Actuators	Actuation method	Joint Coupling method	Adaptive grip
Sensor Hand (2011)	Otto Bock	350-500	Glove Sizes 7-81/4	2	1	1	DC motor	Fixed Pinch	No
Vincent Hand (2010)	Vincent Systems	-	-	11	6	6	DC Motor Worm gear	Linkage spanning MCP to PIP	Yes
i-Limb (2009)	Touch Bionics	450-615	180-182 mm long, 80 - 75 mm wide, 35 - 41 mm thick	11	6	5	DC Motor Worm gear	Tendon linking MCP to PIP	Yes
i-Limb Pulse (2010)	Touch Bionics	460-465	180 - 182 mm long, 80 - 75 mm wide, 35 -41 mm thick	11	6	5	DC Motor Worm gear	Tendon linking MCP to PIP	Yes
Bebionic (2011)	RSL Steeper	495-539	198 mm long, 90 mm wide, 50 mm thick	11	6	5	DC Motor leadscrew	Linkage spanning Metacarpal Phalange to Proximal Interphalange	Yes
Bebionic v2(2011)	RSL Steeper	495-539	190 - 200 mm long, 84 - 92 mm wide, 50 mm thick	11	6	5	DC Motor leadscrew	Linkage spanning Metacarpal Phalange to Proximal Interphalangeal	Yes
Michaelangelo (2012)	Otto Bock	~420	-	6	2	2	-	Cam design with links to all fingers	No

Some of the problems encountered in the design of prosthetic hands are that they are lacking adequate power supplies, nervous sensitivity and automatic reflexes as in the normal hand. (Fletcher, M; Orthotics and Prosthetics; 1955, Vol 9, no2.). This is still a problem today, although this was written in 1955 some advances have been made. The size of the hand also limits the number and kinds of controls that can be incorporated into the fixed limited area. Another aspect is to provide mechanical substitute motions for normal activities considering the normal motions of the hand and forces required. Other things that affect the design are costs of production and also the time needed to develop the hand.

1.3 THE COST OF PROSTHETICS

The cost of losing an upper limb (hand or whole arm) includes the loss of income for the amputee, the cost of a replacement prosthesis, the cost of therapy and rehabilitation to the patient. There are other "costs" involved including the emotional and physical restrictions placed on the individual, and the psychological and social impact of being classed as disabled. These costs all need to be considered thus it is hard to give an actual figure in terms of Rand or Dollar value of the loss of a limb to the individual.

A summary of prosthetic hand cost prices can be seen below, a benefit to the amputee is if he or she has medical insurance which usually amounts to about $2000 US dollar cover per annum (ZAR R25000) (Source: Discovery Health Priority Series Plan - South Africa ,2017).

Table 1-5. Summary costs of commercially available prosthetic hands.

Type of Prosthetic hand	Cost (US Dollars)
Cosmetic prosthetic hand (no movement)	$5000
Prosthetic hook(Mechanical hand)	$10000
Robohand 3D printed (similar to Enable hand) (Mechanical)	$2000
Bebionic 3 (EMG Control)	$25000-$35000
I-Limb (EMG Control)	$80000-$120000
DEKA Arm (EMG Control)	$100000
Michelangelo Hand (EMG control)	$100000

One can see that the high level EMG controlled prosthetic hands and even most of the lower cost mechanical hands would are quite costly and under the minimal amount provided by most medical plans. Thus it is in the best interests of research and society at large to develop and test prosthetic hands and devices that can be affordable to the general public and amputees. Therefore one can see the need for research in this area to design hands both myoelectric and mechanical that can be affordable to amputees.

1.4 RESEARCH OBJECTIVES AND SPECIFICATIONS

When looking at designing a prosthetic hand there are some design requirements that need to be defined. The design of the prosthetic hand needs to take account of some of the following criteria**:**

- **Hand research and anthropometrics:** In order to design a lifelike and functioning prosthetic hand some research needs to be done into the workings of a human hand, what are its measurements (anthropometrics); what does it do and how does it work?

- **Finger Forces and Kinematics:** These need to be life-like if the hand is 'biologically inspired". The forces should be similar to those seen in the human hand and fingers should move with the same motions allowing the hand to grasp various object.

- **Grip strength and grip patterns**: Grip strength needs to be similar to the human hand which has a maximum of approximately 55 kg. Grip patterns need to be similar so that daily activities can be carried out.

- **Finger design and hand design:** the fingers and hand need to be modular in their construction so that if there are any repairs that need to be done they can be done quickly and easily.

- **Thumb positions:** This is important as the thumb positon determines the grip type.

- **Hand tests:** The hand needs to function well experimentally and be able to handle the grip types in practice. The results need to satisfy the theoretical design.

- **Weight:** The prosthetic hand needs to be as lightweight as possible (less than 750g) allowing the amputee to be able to operate it without much strain.

- **Cost:** the cost of modern day myoelectric prosthetic hands determines who can use the hand, which should not be the case when a person is already disabled. Therefore the cost of construction and materials needs to be kept to a minimum to allow for any user to be able to purchase it.

1.5 CONTRIBUTIONS

The following contributions were developed from this research:

- The modular system should allow for adaptability based on the needs of the amputee depending on what they should require from their device. The prosthetic hand is therefore upgradable.
- A modular system that allows for the selection of a pure mechanical prosthetics hand or and mechatronics system.
- A modular system that allows the mechatronics system to be adaptable to the person's needs and affordability, allowing for the different sensors, actuators and accessories to be added, as they are required.

1.6 CHAPTER SUMMARY

A study has been done on the human hand in this chapter outlining a brief history of prosthetics. A detailed review has been done on the hand and mechanisms of motion of the fingers and various bones making up the hand. A study has been done on grip types and grip strength. Anthropometric data for the human hand has been reviewed. Specification for the design of a prosthetic hand have been outlined with the most important factors crucial to the design laid out.

2 CONCEPTUAL DESIGNS

Since a study of the human hand has been carried out, as well as a study of modern day prosthetic hands and their technologies, the design of a low cost, modular prosthetic hand needs to be carried out and conceptualised. The following sections describe the concepts looked at in designing a prosthetic hand. Two designs are looked at namely the mechatronic option and a mechanical option.

2.1 MECHATRONIC DESIGN OPTIONS

In order to design a mechatronic prosthetic hand that can be operated autonomously by an amputee one needs to look at a few options from a mechanical perspective. Concepts of finger actuation – how the fingers will move; wrist motion – turning the wrist; motor selection;

2.1.1 Finger actuation:

Finger actuation is one of the main contributing factors to the success of the design. Initially there were many thoughts and brainstorms on options.

The Touch hand 2, which was actuated by DC motors for each finger and cable and pulley systems. This hand was quite capable and a great improvement on the Touch hand 1. It had a final power grip strength of 60.6 N for the Touch hand 2 (Jones; 2015) versus 19.5 N for the Touch hand 1 (van der Riet; 2014). Figure 2-1 shows the actuation system used in the Touch hand 2.

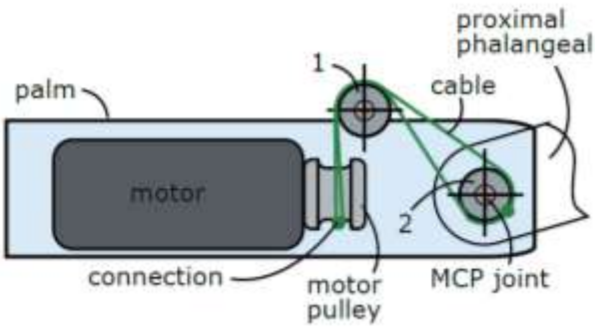


Figure 2-1. Touch hand 2 finger drive system.

An initial test design was done using Nylon fishing line which was fed through guides in the fingers so that the finger joints could be rotated relative to each other. This was decided against as there was too much friction.

Comparison was done between using cables as tendons and linkages and the result was chosen to rather use fixed linkages to actuate the fingers than a cable system. The thought here was that in using linkages besides the strength, one could better positon the fingers if a driven actuator was used. The concept in Figure 2-2 was used to base the final design on.

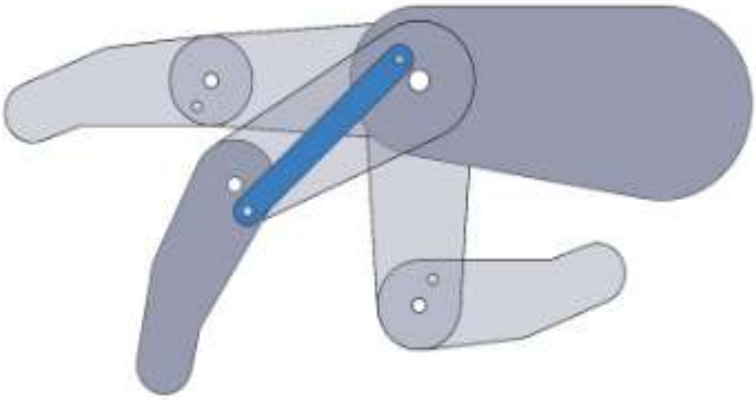


Figure 2-2. Four-bar finger linkage concept.

Research was done on other options including a leadscrew. Leadscrews can generate a large amount of force. It was found that the available leadscrews on the market, which needed to be attached to a DC motor gearhead, were rather expensive and would not suit the purpose in that they never fitted the budget and would not never fitted the dimensions needed in the hand. The leadscrew however could be a good option and is what is used on the Bebionic hand. A leadscrew system would work similar to Figure 2-3, an initial design that was used in closing the finger joint. Figure 2-4 shows a leadscrew and stepper motor combination.

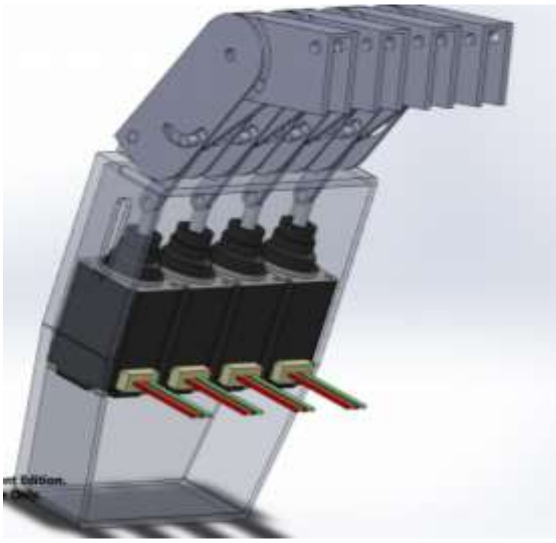


Figure 2-3. Initial design concept: leadscrews.

Figure 2-4. Stepper motor/leadscrew.

2.1.2 Motor selection

An actuation method for the fingers needed to be the next step in the decision making process. The Touch hand 2 used the pulling force generated by pulleys to open and close the fingers, this has its inherent flaws in that there could be slippage between the cable and pulley system.

A linear actuator was the next concept. Research was done into the various types available and micro linear actuators were researched due to the small size and fit required in the hand. A linear actuator would provide the ideal system for the finger motion as rotational motion was already converted to linear motion in the gear system internally hidden by the housing so that all that needs to be done was place the actuator in the correct position in the hand.

In order to select the correct motor and actuating system for the design many factors were considered including the price of the motor or actuator, the speed and time the fingers would move at to open and close, the force and torque that was needed to be generated by the fingers opening and closing, the weight of the motors, and the reliability of the motors. One would also consider how the motors would interact with the electronics and the dynamics involved in the different motors – i.e. what kind of gear system or actuating system would be needed. There were various factors that would affect the complexity of the design and along with the decision made already for linkages over tendons for finger actuations also affecting the type of actuator chosen. In essence what is needed to close the fingers was a downward stroke of an actuator and this was much easily completed if it was already the actuators function rather than converting the motion from angular motion to linear motion. The table below shows the selection criteria on which the final motors for finger actuation, the Firgelli PQ 12 (100:1) were chosen.

Table 2-1. Comparison of various factors influencing actuator choice.

	Travel mm/	Estimated tra	Closing tim	F1 Max forc	Grip Strength	Price per eac	Size of body	Stroke leng	Mass(g)	total mass
Firgelli PQ12(35:1)	28	25	0,892857	15	75	R5 200,00	36,5x21,5	20	15	75
Firgelli PQ12(63:1)	15	25	1,666667	30	150	R5 200,00	36,5x21,6	20	15	75
Firgelli PQ12(150:1)	10	25	2,5	40	200	R5 200,00	36,5x21,7	20	15	75
Firgelli L12(50:1)	23	25	1,086957	12	60	R5 200,00	37x15	30	28	140
Firgelli L12(100:1)	12	25	2,083333	23	115	R5 200,00	37x12	50	34	170
Firgelli L12(210:1)	5	25	5	45	225	R5 200,00	37x12	100	56	280
Firgelli L16(35:1)	32	25	0,78125	50	250	R5 600,00	53x18	67,5	56	280
Firgelli L16(63:1)	20	25	1,25	75	375	R5 600,00	53x19	67,5	74	370
Firgelli L16(150:1)	8	25	3,125	175	875	R5 600,00	53x20	67,5	84	420
*Touch Hand 2 *final testing value			1		60	R5793(R965,5 each)				450
* Touch Hand 1* final testing value			2		20					
Portescap p110 015 12 with R16 gearbox Torque 0,3N				0,002						

The Firgelli PQ12 (100:1) is a type of micro linear servo-driven linear actuator and is often used on RC cars and the like to produce linear motion. The actuator whose specification is given in part A of the appendices is small enough for the application and produces a force of 50 N with a travel of 20 mm. This is then ideal for the mechatronic hand and one can be used per finger to get close to the grip strength required.

2.1.3 Mechatronic design specification for prototype and final design

For the prototype mechatronic design the following specifications were developed:

- **EMG sensors:** Electromyography (EMG) is a used for evaluating and recording the electrical activity produced by skeletal muscles, the instrument used is an EMG sensor, and electromyography detects electric potential developed by muscle cells when the cells are neurologically activated. The EMG signal is used as the control signal for the prosthetic hand.

- **Microcontroller board:** The Microcontroller board selected for the design was initially the Arduino UNO microcontroller.

- **Electronic board:** Two separate electronic boards would need to be developed – one for the motors and one for the EMG sensors (input sensors). designed by the electronic engineer (Mangezi, A.; 2016)

- **Pressure sensors:** The final motor electronic board was designed such that pressure sensors could be plugged in to the board and then routed to the finger tips.

- **Temperature sensors:** Temperature sensors were also included in the final motor electronic board and these were also incorporated into the final finger design. Although provision was given for both types of sensor they were not used in the final testing.

2.2 MATERIAL SELECTION FOR PROSTHETICS

Early prosthetics used strong, heavy, inflexible iron shafts which were functional but not easy to control. Leather, wood and steel were used in the early 20^{th} century in designs such as the split hook developed by amputee D.W. Dorrance to be used in place of the hand. The 20^{th} century saw the greatest development in prosthetic limbs. Materials such as modern plastics have yielded prosthetic devices that are stronger and more lightweight than earlier limbs and they are even able to look realistic like real skin.

The requirements of a prosthesis are specifically biocompatibility meaning that the device needs to be compatible with living tissue and are not rejected by the human body. Other factors are strength, durability, light weight and ease of fabrication. The most common modern materials are various plastics but more traditional materials are wood, leather, metal and cloth.

2.2.1 Wood, leather and cloth

Wood is more used in lower limb prosthetics to provide strength and shape. Leather is often used for suspension straps and is easy to work with, with a soft natural feel and very biocompatible. Cowhide is most often used, but more recently plastics have replaced leather in some applications. Types of cloth used for socks and harnesses for example are made of wool which has elasticity and cushioning, as well as the ability to absorb moisture. Cotton is also used as it is easily washable and less expensive than wool.

2.2.2 Plastics

Plastics are materials consisting of a wide range of synthetic or semisynthetic organic compounds with their main property being that they are able to be moulded or shaped into any shape. Plastics are malleable and can be cast, pressed or extruded into many shapes. Plastics are divided into two main groups: thermoplastics and thermosetting plastics, thermoplastics do not undergo chemical change when heated, whereas thermosets stay solid once heated, with their shape irreversible.

Nylon is commonly used in prosthetic sheaths, bushings and nylon stockings used to cover prostheses. Nylons advantages in its use in prostheses are its strength, elasticity and low coefficient of friction. Nylon is a thermoplastic which can be heated and remoulded without adversely affecting its physical properties.

Acrylics have greater durability and strength than polyesters and are used more in socks.

Polypropylene is a plastic which is used for hip joints, knee joints, and lightweight prostheses. It is an opaque white material that is relatively inexpensive, strong, durable and easy to mould. Polypropylene sheets of 1 to 9 mm thick are usually heated and vacuum formed over the mould of a socket or complete limb.

Polyethylene is an opaque white thermoplastic that has a waxier feel than polypropylene, the properties of polyethylene vary depending on the density of the material. Low density Polyethylene (LDPE) is very flexible and easy to mould and used for triceps cusps in trans-radial (below-elbow) prostheses. High-density polyethylene (HDPE) is more difficult to modify and is used in bushes for joint mechanisms. Ultrahigh-molecular weight (UHMW) polyethylene is used more in partial-hand or partial-foot prostheses due to its tear resistance.

Polyurethane foams are used in prosthetics for soft foam covers and rigid structural sections. Polyurethane types are flexible urethane foams, rigid urethane foams and elastomers.
Silicones are used for distal end pads in sockets and for gel inserts. Silicones can be classed as fluids, elastomers or resins, with all three types being used in prosthetics. Silicone is synthesised from sand and undergoes a number of chemical reactions to form both solid and liquid states. Room temperature-vulcanizing (RTV) silicones are widely used in prosthetics and have uniform properties over a wide temperature range, repel water, are chemically inert, resist weathering and have a high degree of slip. Silicone fluid is used for lubrication of moving parts. Silicone gel-impregnated gauze is an excellent cushioning material. Silicone is the material of choice when recreating cosmetic hand restorations.

2.2.3 Fibre reinforcements

Glass and carbon fibre provide high strength reinforcements in modern prosthetics. Fibreglass is used to reinforce polyester resin laminations where mechanical attachments such as bolts and screws fasten. It is also used to stiffen thin areas and prevent breakage in vulnerable areas. Fibreglass is quite difficult to finish smoothly. Carbon fibres are more expensive than fibreglass but have better strength and stiffness, and are also being used in some cases to replace metal. Carbon fibres are set epoxy and can provide a material with a stiffness twice that of steel and at a fifth of the weight, a high strength-to-weight ratio. Prefabricated carbon fibre prosthetic components can reduce the weight of the prosthesis while increasing its strength.

2.2.4 Metals

Aluminium is considered as a lightweight alternative to steel. It is not as strong but is often strong enough to meet the design criteria.

Steel is strong but is relatively heavy, and is used to create small components that rely on the strength of the material rather than geometry.

Titanium is a strong lightweight material that comes in at a higher cost. The advantages and disadvantages need to be weighed up wisely when choosing materials.

2.2.5 3D printing

3D printing otherwise known as additive manufacturing is a relatively modern method used for manufacturing and rapid prototyping that has gained popularity over the last ten years. The process begins when a 3D CAD file is sliced up into layers by the 3D printer software. The file is sent to the 3D printer which then prints the object in layers, layer by layer until the designed object can be removed from the printing bed. 3D printers can be setup with various settings and can print different materials, although mainly thermoplastics, Polylactic acid (PLA) and Acrylonitrile butadiene styrene (ABS) are some of the more common materials used in 3D printing. ABS is the stronger and tougher of the two and was used in the design of the touch hand 1 and 2 prosthetic hands. 3D printers can now be purchased relatively cheaply for home use as well as commercial use which makes their choice in developing open source and prototype prosthetics an obvious one. See the properties of a comparison of various 3D printer materials and their material in the Table 1-6. (“What material should I use for 3D printing”, 2017).

Table 1-2. Properties of 3D printing materials.

	ABS	**PLA**	**PVA**	**Nylon**	**PET, PETG**
Scientific designation	Acrylonitirile butadiene styrene	Polylactic acid	Polyvinyl alcohol	Nylon	Polyethylene Terephthalate
Produced from	Petroleum	Plant starch	Petroleum	-	-
Properties	Durable	Tough	Water soluble	Strong	Non-biodegradable
	Strong	Strong	Excellent film formation	Flexible	Durable
	Slightly flexible		High bonding power	Shatter resistant	Flexible
	Heat resistant		Good barrier properties		Heat resistant
Extruder temperature	210-250 degrees C	160-220 degrees C	190-210 degrees C	250-260 degrees C	245-255 degrees C
Price	14-60$/kg	19-75$/kg	80-120$/kg	73 $/kg	48$/kg
Post processing	Easy sanding	Sanding possible	Soluble in water	Dried before printing	
	Easy glueing	Limited glueing			
	Easily soluble in acetone				
Cons	Petroleum based	Slow cooling down	Expensive	Fairly expensive	Slow to print
	Non-biodegradable	Low heat resistance	Deteriorates with moisture	High melting point	Requires heated printer bed
	Heated print bed necessary	Easily breakable	Special storage necessary		
	Fumes	Needs thicker walls than ABS			
	Deterioration through sunlight				
Material properties					
Density (g/cm^3)	1,01-1,21	1,25	1,23	0,93	1,335
Youngs Modulus E (GPa)	1,1-2,9	3,5	3,86	1,7	1,41
Yield Stress (MPa)	18,5-51				
Tensile Strength (MPa)	25-50	36-55	78	66	172
Ultimate Tensile Strength UTS (MPa)	33-110	35			

2.2.6 Laser cutting

Laser cutting is used to cut materials using a laser. It works by directing the beam of a high powered laser through optics to cut the material. The laser head is moved around the gantry using a CNC or G-code at great speed to position the cutter and cut the material. The focussed laser beam is directed at the material where it melts, burns and vaporises the material leaving a high quality edge surface finish. Lasers typically move in the X and Y axes with the cutting head being controlled in the Z-axis. Laser cutting can create flat pattern parts from different materials (mostly steels) with varying thicknesses. Laser cut parts can then be bent on CNC bending machines into the required shape for final assembly.

2.3 MECHANICAL CONCEPTUAL DESIGN

For the prosthetic hand strength to equal that of the human hand it has to equal an average strength to act and be able to pick up objects as a human hand would. Looking at the chart of normative strengths - a grip strength of 55 kg, for the 30 - 34 year old male is seen to be a good average strength that the design can be based on. This would give a grip strength of 550 N for the hand and then would give 550/5 for each finger a grip strength of approximately 110 N or 11 kg on average. From this average value a suitable spring or actuator can be chosen for each of the pure mechanical and mechatronic designs.

2.3.1 Prototype mechanical design

Before looking at the interchangeable chassis and modular parts shared between the two hands a feasible “mechanical only” option needed to be pursued. This is a system that only works with mechanical force which could be provided via a sling system that could be placed over the amputees shoulder and operated by the opposite shoulder providing the tension needed to open and close the hand.

A prototype mechanical design was constructed based on a similar design found which was produced commercially. The design which can be seen in Figure 2-5 below works simply with a clock spring which keeps a high tension on the aluminium fingers. When the cable is pulled the fingers are opened allowing for gripping, which basically only includes the pinch grip but this basic setup allows for most objects to be manipulated. This hand plugs clips into the arm socket via a splined insert and works via a cable which is connected to a harness strapped on the amputees shoulder or strapped over their back. As they move their shoulder or stump they are able to voluntarily open the hand. Since in this design the self-same socket which is pictured here is used to connect the hand to an amputees socket making the design universal.

Figure 2-5. Voluntary opening cable system hand.

The concept of the prototype mechanical design here can be seen below in Figure 2-6, this hand was designed and a basic prototype tested. It worked although the spring pressure was not enough to hold objects. The design would need to be developed but the prototype showed that it was possible to make the designs interchangeable.

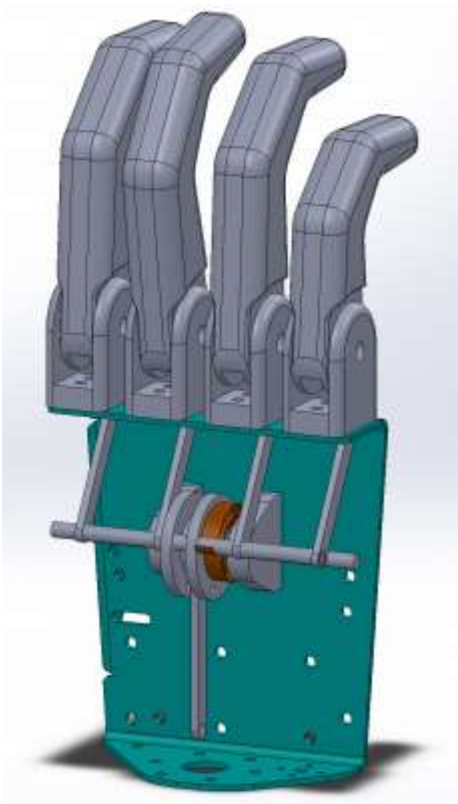


Figure 2-6. Prototype mechanical prosthetic hand.

2.3.1.1 Spring calculation using a clock spring as in prototype mechanical hand design

Clock springs are used to provide torsion. Clock springs made of stainless steel have a better fatigue life than those made of mild steel. The formulae used for clock springs are described below.

D is outer diameter;
B is width of strip;
d is inner diameter;
t is thickness of spring strip;
n is number of turns;
k is spring rate;
E is Young's Modulus;
M is moment/torque on spring;
L is length of strip;
G is modulus of rigidity (N/m^2);
I is second moment of Inertia (m^4);
F is force to deflect spring (N);
y is distance from neutral axis;
ϑ is deflection (radians), and
α is tensile/compressive stress resulting from deflection (N/m^2).

Spring rate:

$$k = \frac{M}{\theta} \ldots\ldots\ldots\ldots\ldots (2.1)$$

$$k = \frac{Ebt^3}{12L} \ldots\ldots\ldots\ldots (2.2)$$

Length of strip:

$$L = \frac{\pi n(D+d)}{2} \ldots\ldots (2.3)$$

Spring surface stress:

$$\delta = \frac{6M}{bt^2} \ldots\ldots\ldots\ldots\ldots (2.4)$$

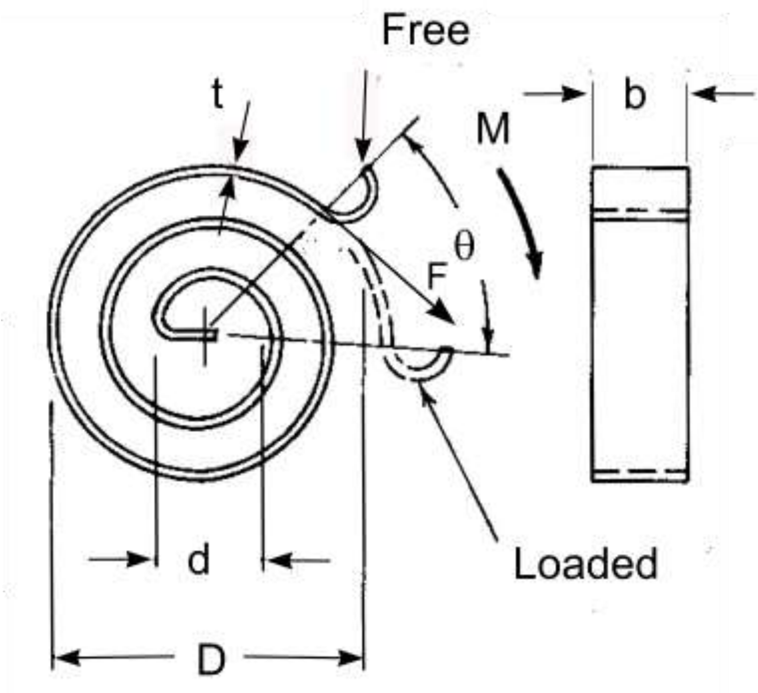


Figure 2-7. Spiral spring parameters.

2.3.2 Finger actuation

The way that fingers actuate in reality is via a tendon-pulley system. This was discussed in depth in chapter 1 in how the human hand and fingers function. For the application of the prosthetic hand being a mechanical hand there are a few more options than the tendon system. One needs to consider finger positioning, durability, strength, repeatability of the fingers. The pros and cons of a tendon cable system versus a linkage system were looked at in this design and it was decided that a linkage system would better suit this design. The table below shows the advantages and disadvantages of the two, this was decided early on in the design phase and set the course of the design.

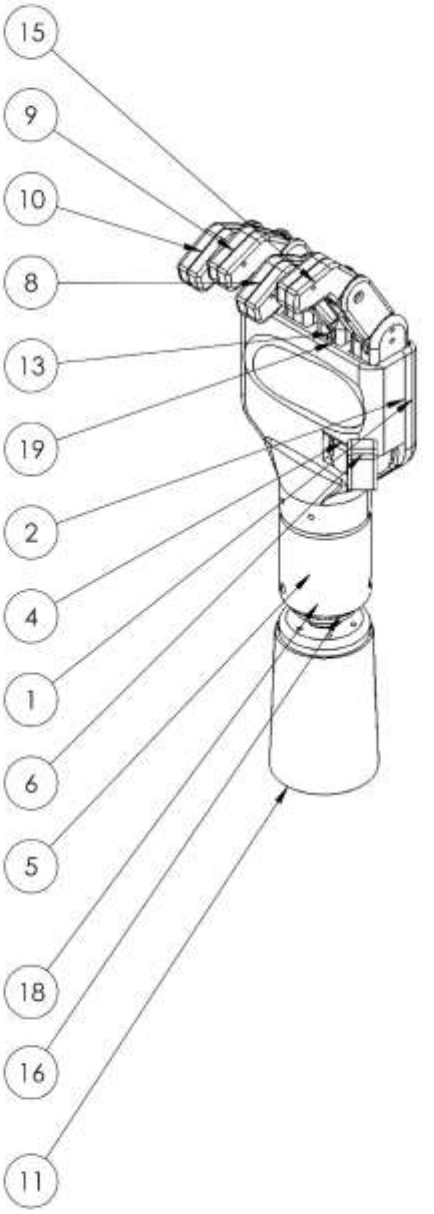
2.4 PRELIMINARY PROTOTYPE

To begin the design process a preliminary prototype of the prosthetic hand was put together fairly rapidly to test the basic design concepts.

2.4.1 Mechatronic prototype

The mechatronic prototype design as seen in Figure 2-8 the assembly and layout drawing in Figure 2-9, was developed on 3D CAD and 3D printed using 1.75 mm ABS plastic. The design allowed for actuating fingers driven individually by the Firgelli PQ 12 linear actuators with a DC motor connected in the wrist to allow for rotation of the hand about the wrist joint. The thumb was also actuated to move vertically (in and out of the palm) so as to grasp objects.

The parts were simply bolted together using 304 Stainless Steel nuts, bolts and washers. This design did not allow for incorporation of the electronics but just motors and was fully 3D printed. It was made to attach onto the socket via a standard connector. Figure 2-10 shows an exploded assembly view where one can see how the parts all fit together.



ITEM NO.	PART NUMBER
1	Palm back
2	Palm front
3	Linear Actuator PQ12
4	Linear Actuator PQ12
5	Socket
6	Thumb
7	Pin
8	Middle Finger assembly
9	Ring Finger assembly
10	Pinky Finger assembly
11	Arm Socket
13	pq-12-20_closed
14	Motor Gearhead
15	Index finger assembly
16	Wrist
17	Motor support
18	Wrist Socket
19	Motor link

Figure 2-8. Mechatronic prototype assembly view.

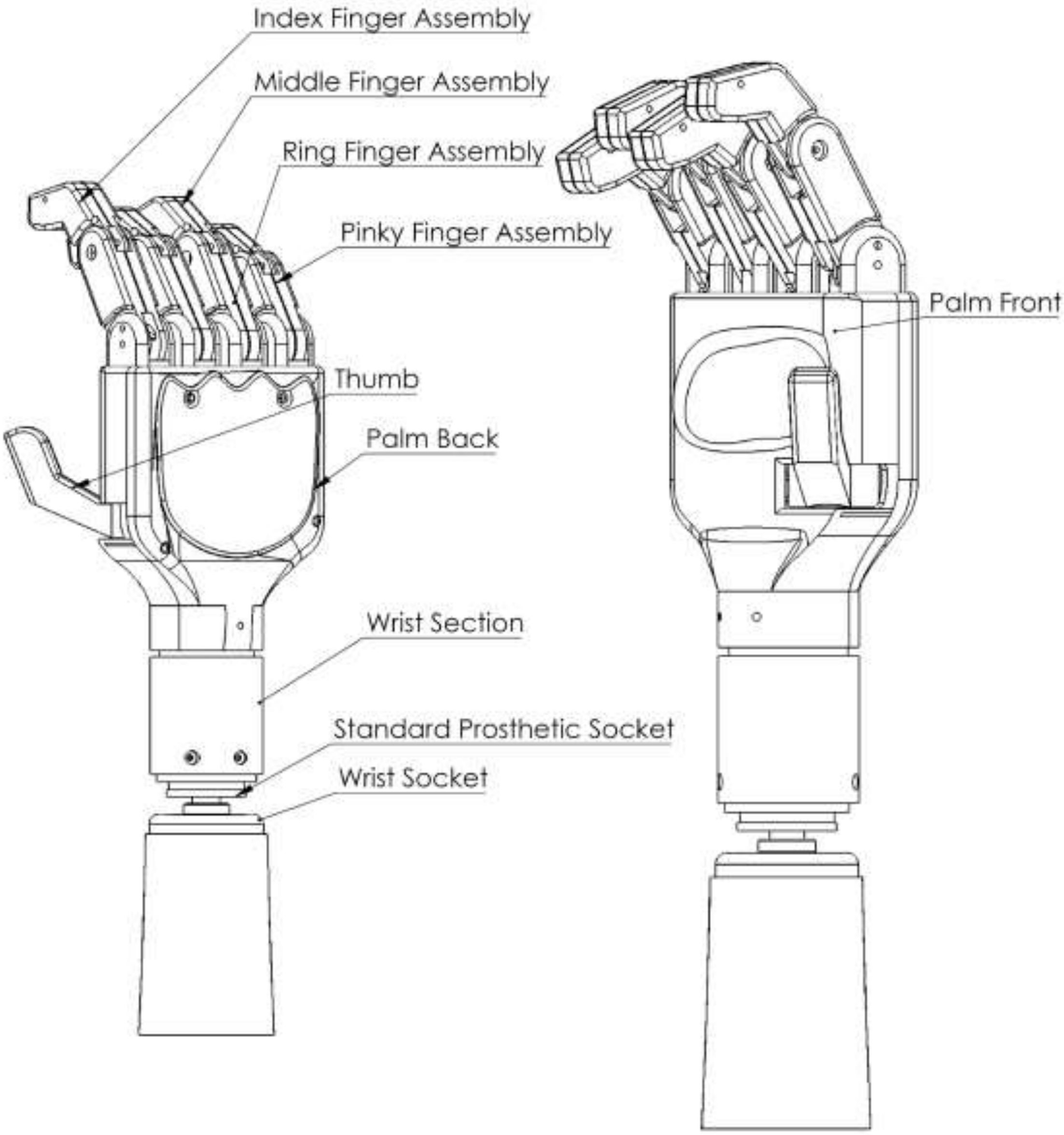
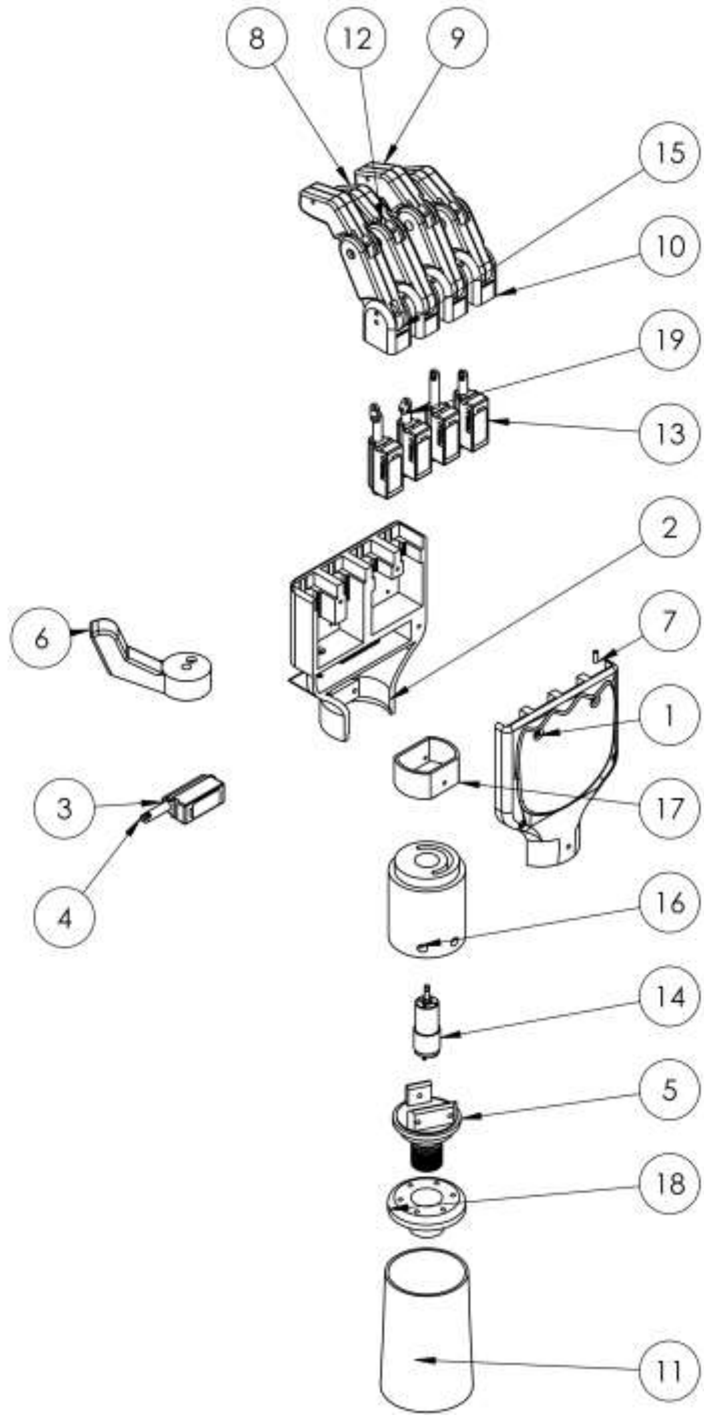


Figure 2-9. Mechatronic prototype.



ITEM NO.	PART NUMBER
1	Palm back
2	Palm front
3	Linear Actuator PQ12
4	Linear Actuator PQ12
5	Socket
6	Thumb
7	Pin
8	Middle Finger assembly
9	Ring Finger assembly
10	Pinky Finger assembly
11	Arm Socket
12	Middle proximal 45mm mirror
13	pq-12-20_closed
14	DC Motor
15	Index finger assembly
16	Wrist
17	Motor support
18	Wrist Socket
19	Motor link

Figure 2-10. Prototype hand exploded view.

The Touch Hand 3 prototype is a prosthetic hand that allows an amputee to attach to their stump via their socket. It receives signals from the user through EMG electrodes, which then is translated to the motion of the fingers and the wrist within the hand. The Touch Hand 3 has the DOF motion about the wrist, a DOF of motion with the thumb, 2 DOF motion with the pointing and middle finger, while the ring and little finger has a single DOF. The pointing finger, middle finger and thumb have each an individual actuator while the ring and little finger are controlled together by a single actuator.

Prototype touch hand 3 specifications

A description of the specifications of the prototype Touch hand 3 are laid out in the sections to follow.

2.4.1.1 Hand

The hand (1, 2) is the main chassis of the Touch Hand 3. The fingers (8, 9, 10, 15) and thumb (6) are attached to the chassis which contains the majority of the electronics and actuators (3, 13).

- **Wrist/Socket**
  The Arm Socket (11) is attached to the amputee. It contains the EMG electrodes, and the EMG amplifiers and the battery packs are attached to the socket. The wrist socket (18) is attached to the arm socket (11), which is the standard industry connection. The socket connection attached to the hand (5), allows for connectivity to the wrist socket (18), which is also a standard industry connection. A DC motor (14) which is attached to the wrist (16) and motor support (17), allows for the wrist to turn. The wrist section that is made with ABS plastic, allows the hand rotation about its axis and weights approximately 100 g. It contains a 6 V DC motor and is also a conduit for the cables for the electronics within the hand to communicate and be controlled with electronics on the socket. The socket is connected onto the amputee's arm and made of aluminium, weighing approximately 300 g. It's a standard connection used in prosthetic devices.

- **Fingers / Thumb**
  The fingers (8, 9, 10, and 15) /thumb (6) is attached to the hand (1, 2) and are able to move at different DOF to allow gripping. The fingers/thumb are able to move due to the actuators (3, 13) within the hand. The fingers and thumb dimensions are made of ABS plastic and stainless steel linkages and fasteners, their lengths are based on anthropometric data measurements as in the chart below with a width of 20 mm. The finger's weight is approximately 80 g each with the fingers having a stainless steel link, which allows the distal part to pivot for closing and opening purposes. The fingers are actuated by linear actuators situated in the palm section. They follow a modular design. The Thumb is made with ABS plastic and contains a pin fastener, which allows it to rotate on one axis. Its weight is approximately 20 g, its dimensions follow the anthropometric data.

Table 2-3. Prototype/final hand finger anthropometry.

Finger dimensions: (mm)			
	Distal phalanx	Medial phalanx	Proximal phalanx
Thumb	22		34
Index	16	24	45
Middle	18	26	45
Ring	18	26	42
Pinky	16	18	35

- **Hand Chassis**
  The hand chassis or palm body is made of ABS plastic and can be fastened together with stainless steel bolts. It is split into 2 parts and contains the linear actuators of which three are used in the present design. The weight of the Hand Chassis or palm section is approximately 150 g.

- **Motors**
  Micro-linear servo motors: The fingers are driven by micro-linear servo motors of 6 V each, with a stroke of 20 mm. They weigh approximately 15 g each. They contain limit switches. The wrist is driven directly by a 6 V DC motor and weighs approximately 10 grams.

2.4.1.2 Electronics

The specifications of the electronics in the prototype Touch hand 3 are described here.

- **Microprocessors:** Two microcontrollers used: One microprocessor receives and analyses the signal from the EMG's and sends commands to the second microprocessor which controls the movement of the motors in the fingers and wrist. The power requirement is 5 V.

- **EMG Electrodes and amplifiers:** EMG Electrodes: The Electromyography (EMG) electrodes read the potential difference between the muscles. Two sets of three electrodes are used to control the operation of the prosthetic hand. Four electrodes are applied to the forearm muscles and the other two are connected to the neutral/ground part of the body, such as the elbow.

- **Amplifiers:** The amplifiers are used to boost the EMG signal to a reasonable level for the microprocessor to read. The amplifiers used, requires a +5 V to -5 V input. There are two amplifiers for the input electrodes.

- **Battery packs:** The battery pack is a 2 cell battery pack which needs to be connected to provide a range of 6 - 8.4 V. Placing two battery packs in series allow for the range required for the -5 V voltage. The battery pack required needs to have a minimum capacity of 2.6 Ah. The battery pack consists of Lithium ion cells.

- **Sensors:** Force Sensors: The force sensor gives the hand more control over how an object is held and exhibits a decrease in resistance with an increase in the force applied to the active surface, it can be used in a feedback loop controlling the force the finger exerts on the object.

- **Vibration sensor:** The hand is to be fitted with one piezo-vibration sensors which measure vibration, impact and flexibility. They are also used to regulate the pressure that the prosthetic hand applies to the object it is gripping, by detecting the vibration when an object slips out of the hand.

2.4.1.3 Safety specification: general safety measures

The Touch Hand 3 is to be used indoor, in a dry, dirt-free and stable place. The amputee / user is to read the operator manual or get instruction and advise from the developers, before attempting to use it.

The user is to perform a pre-inspection on the device to validate performance, and to prevent malfunctions. In the event that any part of the Touch Hand 3 seems to be damaged, the amputee should cease to use it and get it repaired as soon as possible.

The Touch Hand 3 should go for maintenance on a yearly basis and prevent malfunction. The hand contains fuses to protect from overloading providing current protection of the circuits. The hand is waterproof to an extent using silicone sealant to protect the electronics. It has mechanical stops, for example in the fingers, to control to range of motion as well as limit switches built into the motors.

2.4.2 Prototype testing

The prototype prosthetic hand after being printed and assembled was first tested in the laboratory by the electronic engineer Mr. Andrew Mangezi, and thereafter tested by an amputee Mr. Darren Hauptfleisch.

Andrew was responsible for the EMG and electronic board design which made use of Arduino technology. He was able to use EMG sensors as inputs to the Arduino and by programming the boards able to open and close the linear actuators of the fingers. The driving signals came from the sensory muscle contraction information provided by the EMG sensors. He tested the hand prior to it being tested on an amputee. During the testing the finger linkages were adjusted before testing on an amputee. There was a lot of laxity in the finger joints although it was enough for basic testing and allowed some objects to be picked up.

With the EMG sensors attached to the posterior muscles of the forearm , the extensors in this case (flexor capri ulnaris muscle) the prosthetic hand is able to be controlled using the muscles at that point so is suitable to be used for the below elbow amputee although they can be used, any muscles that can be voluntarily contracted. Figure 2-11 is an image of the muscles of the forearm (“Human muscle system”, 2017).

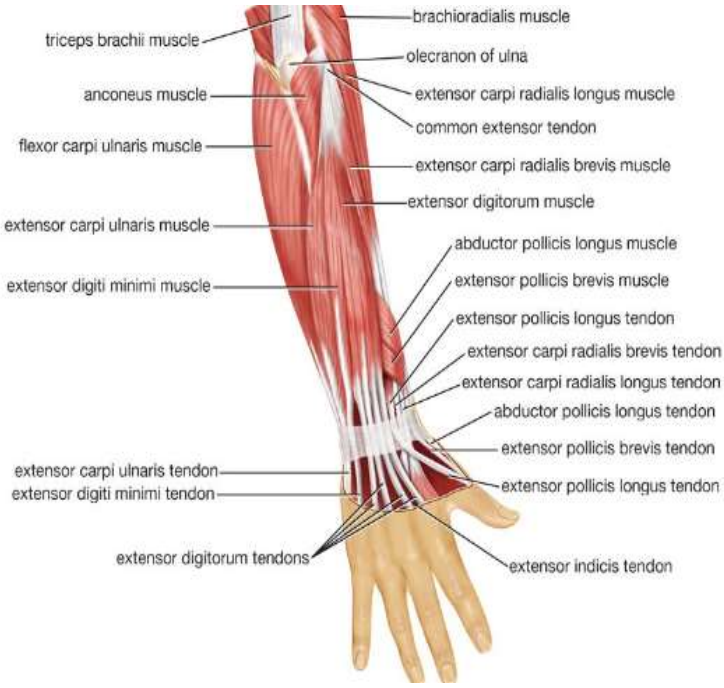


Figure 2-11. Posterior muscles of the forearm.

The prototype test setup can be seen in Figure 2-12 below. The two Arduino UNO boards are connected together, one receives the signals from the EMG's, decodes them and sends them to the motor board which drives the prosthetic hand.

Figure 2-12. Prototype test setup.

Figure 2-13 shows the hand being tested by Mr. Andrew Mangezi. The figure also shows the position of the EMG's on the forearm picking up the signal which could be decoded and sent to drive the prosthetic hand.

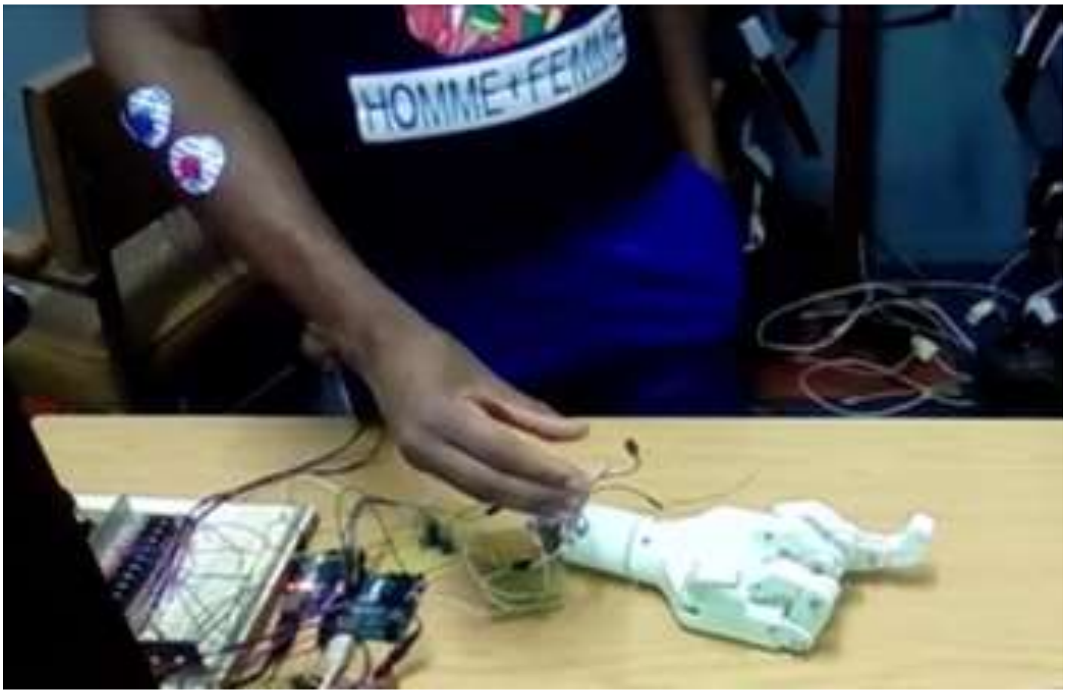


Figure 2-13. Testing: Video analysis of touch hand 3 prototype.

For the case of our test subject, Darren, he was amputated just below the elbow and still had some of the radius and ulnar bones remaining in his forearm so that his socket could be connected just below his elbow. The EMG's were connected then to the remaining muscles in his upper arm and these were used to control the hand. Figure 2-14 shows the amputee without his socket on, with EMG's connected to his stump testing the prosthetic hand before it is fitted to the socket specially designed for him. This prototype used a standard connector found on all prosthetics to connect to the amputee's socket.

Figure 2-14. Testing the prototype without attachment.

Figure 2-15 shows the socket and prototype hand being fitted to the amputees stump.

Figure 2-15. Attaching the prototype to the amputees stump.

Figure 2-16 shows the attached prototype hand and the amputee learning to operate it.

Figure 2-16. The prototype attached.

Figure 2-17 is of the amputee trying to pick up a chalk duster, the amputee is learning to grasp objects using the prototype hand.

Figure 2-17. Setup to pick up a chalk duster.

Figure 2-18 shows the amputee grasping the chalk duster.

Figure 2-18. Grasping a chalk duster.

Figure 2-19 shows the chalk duster being raised off the table in the grasp of the middle finger of the prosthetic hand.

Figure 2-19. Picking up the chalk duster.

Figure 2-20 shows the amputee holding the chalk duster. The chalk duster is now firmly in the grip and control of the amputee.

Figure 2-20. Holding the chalk duster.

Figure 2-21 shows the amputee moving the chalk duster. This is taking quite a bit of skill by the amputee.

Figure 2-21. Moving the chalk duster.

Figure 2-22 shows a different grip the amputee is using, known as a cylindrical grip to try to position the chalk duster on a plastic container. This is an easier grip and two fingers, index and middle are used to wrap around the chalk duster giving more grip strength. This shows the hand is working well in positioning these small objects.

Figure 2-22. Grasping the chalk duster between index and thumb.

Figure 2-23 shows the amputee preparing to position the chalk duster on the plastic container. This was carried out successfully.

Figure 2-23. Placing the chalk duster on a plastic container.

Figure 2-24 shows the amputee positioning the chalk duster to balance it on a small cylinder. This required more fine motor skill than positioning the chalk duster on the plastic container and was a good test showing the capabilities of the prototype hand.

Figure 2-24. Manoeuvring the chalk duster to place on small cylinder.

Figure 2-25 shows the amputee balancing the chalk duster on the small cylinder. This was carried out successfully.

Figure 2-25. Balancing a chalk duster on top of a small cylinder.

From the brief initial testing it was observed that the prototype design performed fairly well and some basic and slightly complex objects could be grasped and manipulated using the hand, the fingers could close around the objects and provided a fair amount of grip. Some fairly complex gripping and manipulation was carried out in the positioning of a chalk duster on top of a plastic cylinder. Problems with the design could be seen in the electronic system being slow to respond although with a bit of practice the amputee was able to get things working properly, understanding the way the EMG system operates and flexing his remaining muscles in the stump appropriately took a bit of practice.

From a mechanical point of view the problems with the prototype were its inherent bulkiness, fingers although actuating well did not close properly, weight was also a factor, the hand was quite heavy and its design had much to be improved on. Objects slipped easily from the hands grip. In order to solve this problem it was decided that further design needed to be done and possibly a glove employed which required a redesign of the fingers on the hand, making them narrow enough to fit into a glove. The hand also needed to be more lightweight and modular to allow for ease of assembly and repair. The weight needed to be reduced and the electronics needed to be incorporated into the hand.

2.5 CHAPTER SUMMARY

This chapter has looked at the various types of prosthetic hands on the market and also specifically at the design criteria looked at in designing a prosthetic hand such as materials, costs, options involved in construction of prosthetics. A further study was done in the construction and testing of a preliminary Touch hand 3 which was 3D printed and assembled. The design was tested with an amputee and found to be fairly successful at grasping basic objects and positioning them.

3 ELECTRONIC SYSTEMS TO BE CONTAINED

For the prototype design of the Touch hand 3 the electronic system was kept fairly simple. In this design one microcontroller was used and simply connected up to a power source, the EMG sensors, motors, sensors etc.

The full final electronic design was completed by an electronic engineering student, Mr. Andrew Mangezi. In the final design modularity needed to be included in the electronics. The electric circuits in the final design include the H-bridge, EMG sensors, external sensors (temperature, pressure, and vibration) and sensory feedback (vibration motor). In the final design two microcontrollers were used, one to receive and decode the information from the EMG sensors and other sensors employed in the hand, and a second microcontroller to implement the response in the hand motors.

3.1 ELECTRONIC SYSTEM

A block diagram for the layout of the electronic system can be seen in Figure 3-1:

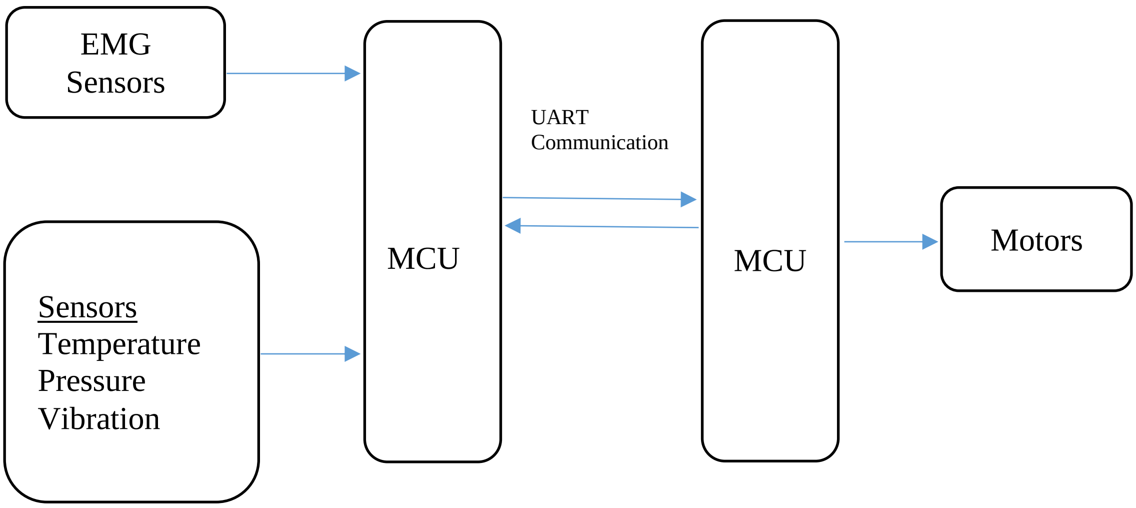


Figure 3-1. Electronic system block diagram.

The idea of using two microcontrollers allowed each board to be dedicated to a specific task, (A. Mangezi, 2016),

- The EMG board was dedicated to decoding the EMG signals, whilst the motor control board was dedicated to controlling the motors.
- The electronic parts to be contained in the final hand then are the motor microprocessor and motor board, finger motors, the wrist motor.
- Parts that are external to the hand would be the EMG control board and microprocessor, EMG sensors, pressure, temperature and vibration sensors.

These were all allowed for in the mechatronic design of the hand, so enough space needed to be left when designing the hand chassis and cover to contain the parts.

3.1.1 MCU (Microprocessor):

The two microprocessors that were chosen for the final design are Arduino M0 boards. Figure 3-2 shows the Arduino M0 Pro, the microprocessor board chosen for the final design. (“Arduino M0 Pro”; 2017)

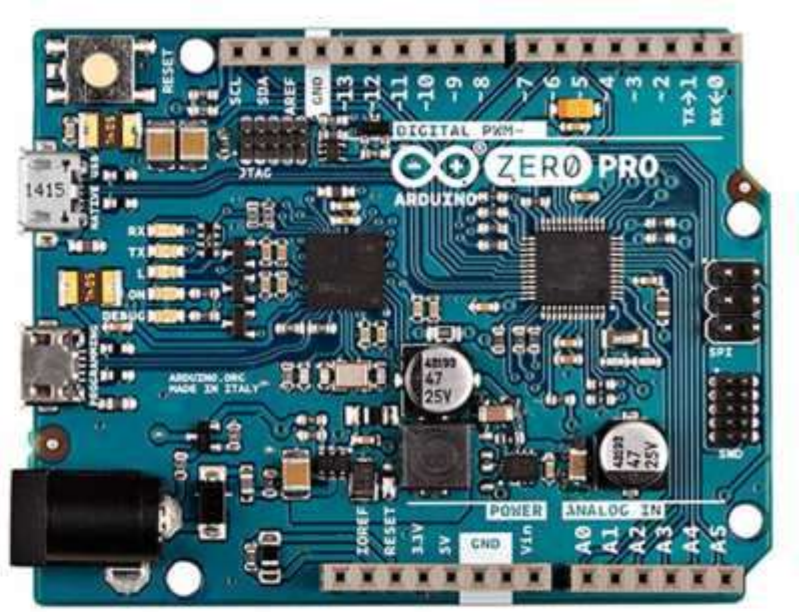


Figure 3-2. Arduino M0 Pro board.

The reason for the choice of the M0 board was its faster clock speed. Issues were experienced with the prototype hand with a delay in the communication between the boards when testing. Other considerations for the choice of the boards were their size, at 53 x 68.5 mm the boards could easily fit into the hand. Table 3-1 shows the specifications of the Arduino M0 Pro.

Table 3-1. Arduino M0 Pro specifications.

Microcontroller		**General specs**	
Architecture	ARM Cortex M0+	Input Voltage	5 - 15V
Operating Voltage	3.4 V	Power Consumption	29 mA
Flash memory	256 KB	PCB Size	53 x 68.5 mm
SRAM	32 Kb	Weight	21 g
Clock Speed	48 MHz	Product code	A000103
Analogue I/O pins	6+1 DAC	Digital I/O Pins	20, with 12 PWM and UART
DC Current per I/O pins	7 mA (I/O Pins)		

3.1.2 Sensors:

Sensors are needed in the hand to measure the EMG signal coming from the remaining muscles of the amputee’s stump, in order to position the fingers. Other sensors that were incorporated into the design are temperature sensors, pressure sensors and vibration sensors.

3.1.2.1 EMG sensors and amplifiers:

Research and testing was done by Mr. Andrew Mangezi into the best choice of electrode to be used by the EMG sensors. The general conclusion was that contact electrodes produced the least noise as noise in voltage signal affects the output signal. For example a lot of noise in EMG signal could cause the hand to operate ineffectively - a clear signal with reduced noise was vital. Figure 3-3 (Mangezi, A; 2017) shows a contact electrode which is placed on the persons forearm to read the EMG signal.

Figure 3-3. Contact electrode.

3.1.2.2 EMG sensors:

EMG sensors come in three parts generally, one negative, one positive and a ground electrode – the electrodes are connected to contact electrodes which stick onto the skin of the person being tested. Simply the idea is that the negative and positive voltages from the electrodes are compared in the EMG signal to give a reading of the electrical potential difference in a person's muscles in this case. A comparison between the readings allows for a threshold value to be obtained from which one can decide whether the hand is opened or closed. EMG amplifiers were used to process and amplify the signals. Figure 3-4 shows the EMG cables and the EMG amplifier used to amplify the EMG signal. (Mangezi, A; 2016)

Figure 3-4. EMG cables, and EMG amplifier.

3.1.2.3 Temperature sensors:

The purpose of using temperature sensors in the design of the prosthetic hand was to avoid damage that could be caused by heat. The temperature sensors can be positioned inside the fingertips such that they could make contact with the objects. Figure 3-5 shows the type of temperature sensor which was suitable for the design. (Mangezi, A; 2016)

Figure 3-5. Temperature sensor.

3.1.2.4 Pressure or force sensors:

Force sensors change mechanical force into an electrical signal. The type of force sensor chosen for the final design was a Force Sensing Resistor (FSR). Figure 3-6 is an image of the force sensing resistor. (Mangezi, A; 2016)

Figure 3-6. Force sensing resistor (FSR).

3.1.2.5 Vibration sensors:

The vibration sensors employed in the final design were Minisense 100 vibration sensors. These sensors were composed of a thin strip of piezoelectric material with a rivet on the end that act as a weight, when there was vibration the stress produced a spike in voltage in the piezo material. Connecting these up to the microcontroller allowed for vibration sensing in the hand. Figure 3-7 shows the vibration sensors.

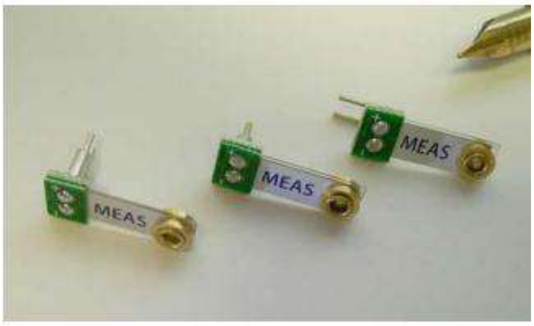


Figure 3-7. Vibration sensors.

3.2.1 Motors:

Motors that needed to be incorporated into the final design of the mechatronic hand were the motor and gearbox for wrist motion and motors linear actuators for finger motion.

3.2.1.1 DC Motor:

A DC motor was used for wrist motion. In order to operate, the DC motor had to have an H-bridge designed into the control board. The DC motor incorporated in the hand was the Faulhauber 1717SR Motor in combination with the 15 A Faulhauber planetary gearhead (152:1). The motor requires 6 V to be driven and in combination with the gearbox produces 2.1 mN.m of torque and moves at 6540 rpm. The weight of the motor is 24 g. ("Faulhauber"; 2017). The DC Motor is shown in Figure 3-8.


Figure 3-8. Faulhauber motor and planetary gearbox.

3.2.1.2 Micro-servo linear actuators:

Micro-servo linear actuators were selected to be used in the fingers. The type of linear actuator used is the Firgelli PQ-12, known as one of the smallest linear actuators on the market. A full data sheet can be seen in the appendices. The Firgelli PQ-12 linear motor is driven by a 6 V supply and the option selected had a 100:1 gear ratio giving a maximum pull force of 50 N. The linear actuator has a stroke of 20 mm and a mass of 15 g. One of these linear actuators can be mounted directly to each finger and chassis and controlled from within the microcontroller in the hand. Dimensions of the actuator are 42.5 mm (long) x 21.5 mm (wide) x 15 mm (thick). The linear actuator works via a leadscrew which strokes the actuator up and down. One can see a cutaway view with one cover removed in Figure 3-9.

Figure 3-9. Actuonix/Firgelli PQ12 microlinear actuator (cutaway to show leadscrew).

3.2.3 PCB control boards

PC Boards needed to be made up are the EMG control board and the Motors control board.

3.2.3.1 EMG control board:

An EMG Control board and Arduino M0 Pro coupled together externally in combination with the EMG electrodes and EMG amplifier which were external to the hand. This includes two battery packs needed to drive both EMGs. Figure 3-10 shows the EMG board designed for this purpose.

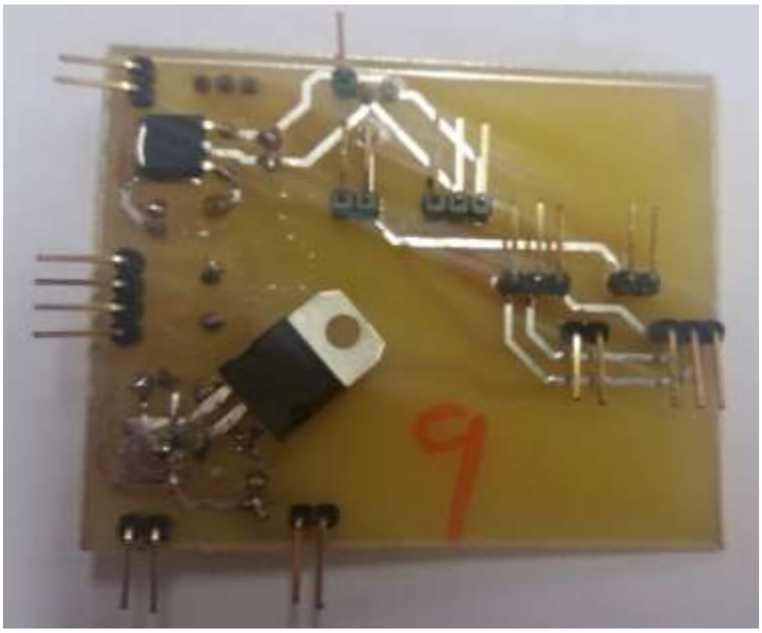


Figure 3-10. EMG sensors board (outside hand).

3.2.3.2 Motors control board:

A Motor control board coupled with an Arduino M0 board had to be contained within the hand which control the operation of hand motors mainly. A single battery pack needed to be contained within the hand to drive the motor board. Figure 3-11 is of the motors board housed within the hand.

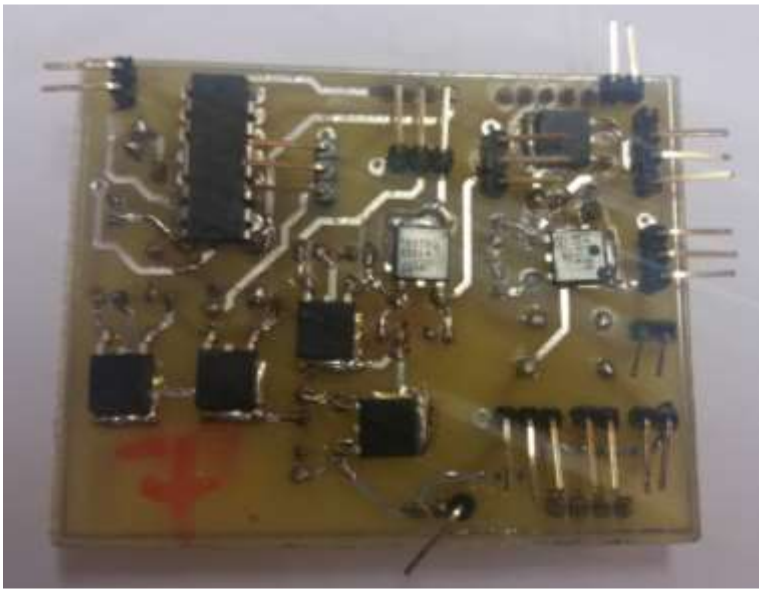


Figure 3-11. Motors board (inside hand).

3.3.3 Batteries

The type of battery used was a Lithium ion battery (LiPo). These batteries were chosen due to them being relatively cheap and lightweight. Also they are easy to charge, hold their charge well and are safe to use. Two 4.5 V batteries were coupled together to produce a nominal voltage of 6.0 - 8.4 V (A. Mangezi, 2016). A voltage regulator was employed in the final control board to maintain a regulated voltage of 5 V to the Arduino M0 Pro.

Two battery packs were required to drive the EMG board, while one was needed to power the motor board. Figure 3-12 shows a battery pack used, with two 3.7 V batteries of 1400 mAh joined to provide power to the power points on the boards.

Figure 3-12. Battery pack.

3.4 ELECTRONIC SPECIFICATIONS

The Table 3-2 shows a summary of the final electronic specifications in the Touch hand 3.

Table 3-2. Summary of the electronic specifications of the mechatronic touch hand 3.

Inside hand (Motor Board)		External to hand (EMG Board)	
Microcontroller	Arduino M0 Pro	Microcontroller	Arduino M0 Pro
Motors (Quantity)	Faulhauber 1717 SR Motor & 15 A Gearhead (152:15) (1 off) (wrist)	EMG Sensors	3 off
Microlinear actuator (Quantity)	Firgelli/Actuonix PQ12 (5 off – 4 used in final) (fingers)	EMG Electrodes	Contact Electrodes
Sensors	Force, Vibration	Sensors	EMG
Power requirement (V)	1 x 7.4 V Battery (9 V max)	Power requirement (V)	2 x 7.4 V batteries (9 V max)

3.5 CHAPTER SUMMARY:

This chapter has looked at the electronic design and specifications for the touch hand 3. The electronic parts that are to be enclosed in the hand as well as the EMG sensors have been described and the overall electronic specification of the hand tabulated.

4 MECHANICAL DESIGN

For the design of the mechanical hand the Touch hand 3 needed to be modular to comply with being adaptable between a mechatronic and mechanical hand. In the following sections the optimisation of the design of a generic chassis or shell that can incorporate both mechanical and mechatronic designs is laid out along with stress analysis on the various components making up the hand.

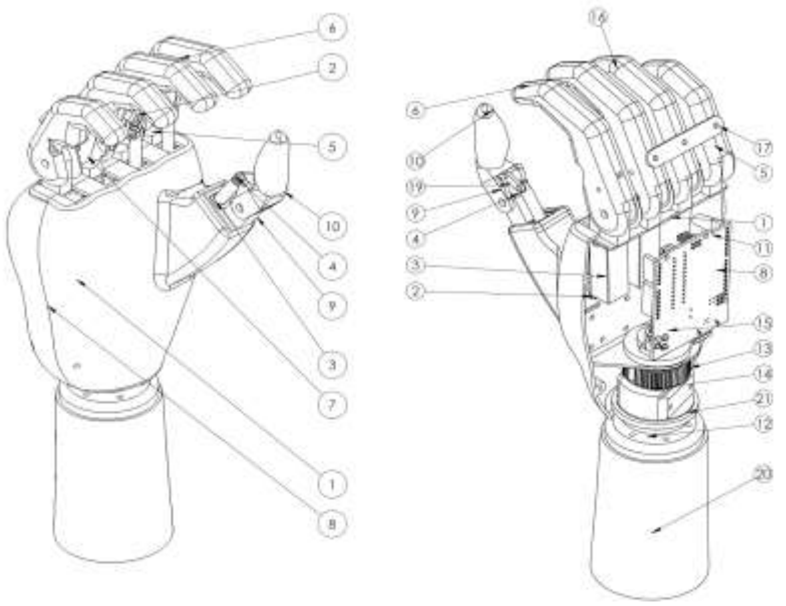
4.1 OPTIMISATION

The mechanical design referred to here includes a modular mechanical system that can be interchanged between a mechatronic and mechanical hand option. The idea is to keep the basic components – chassis, fingers, finger hinges, connections and shell, the same for both systems such that they are interchangeable parts. The initial design fared well as a prototype but the design needed to be developed to incorporate more electronic components and needed to be improved in modularity and strength from a mechanical point of view.

4.1.1 Intermediate mechatronic design

An intermediate design was done as part of the design process to test and combine a new electronic system incorporating two microcontroller boards with one in the hand used to control the motor motion and one exterior to the hand evaluating the EMG signals. Here the fingers were modelled as solid and not actuating and an aluminium chassis was chosen to fasten the actuators to providing a stiffer framework to the hand. The idea with this hand being to streamline and make the hand more compact. A gear and DC motor was added to allow for wrist motion in this design.

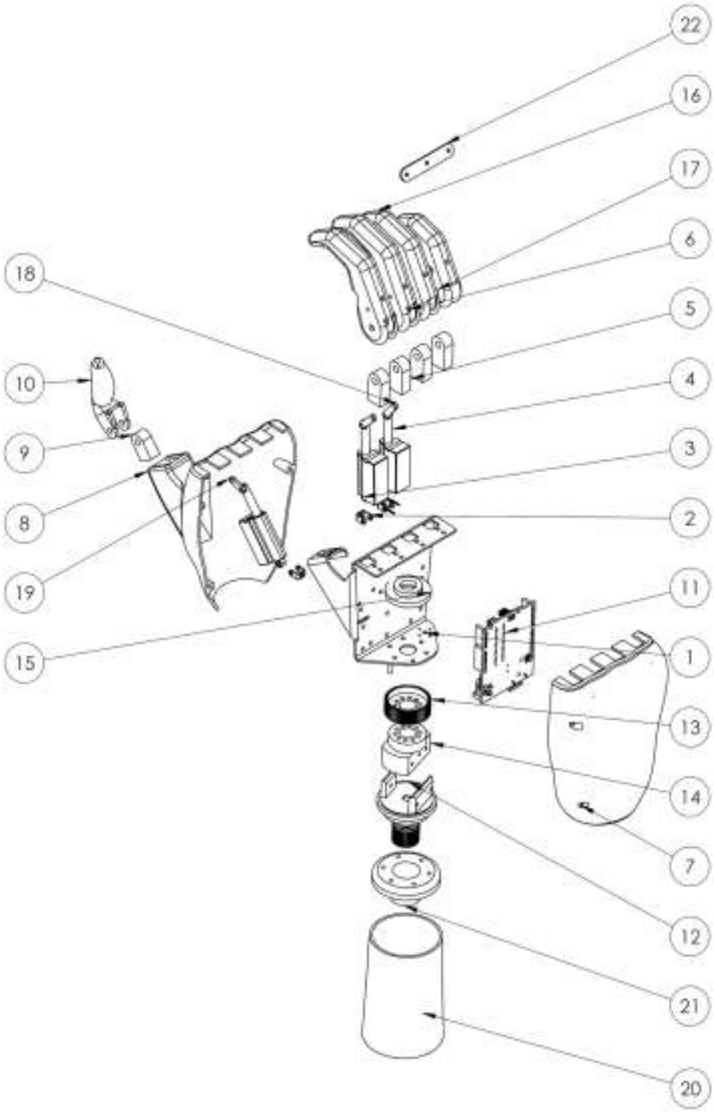
There were inherent errors in this hand such as the holes in the bent over section of the chassis plate (Item 1 in Figure 4-1) not allowing the actuators to close fully and the incorrect positioning of the thumb. Although this hand was not chosen for the final design and was eventually abandoned it allowed the progression from the basic first hand to a more streamlined design. Minimal testing was performed with this hand before the design was abandoned in favour of progression towards the final design.



ITEM NO.	PART
1	chassis
2	firgelli bracket
3	Firgelli PQ12 base
4	Firgelli PQ12 Arm
5	hinge
6	Middle Finger
7	Back cover
8	Front cover
9	thumb hinge
10	thumb
11	Controller
12	Socket
13	gear
14	Support
15	bearing flange
16	ring finger
17	pinky finger
18	14mm link
19	10mm link
20	Arm Socket
21	Wrist Socket
22	retaining strip

Figure 4-1. Intermediate hand.

Figure 4-2 shows an exploded view of the intermediate prosthetic hand. This design was more compact and stiffer than original prototype design.



ITEM NO.	PART NUMBER
1	chassis
2	firgelli bracket
3	Firgelli PQ12 base
4	Firgelli PQ12 Arm
5	hinge
6	Index finger
7	back cover
8	front cover
9	thumb hinge
10	thumb
11	Controller
12	Socket
13	gear
14	support
15	bearing flange
16	ring finger
17	pinky finger
18	14mm link
19	10mm link
20	Arm Socket
21	Wrist Socket
22	retaining strip

Figure 4-2. Exploded view on intermediate hand.

Figure 4-3 shows a view of one another optimised mechatronic design with the actuators connected to the inside of the fingers. Although this design seemed to work well with the fingers closing properly, was abandoned due to the large size of the cover – the cover became much larger and had to house the actuators on the one side and the motor board on the other. Even if the motor board was placed on the inside of the hand below the actuators it would make the boards difficult to access.

Figure 4-3. Internals of optimised hand showing chassis.

Looking at the previous designs (Touch hand 1 and Touch hand 2 produced by the department) as well as the initial fully 3D printed design here and second design the need for optimisation is clear. The first design discussed here although fairly low cost has inherent flaws in that the actuators are not bolted firmly in place. There are many parts that are assembled loosely, nuts and bolts are sticking out and the fingers do not close properly in order to grip an object.

In order to solve the problem of fixing the actuators and hinge joints in keeping them modular the idea of a universal chassis was conceived such that individual finger and thumb hinges could be bolted on and adapted where needed, as well as the actuators and Arduino and electronic boards. It allows for various combinations and positions, for example the thumb is able to be positioned at various distances from the top of the hand allowing for adjustment if necessary in the testing and final design stage. The idea of the hand chassis is in essence providing a skeleton for the palm of the hand much as the metacarpals of the hand do provide the strength needed to hold palm together and support the fingers and bones of the wrist. It should therefore be strong but also lightweight and allow for the various attachments with drillings for the components. It is the backbone for the modular hand. Another important aspect is that the main chassis needs to be anatomically correct not being too big or too small keeping with the anthropometry of a human hand.

The finger hinges posed a problem in the first iteration, although they allowed for articulation of the finger tips there were problems in their connection to the main shell. The 3D printed hinges were designed well but their flaw was in their connection to the main chassis, the second iteration made it difficult to remove replace the hinges, therefore it was thought to make the hinges out of bent up stainless steel such that they can be bolted onto the main chassis. A few variations were also looked at in order to find the best combination.

Thumb design was also optimised. The first design only allowed for the thumb motion in the x-direction with reference to the palm. In the instance of the hand the thumb is able to move in both the x- and y-direction. Motion in the x-direction moves the thumb towards and away from the palm which is not needed so much in grasping an object but allows the hand to open and close to release an object. From the initial testing of the hand this was seen to be a problem as grasping or gripping an object is seen to be more important such as in the successful task of picking up the chalk duster which was performed successfully in the initial hand. Therefore in the optimising process it was thought that the more necessary grip needed by the prosthetic patient would be the pinch or “bicycle handlebar” grip, eliminating the need for motion in the x-direction to an extent. Two designs or combinations were developed with a fixed thumb option, and a rotating or articulating thumb which can be positioned manually in the x-direction. The fixed thumb option consists of a bracket that can be firmly bolted to the main chassis with means of two M3 bolts which contains a prosthetic thumb also bolted to the bracket. This merely serves as a dummy thumb and allows mainly for the pinch grip, the index finger closing on the thumb. This would be thought of as a more basic combination option for the prosthetic hand being developed here, it also allows for the fingers to close at the same time but is rather limited in grip combinations. Another option explored would be the use of two brackets which allow for the manual or in time motorised positioning of the thumb in the x-direction. This takes the form of a bent up bracket with a slot allowing for adjustment and fixing of the thumb in position between the index and middle fingers, also allowing for the thumb to be positioned in the “open hand “ position, away from the palm. This simple bracket provides for adequate positioning of the thumb in the x-direction. The second bracket or “first metacarpal” of the thumb contains the actuator allowing the second metacarpal or thumb tip to close and open as a real thumb would. This allows for both the power grip and precision grip as explained previously, the thumb tip can be positioned in 90 degrees for more accurate grasping.

Various combinations of chassis orientation were considered with the idea of the most modular and adaptable final option in mind. They can be seen in figures 4-4 and 4-5.

The best option which was decided on after much debate was to have the actuator positioned on the inside of the chassis such that the fingers could close onto the face opposing the bent section a flat surface which serves as the palm. On the back of the hand then access is given to the actuators, wrist motor, Arduino and electronic boards. This the most modular and allows the best access to all of the mechanical and electronic equipment in the hand.

Figure 4-4 shows the optimised chassis layered over a photo of a person’s hand. This shows how the chassis size was optimised to fit a person’s hand.

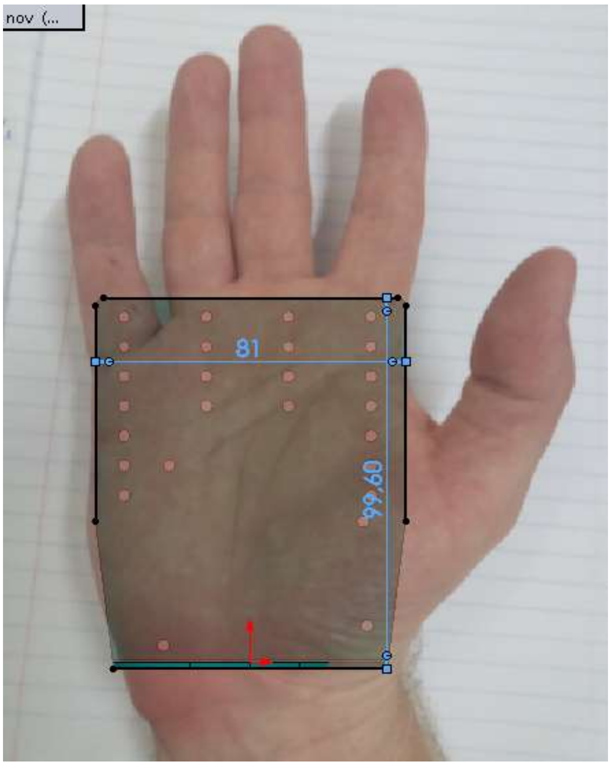


Figure 4-4. Showing the layout of the chassis compared to a hand.

Figure 4-5 is an overlay of an optimised design of the prosthetic hand with fingers and thumb brackets shown here. In this photo although there is an offset, the dimensions of the prosthetic hand are very similar to those of a human. The wrist can be moved down in this photo.

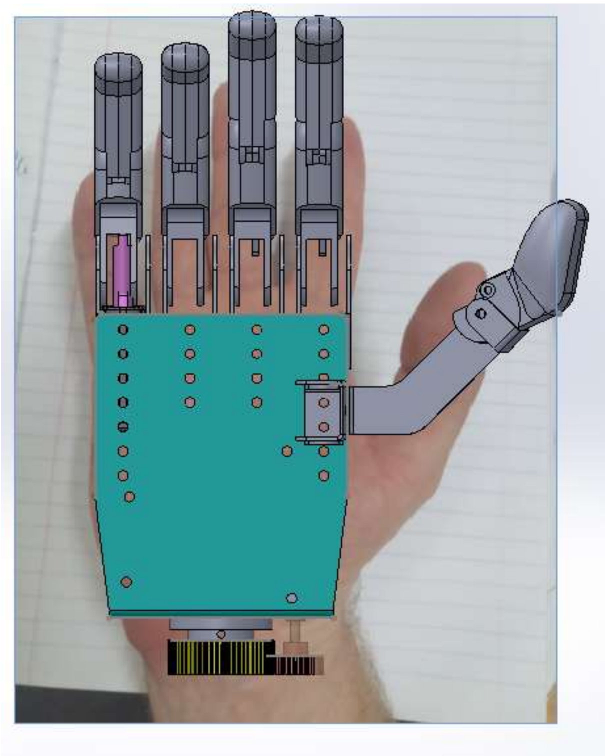


Figure 4-5. Showing the layout concept of the prosthetic hand design compared with human hand.

Optimisation has also been carried out on the fingers, with various changes made from the first iteration. Two options are needed in the development of the hand, such that the fingers can be either rigid or articulated just allowing for more and less motion constraint, giving options again for a more and less complex but also flexible hand. The design required that fixed non articulating fingers be hollowed out such that wires for sensors could be installed in the fingertips. The rigid hollowed fingers are printed from 2 mm wall thickness ABS plastic and articulate around the hinge joint, with only one actuation point where the linear actuator is connected.

Allowance for sensors to be positioned in the fingertips was provided for with cut-outs in the finger tips, finger tips were to be removable. In this design finger tips can be screwed via two millimetre screws mounted opposite to each other to the main finger or second part of the actuating finger. The finger tips we also developed to be modular in the sense that the index, middle, ring and pink finger tips are all interchangeable and the same design is used so that the entire design is more modular, therefore if a fingertip needs to be replaced there is one design for these fingertips and that design alone needs only to be printed, spares can then be easily provided for.

The cover or shell of the hand has also gone through various developments from the initial bulky design of the first iteration. The cover in the second and following iterations was required to wrap around the aluminium chassis. It was decided that the thickness of the cover need only be 2 mm ABS plastic and would be sufficient to carry the force of the fingertips closing on the outside and should be strong and light enough to withstand most forces encountered by the hand, adequately performing the function of a “skin” around the “skeleton” of the chassis. Analysis has been done on this in the next section.

4.1.2 3D scanning

A 3D scan was performed of the author's own hand to aid the design process. This was done using the Artec 3D scanner which uses bursts of light to produce the 3D image. The 3D image is saved on the computer as a .STL file which is the same file format used in 3D printing but can't really be manipulated or used in the mainline CAD software. It was broken up into layers using Rhino software which works on NURBS (Non-uniform rational B-spline) mathematical modelling to produce surfaces which can then be exported to the relevant CAD software and used to create a model. The 3D scan of the author's own hand come out fairly well but the information was not sufficient to be used in the design although accurate it was only used as a comparison model and could not be used in the modelling of the hand. (“Artec”; 2017)

The Artec Eva 3D scanner is a 3D scanner which was used to produce a 3D model of a hand that could be used in the research pictured in Figure 4-6.

Figure 4-6. Artec 3D scanner.

A resulting image of the 3D scanned model of the authors hand can be seen in Figure 4-7. This could be imported into the 3D CAD software and used to verify the dimensions of the designed hand.

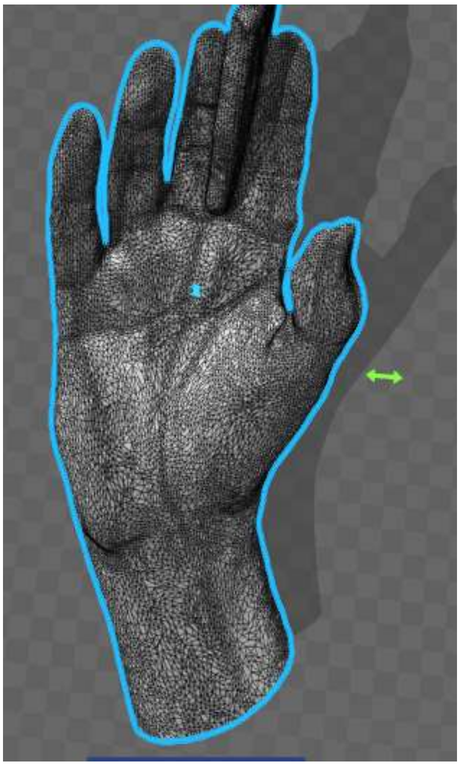


Figure 4-7. 3D Scan of hand.

4.2 FINAL GENERIC SHELL DESIGN

After some optimisation and research the parts common to both designs were seen to be the chassis, finger hinges, fingers, wrist parts, and basic hand cover. These are detailed below:

4.2.1 Chassis:

The chassis plate needed to be rigid enough for both the mechanical hand and mechatronic hand, consideration needed to be given to the mechanical hand taking more stress due to the forces from the internal springs connected to the fingers and chassis. Two materials were chosen for the chassis these being 1.6 mm 6065 Aluminium plate and 2 mm thick stainless steel plate. Both of these were tested in the physical models and will be described in their specific sections. A 2 mm stainless steel can be used as a common material for both. The chassis design had to allow for adjustable bolt holes for the mounting of the four actuators, mounting holes for the thumb and holes for the wrist assembly. Holes were also cut for the wrist motor. Figure 4-8 shows the final design for the chassis with many holes spaced at 8 mm allowing for connection of the hinges and linear actuators as well as the electronic components. This modular design provided for adjustment in the actuator position in the final assembly as well as the thumb position.

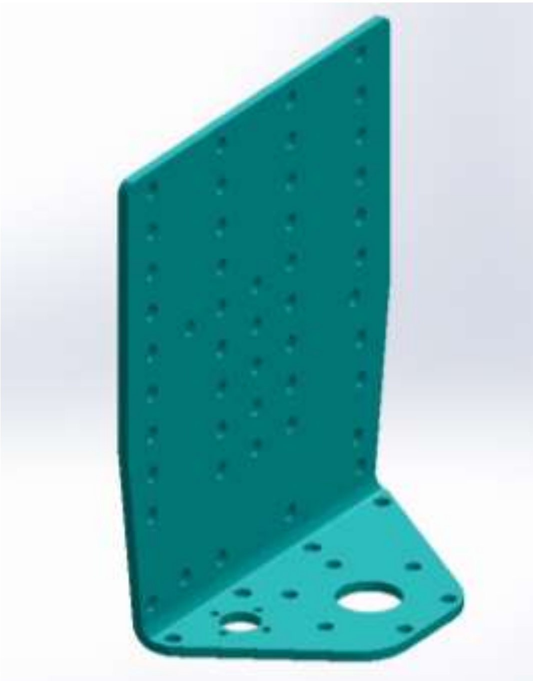


Figure 4-8. Chassis.

4.2.2 Finger hinges:

During the optimisation process it was found that finger hinges that could mount onto the chassis and allow for actuator motion, had to be designed such that these was an open space for the actuator to move as close to the chassis body as possible. The design for these required holes for the finger threaded pins and linkage holes, as well as mounting holes to the chassis were pre-cut. The hinges needed two bends, and were finally manufactured from 2 mm 304 stainless steel. Figure 4-9 below shows the final design of the hinge, bent out of stainless steel. The two holes at the bottom are spaced 8 mm apart and provide for bolting onto the chassis plate, the top holes allow for connection of the finger proximal phalanx and the linkage – these are spaced 7 mm apart.

Figure 4-9. Modular finger hinge design.

4.2.3 Fingers:

In optimising the finger design it was decided that the fingers be kept as modular as possible. The final design of the fingers spit the finger in two parts, unlike the prototype finger which was split in four parts. Another part of the finger design is that common parts were used for the distal and medial phalanx for all fingers and for fingers index to ring a common proximal phalanx was used with only the pinkie having its own proximal phalanx part (initial finger part). This increases the modularity of the design so that finger parts and also linkages can be interchanged and cuts down on the number of parts needed to be designed, keeping assembly simple as well. In this final design the actuator connects directly to the proximal part of the finger, eliminating the need for an extra linkage as used in the preliminary prototype design. Figure 4-10 shows the finger cutaway with the finger in the open and closed position and the linkage position.

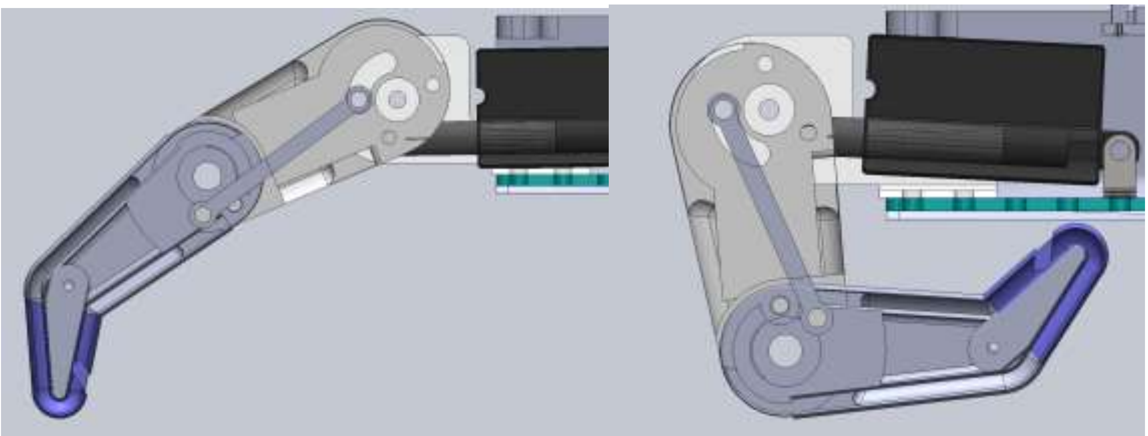


Figure 4-10. (a) Finger in open position (b) Finger in closed position.

The finger parts are actuated via the linkages and were designed such that the fingers could open and close fully. The fingers also needed to be designed such that pressure, temperature and vibration sensors could be mounted in their tips with allowance for their cables to pass through. The final design was 3D printed from 2-3 mm thick ABS plastic.

4.2.4 Wrist:

The chassis in both cases has a hole cut out such that a boss with a bearing can be fitted and a brass tube which passes through the bearing allowing for wires to pass through. The bearing used here was a 13.1 mm ID with 26 mm OD. The 3D printed bearing boss, in which the bearing is pressed is bolted down to the chassis via six M 3 x 5 mm (length) stainless steel screws. A fixed spur gear was attached to the wrist to allow the hand to rotate around it, a motor with a small pinion was connected to the chassis and this drives the hand around the wrist. This is shown in Figure 4-11.

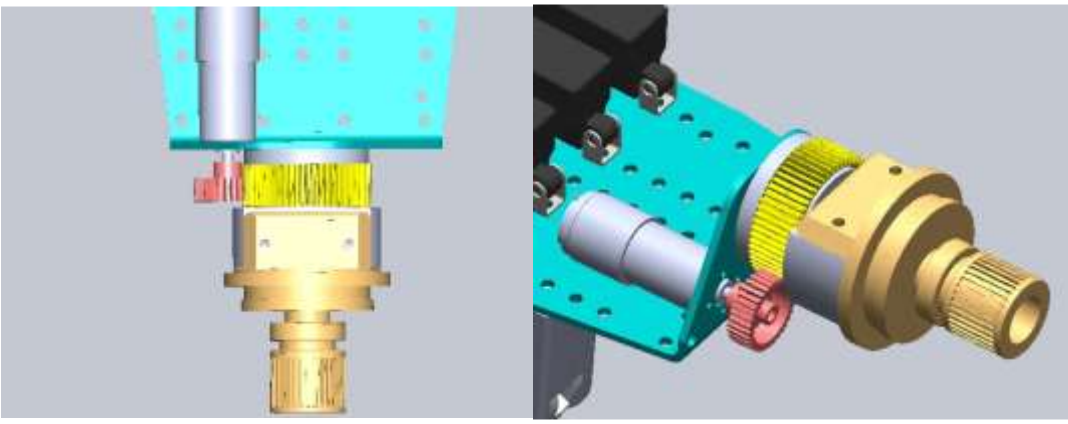


Figure 4-11. (a) Wrist layout (b) Wrist layout close-up

A calculation was done to determine the speed at which the hand would rotate.

$$U = \frac{Z_2}{Z_1} = \frac{n_1}{n_2} = \frac{d_2}{d_1} \qquad (4.1)$$

Table 4-1. Spur gear calculation.

N_p	34
N_g	55
Speed motor (rev/min)	6540
reduced speed gearbox (152:1)	43,02632
Gearbox output torque	0,0021
Gear ratio (U)	1,617647
$n_2 = n_1/U$ (rev/min)	26,59809
Pitch Diameter	34,5
Circumference (1 rev)	0,108385
Rotation speed (m/min)	2,882832
Rotation speed (m/s)	0,048047

4.2.5 Cover:

The 3D printed cover needed to incorporate both the mechanical and mechatronic systems. The mechatronic system gave some small problems in fitting all the parts in but a lifelike design was successfully able to incorporate all the parts. The final design was 3D printed from 2 mm ABS plastic and allowed for inclusion of all parts. Figure 4-12 and Figure 4-13 show the final hand cover designs.

Figure 4-12. (a) Front cover (b) Back cover.

Figure 4-13 shows the CAD design of the covers fitting on the hand.

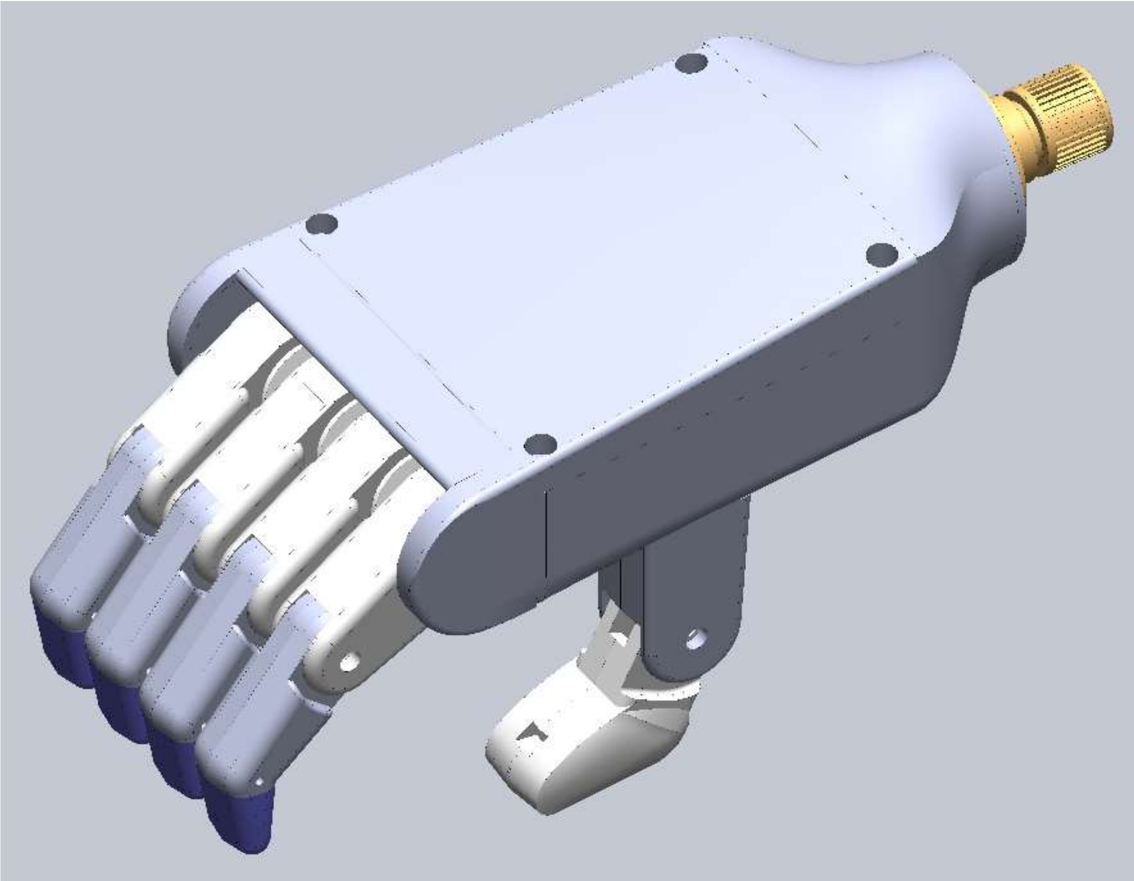


Figure 4-13. Hand with covers.

A view of the final assembled 3D printed mechatronic hand can be seen in Figure 4-14.

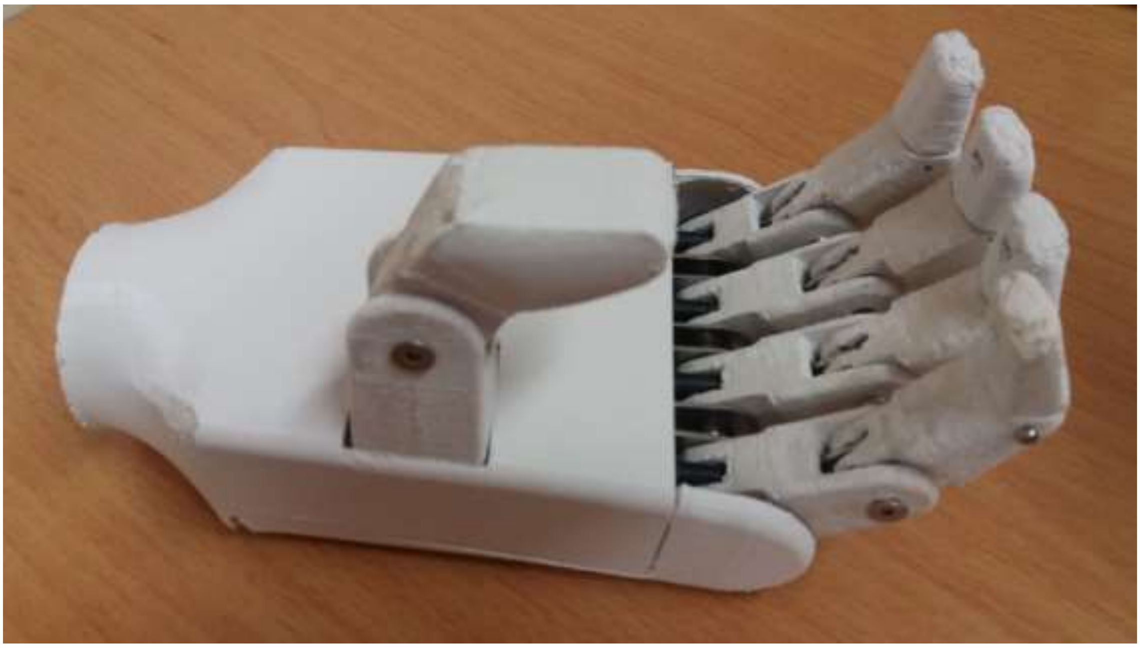


Figure 4-14. Final 3D printed hand.

4.2.6 Finite element analysis of generic Shell

Finite element analysis is a numerical simulation method used for predicting how a model will react in the real world when exposed to forces, heat, vibration and other real world stresses. It is used in engineering as a computational tool for performing engineering analysis. It uses a method of converting the CAD model into a virtual FEA model which can be meshed, the material properties and boundary conditions are defined such that the equations can be solved. The model is meshed into many elements that are bordered by nodes, the accuracy of the results depends on the quality of the mesh and the number of meshing elements. It is used also as a rapid prototyping method where results can be obtained on-screen rather than having to produce the prototype, simulations can be done before it is produced to provide the best results under various real world operating conditions.

For the analysis of the prosthetic hand the main load bearing structures would be the fingers, finger hinge brackets, palm and thumb brackets. These need to be tested or analysed for deflection, strain and stress to see how the hand will stand up to forces in the real world situation.

4.2.6.1 Stainless steel 2 mm finger hinges

Figures 4-15 to 4-17 show Von Mises stress analysis for finger hinge from 2 mm stainless steel shows that the hinges are strong enough with the yield stress of 173 MPa there is also not that much deformation and the safety factor is sufficient.

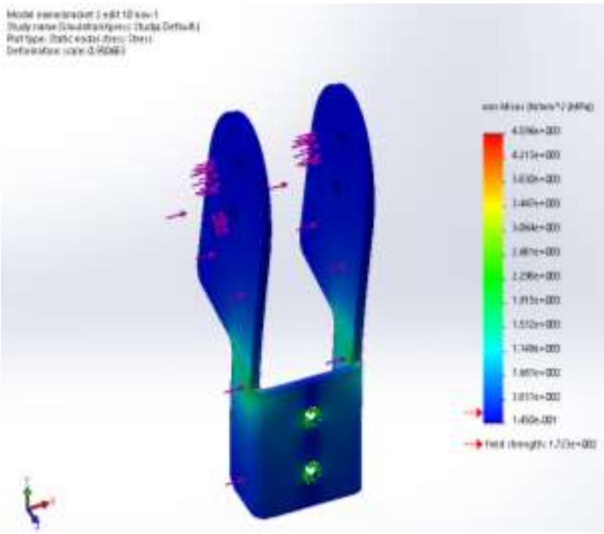


Figure 4-15. Von Mises stress on finger hinge.

Figure 4-16 shows the displacement for the loading condition.

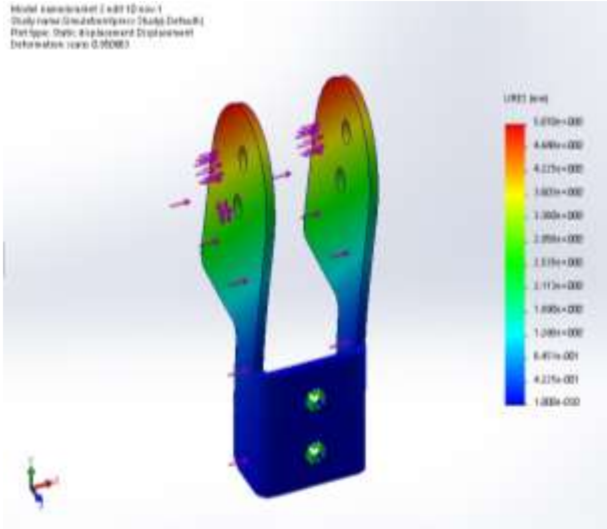


Figure 4-16. Displacement on finger hinge.

The blue part shows where the safety factor is at a minimum in the hinge in Figure 4-17 for the loading condition.

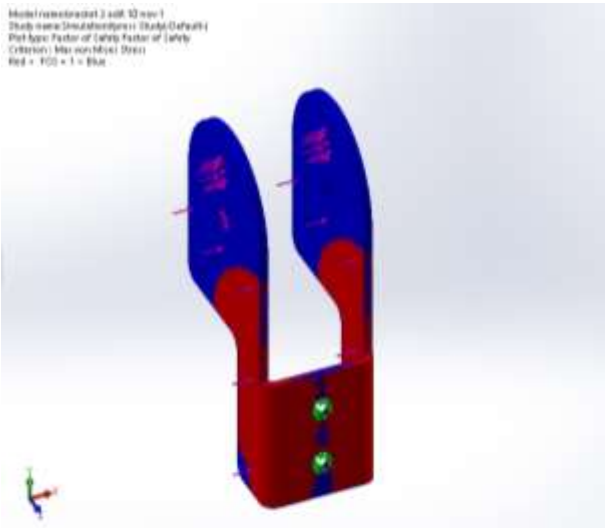


Figure 4-17. Factor of safety of finger hinge.

4.2.6.2 Chassis, 1.6 mm 6016 H14 Aluminium

Figures 4-18 to 4-21 show the loading, stress analysis, deformation and safety factor analysis on a 1.6 mm aluminium chassis. In loading the ABS finger tips with 20 kg one can see that the fingers hold out fairly well and there is minimal deformation and shear failure, stress is mainly concentrated around the joint and deformation is approximately 2 mm at the tip. This is fine for this scenario as the fingers are flexible to a degree being made from ABS plastic. ABS plastic generally has a shear modulus of around 40 MPa but it is less in 3D printed materials.

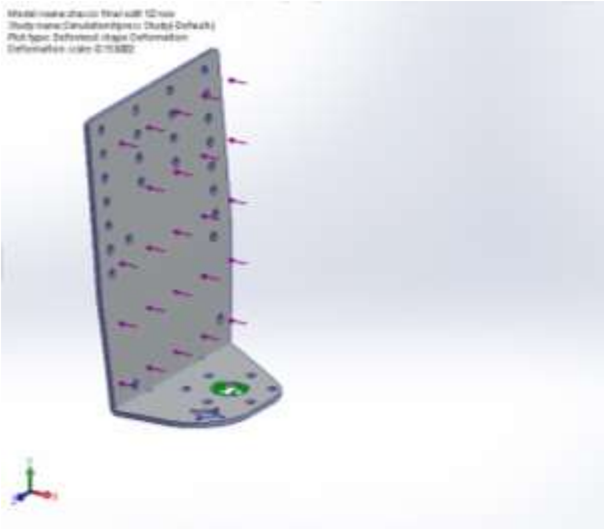


Figure 4-18. Chassis loading (500 N).

The Von-Mises stress distribution is shown in Figure 4-19, here it is shown to be below that of aluminium for the loading condition.

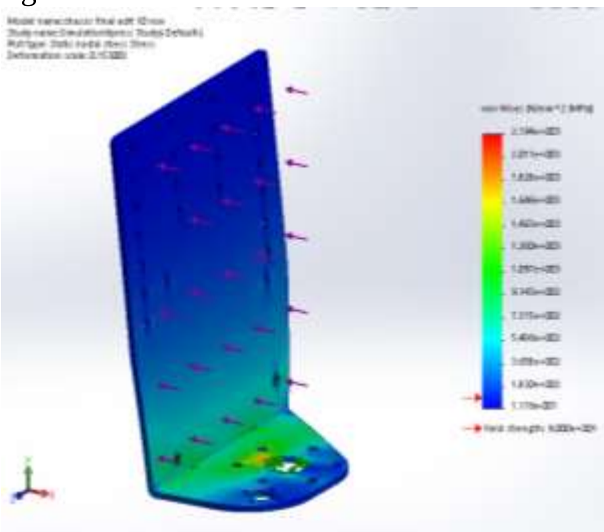


Figure 4-19. Chassis Von Mises test.

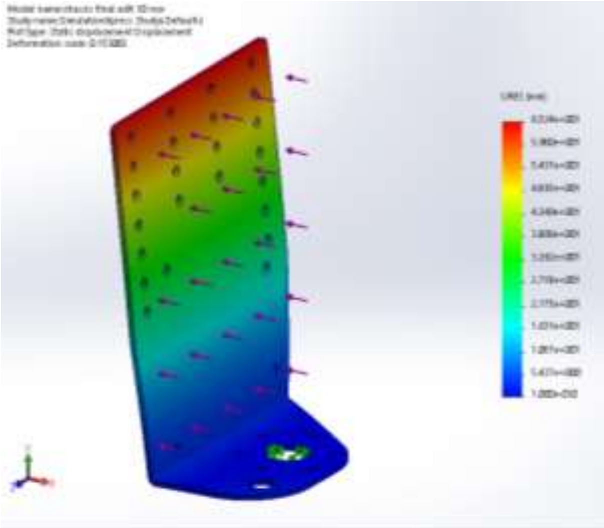


Figure 4-20. Chassis deformation.

Figure 4-21 shows where the safety factor is at a minimum – the blue section shows where deformation is likely to occur.

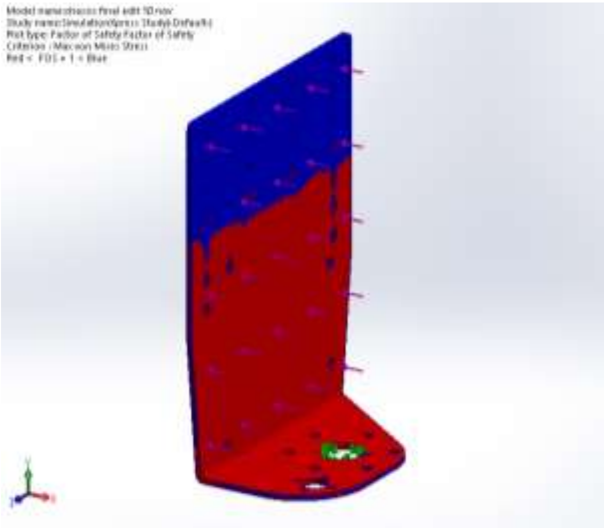


Figure 4-21. Chassis factor of safety.

For the Aluminium chassis which was the first option to go for in the mechatronic hand design, loading the chassis with 500 N as in Figure 4-19, the aluminium provides a yield stress of 90 MPa, with the main problem being the deformation as in Figure 4-20, the aluminium deforms 6 mm at the top of the chassis when loaded with 50 kg.

4.2.6.3 Finger stress analysis: ABS plastic

In loading the ABS finger tips in Figures 4-22 to 4-23 with 20 kg one can see that the fingers hold out fairly well and there is minimal deformation and shear failure, stress is mainly concentrated around the joint and deformation is approximately 2 mm at the tip. This is fine for this scenario as the fingers are flexible to a degree being made from ABS plastic. ABS plastic generally has a shear modulus of around 40 MPa but it is less in 3D printed materials.

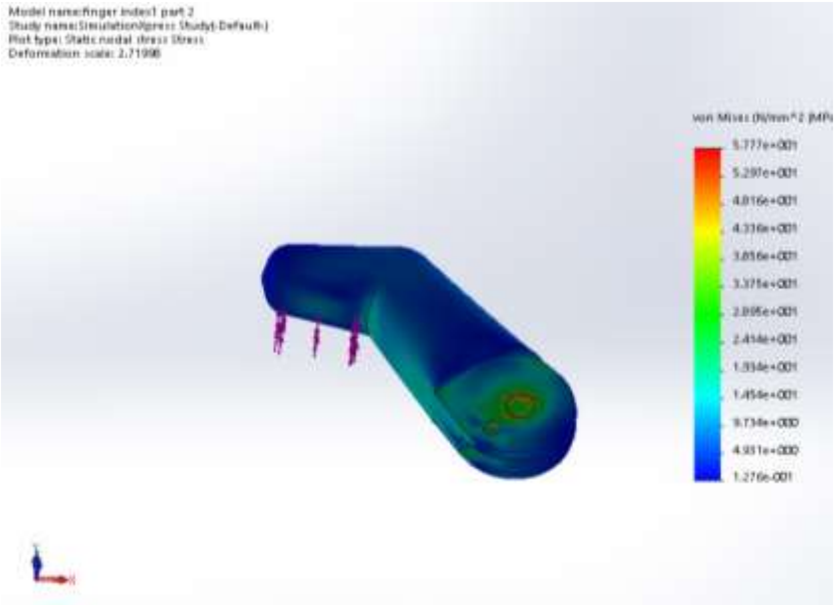


Figure 4-22. Finger part 2 Von Mises stress analysis loading 200 N (ABS).

Figure 4-23 shows the displacement at a maximum of approximately 2 mm at the fingertip.

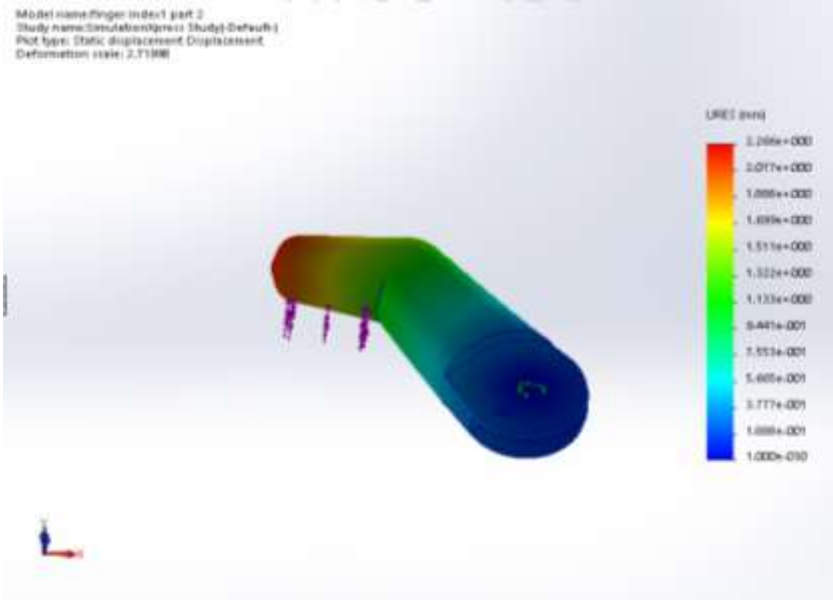


Figure 4-23. Finger part 2 fingertip deformation.

4.2.6.4 Thumb bracket analysis

The ABS (Tensile strength 30 MPa) fixed thumb bracket was loaded with 100 N (10 kg) as shown in Figure 4-24, with the bolted connection set as a support. This shows the bracket being able to withstand the loading condition. There is minimal deflection as shown in Figure 4-25 of 0.36 mm.

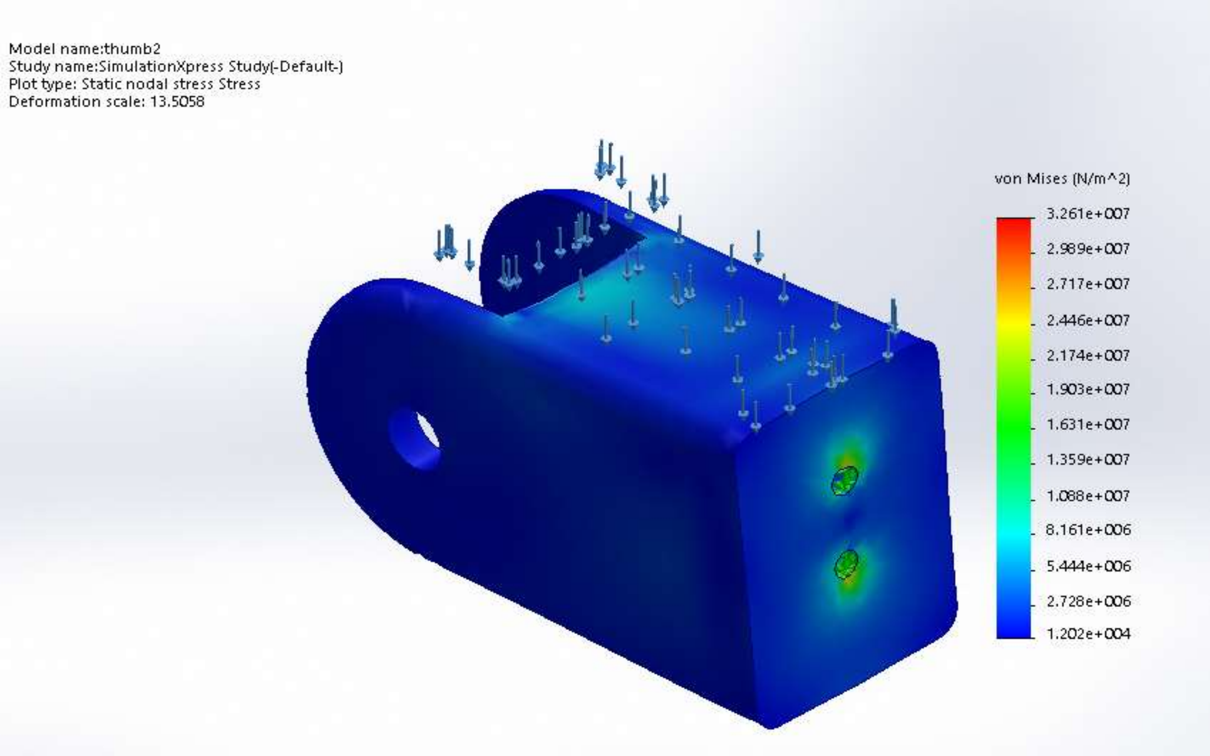


Figure 4-24. Thumb bracket Von Mises stress analysis (100 N).

Displacement is a maximum at the end of the thumb bracket when loaded as in Figure 4-25.

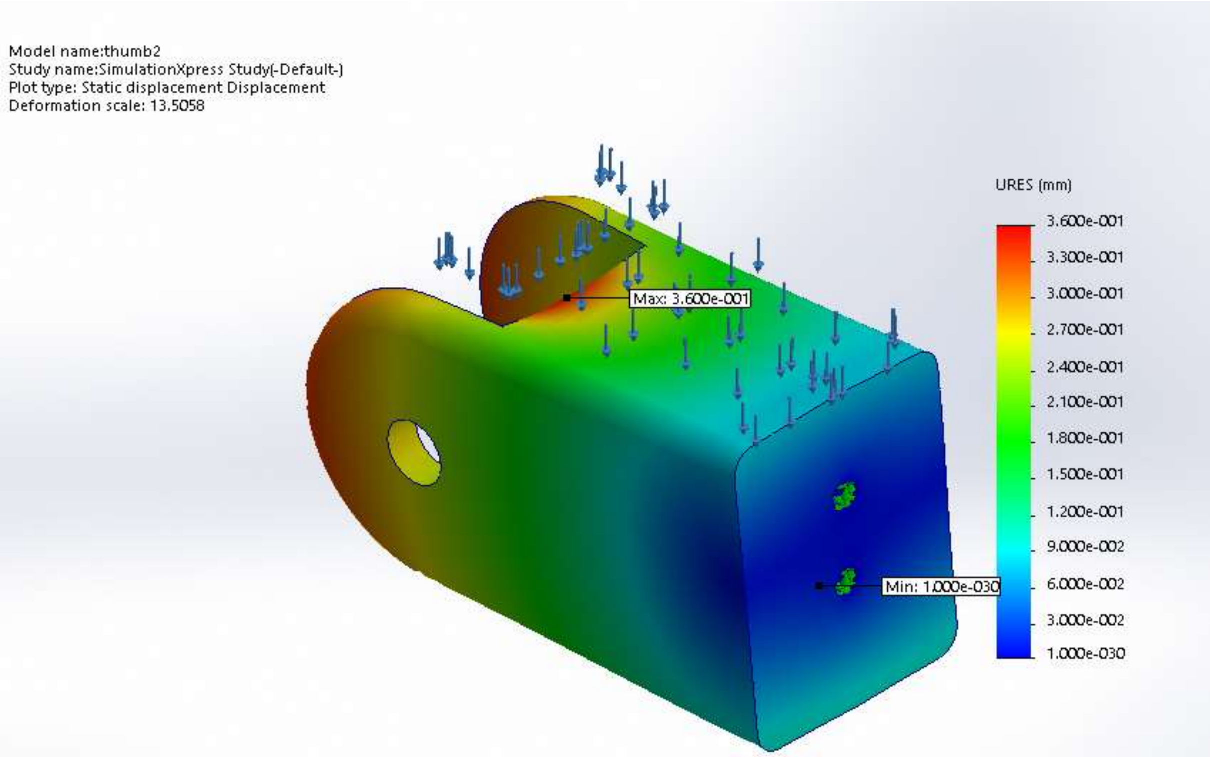


Figure 4-25. Thumb bracket displacement (100 N).

4.2.6.5 Covers stress analysis

The covers were loaded with 50 kg (500 N) and the FEA result of this shown in Figures 4-26 to 4-28. The covers will probably break at this maximum deformation as the ABS plastic is only 2 mm thick – also one needs to remember that this is an unlikely situation in the real design as the chassis plate is behind the cover giving it rigid support, nevertheless it is a good analysis to see what could happen in this scenario.

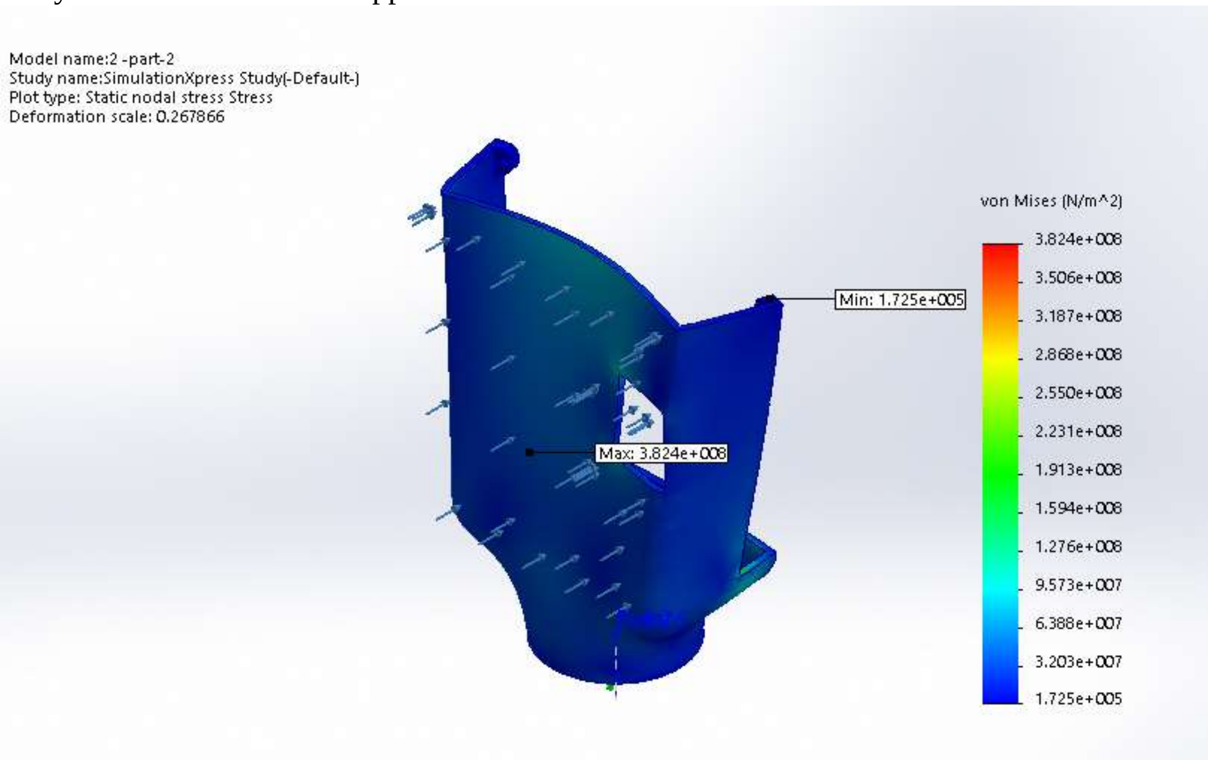


Figure 4-26. Von-Mises stress analysis (loading front cover with 500 N).

Displacement can be seen in Figure 4-37.

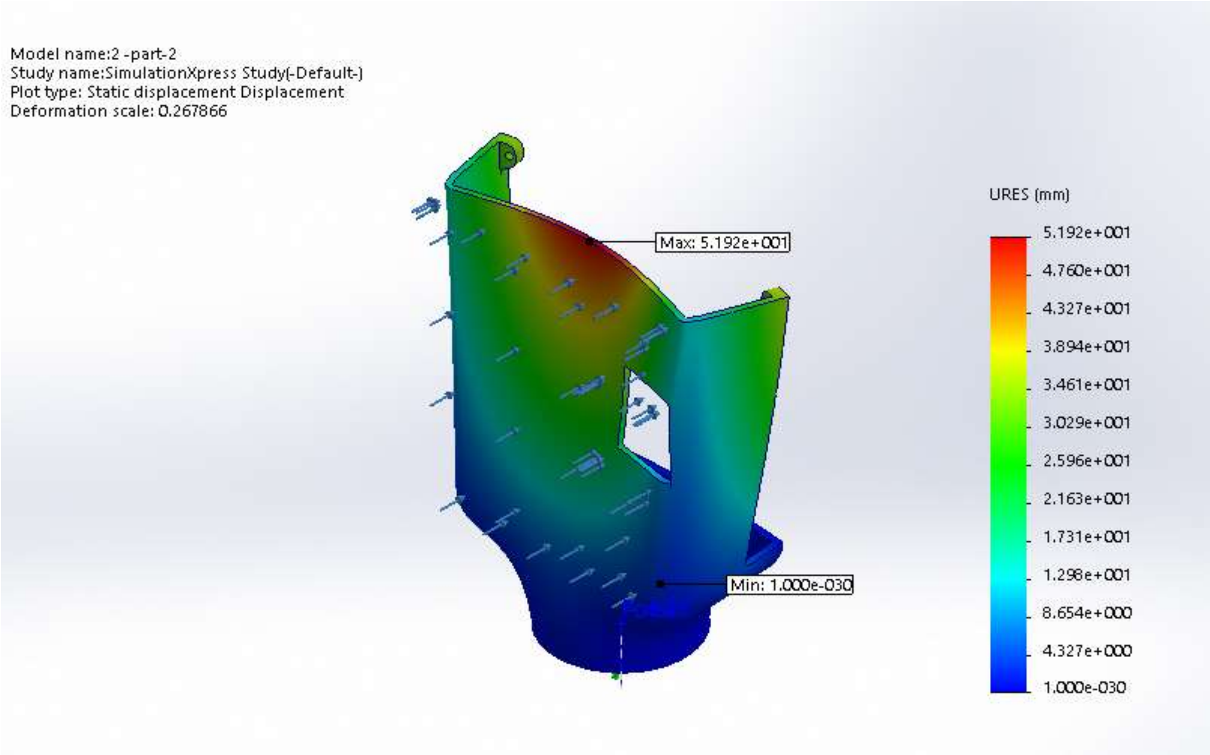


Figure 4-27. Displacement on front cover (loading with 500 N).

Deformation is a maximum in the middle of the cover if loaded as in Figure 4-28.

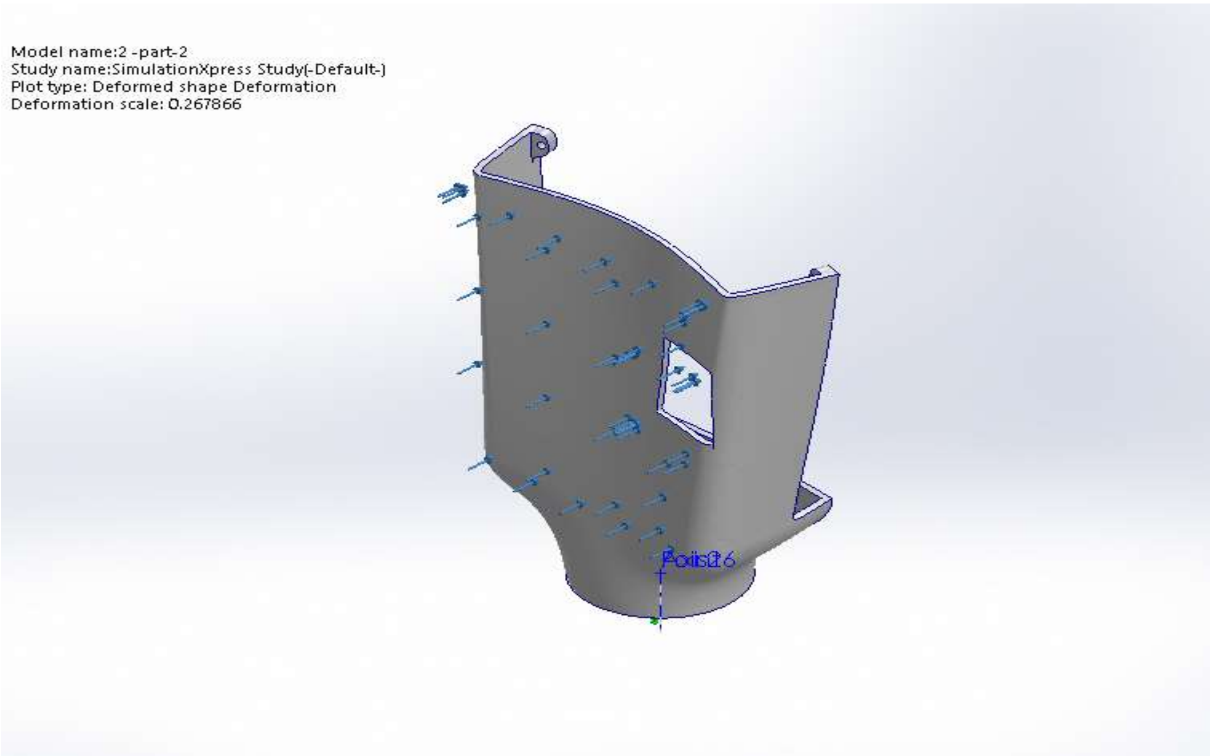


Figure 4-28. Deformation on front cover (loading with 500 N).

4.3 FINAL MECHANICAL DESIGN

For the final mechanical design the same chassis, fingers, socket and covers were employed as in the mechatronic design making the design modular and interchangeable. In the mechanical design springs, links and a lever were added. The proximal phalanx has two connection points at 90 degrees from each other with a linkage and spring from one keeping constant closing force on the finger. The pivot is connected to the other connection point at 90 degrees to the first and allows the fingers to open when a force is applied to the lever. The lever is connected via cable to a harness around the amputees shoulder (that is, the arm that is not amputated). This allows for a voluntary opening system, meaning that the hand is normally in the closed position and can be voluntarily opened.

For the final design of the mechanical hand it was decided to use tension springs rather than the clock spring. Tension springs can be much easily replaced and are more readily available.

The force that the springs exert in closing the fingers determines the grip strength of the mechanical hand. An advantage of this system is the springs can be swapped out at any time. A basic calculation for grip strength can be seen below based on the spring force. This is multiplied by three as there are three springs in the final hand closing the fingers, they connect to all of the fingers via the threaded rod, used as a shaft connection.

4.3.1 Spring calculations

Figure 4-30 shows the tension spring with the parameters in the design – d is the spring wire diameter, D_1 and D_2 the inner and outer diameters, D is the average diameter, L is the length of the spring.

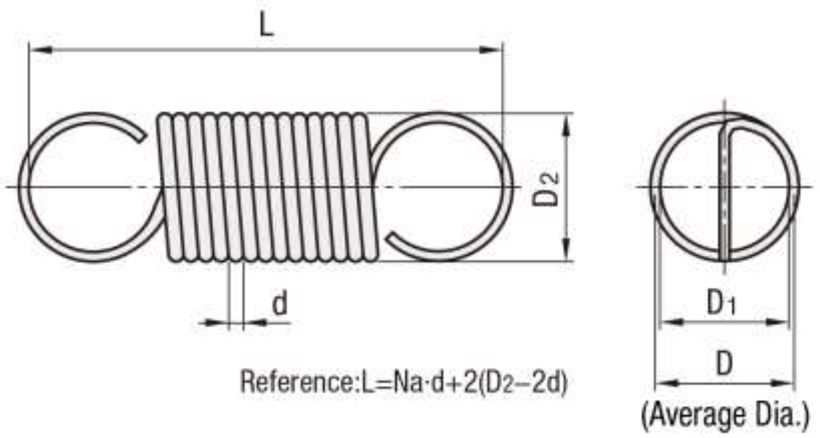


Figure 4-29. Mechanical design: tension spring calculation.

Tension springs are used in applications where tension is needed, their natural state is that they are at a rest length, when a force is applied they extend relative to the force. When designing for tension springs one needs to look at how much force is needed to be generated – in this case that will be to open or return the fingers to their natural closed position to allow for grasping.

The spring rate in the spring is measured in N/mm – this is the amount of force in the spring as it is stretched per millimetre. One also needs to know the initial tension of the spring, this is the energy required to just open the spring. A couple of parameters which pertain to the design of springs are the number of coils in the spring – the smaller the outer diameter of the spring the more force it can exert, the larger the outside diameter the less force it can exert, less coils mean a stronger extension spring whereas more coils mean a weaker extension spring. More coils mean less stress and more fatigue and less coils mean more stress and less fatigue. An extension spring is measured on its free length being the distance between the edges of the insides of the hooks, the length of the spring body, is the length of the spring itself. Hooks are used to transmit the force to the product.

Basically a method for determining a spring length would be as follows: In this case the spring length was also dependent on the space available in the back of the hand, the distance to the base of the chassis

1. Force – how much is needed to be generated in the application? The hand needs to pick up for example, 5 kg.
2. How much initial tension is there?

In this case the initial tension in the spring was worked out from formulae, a spring made from Piano wire was chosen with outer diameter (OD) 9.2 mm and wire diameter (d) 0.8 mm, the initial tension was calculated using the following formulae to be 102 MPa.

$$\tau_i = \frac{8FiD}{\pi d^3}$$

………..(4.2)

With *Fi* being the initial force needed to open the spring, D being the Outside Diameter of the spring in millimetre and d being the diameter of the spring wire

3. What is the spring constant?

The spring constant is the ratio of force over the displacement caused by it in the spring, F=kx is the spring formulae where k there is the spring constant. In other words the spring constant describes how much force in Newton’s is increased per millimetre the extension spring length is changed or drawn out.

$$R = \frac{G}{8}.\frac{d^4}{D^3.n}$$

……........(4.3)

Where
R is spring constant;
G is modulus of elasticity;
d^4 is wire thickness to the power of 4;
D^3 is outside diameter to the power of 3, and
N is active coils

In this case the spring constant was calculated as 16 N/mm, therefore the force of the spring increases by 16 N for every millimetre it is opened – or 1.6 kg's approximately.

For three springs in this case it gives a theoretical maximum force of 4.8 kg's that the hand can grasp.

Table 4-2. Spring calculation.

Extension spring calculation:		
wire diameter (d)	0,8	
Outside Diameter (OD)	9,2	
hook radii	8	
Force	156,96	
D = OD-d	8,4	
C=D/d	10,5	
Kb =(4C+2)/(4C-3)	1,128205128	
Spring length L0	33	
G (MPa x10^3)	793000	
E (MPa x10^3)	207000	
Nb	32	
Na=Nb+G/E	35,83091787	
k=(d^4*G)/(8*D^3*Na)	1,911821567	N/mm
Maximum distance travelled	8,3	mm
Body length		
Fmax (N)	15,86811901	
Fi (N)	1,7	
The deflection under the service load is:Ymax	7,410795678	mm
Spring length becomes	40,41079568	mm
Uncorrected initial stress:		
Initial stress = $8FiD/\pi d^3$	71,02289335	MPa
Shear stress under service load	662,9410141	N
Factor of Safety		
Ssy = 0,45(1045)	470,25	
Safety factor	1,409762922	

The concept of the lever arm has been employed in the lever/pivot system, thus there is a small mechanical advantage which reduces the amount of force required by the amputee to open the hand. This can also be adjusted by attaching the cable at different drilling points on the lever.

A final drawing of the exploded mechanical hand can be seen in part 3 of the appendices, one can see how the various modular mechanical parts fit together. Figure 4-30 shows the design in 3D CAD.

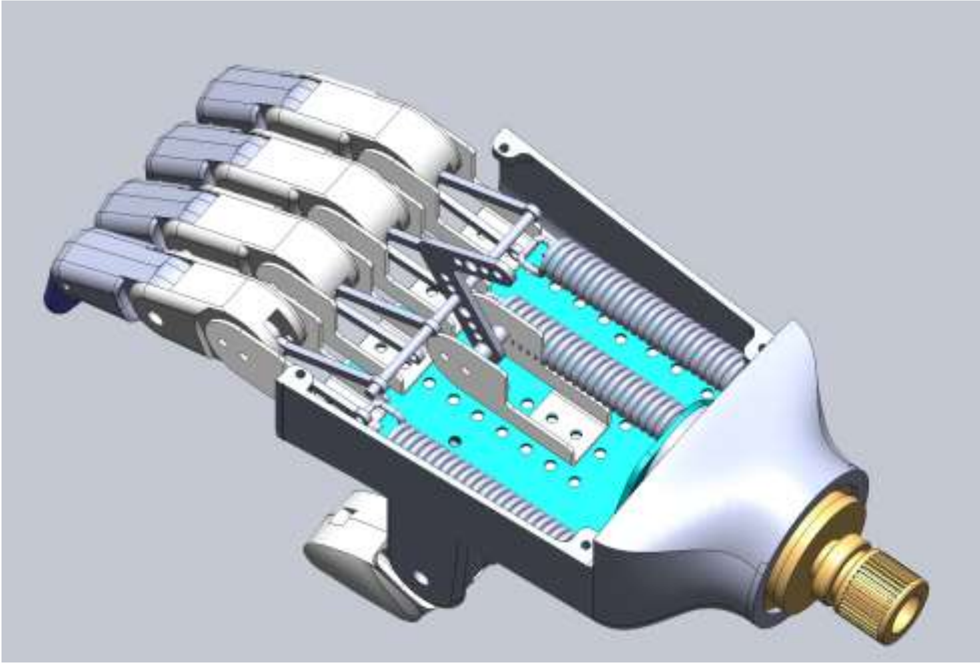


Figure 4-30. Final mechanical design.

4.3.2 Final design assembly: mechanical hand

For the final design assembly of the mechanical hand the following procedure can be followed.

Finger assembly

1. Bolt stainless steel finger hinge joints to hand main stainless steel chassis.
2. Bolt actuator to finger proximal phalanx.
3. Assemble distal finger section and fingertip and connect stainless steel linkage
4. Connect this assembly to finger proximal phalanx with 15 mm bush or pin (screw each side).
5. Pin proximal phalanx to hinge joint via M4 countersunk screws each end.
6. Connect linkage to hinge joint via M3 20 mm countersunk screw and M3 locknut.
7. Complete this for each finger starting from one end of the chassis.
8. For the pure mechanical design add two linkages to the fingers to the holes at the base of the fingers which are opposed at 90 degrees.
9. A hinge is bolted to the chassis and using the same pin the lever is attached to the hinge.
10. Once all fingers and their linkages have been assembled, through one set of the linkages an M3 rod is inserted which also passes through one of the holes of the lever, this allows for the opening and closing of the fingers.
11. To the other set of linkages tension springs are added which attach to the base of the chassis via eye hooks.

Cover assembly:

1. The front palm cover should be added once the initial thumb part is connected.
2. The rear cover is screwed into the front cover using M3 bolts.

Thumb assembly:
1. Assemble the thumb by bolting the main 3D printed thumb part to the chassis using M3 bolts and locknuts.
2. Assemble the thumb tip part by sliding the pin through the aligned thumb tip and main thumb part and screwing in the countersunk M4 bolt on both ends of the pin. The thumb can be fixed with an M3 bolt if necessary.

Figure 4-31 shows the mechanical hand test setup, for the test two tension springs were used to keep the fingers in a closed position. The fingers are connected together by a linkage on each finger which connects to a threaded rod connected to the lever arm. The hand is opened by pulling on the cable.

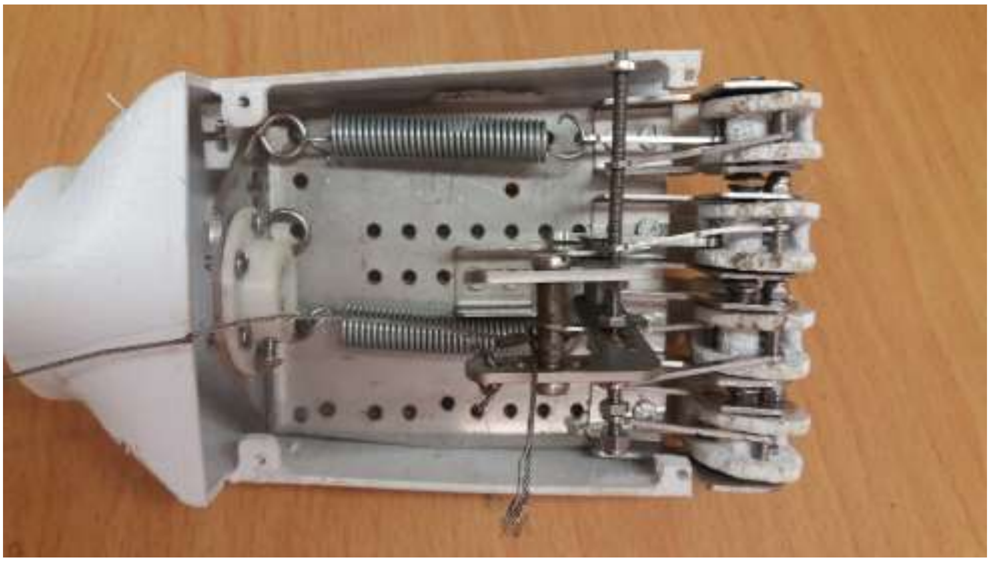


Figure 4-31. Final mechanical hand test setup.

Figure 4-32 is side view of the hand.

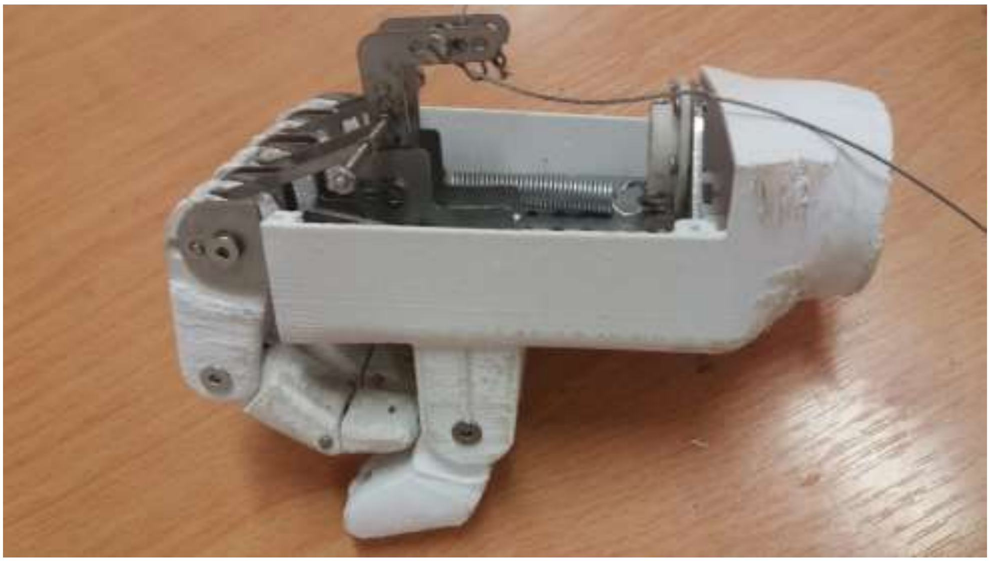


Figure 4-32. Final mechanical hand test setup.

4.3.3 FEA on final mechanical design

For the mechanical hand the 1.6 mm aluminium chassis was not sufficient and it experienced a large displacement and deformation when the springs were added to the setup. It was then decide through practical experience and proved through FEA analysis that it needed to be increased to 2 mm thickness and using stainless steel material. One can see in the next Figures. 4-33, 4-34 and 4-35 the results of loading the stainless steel chassis with 500 N and the reduced Von-Mises stresses and displacement as compared to the aluminium.

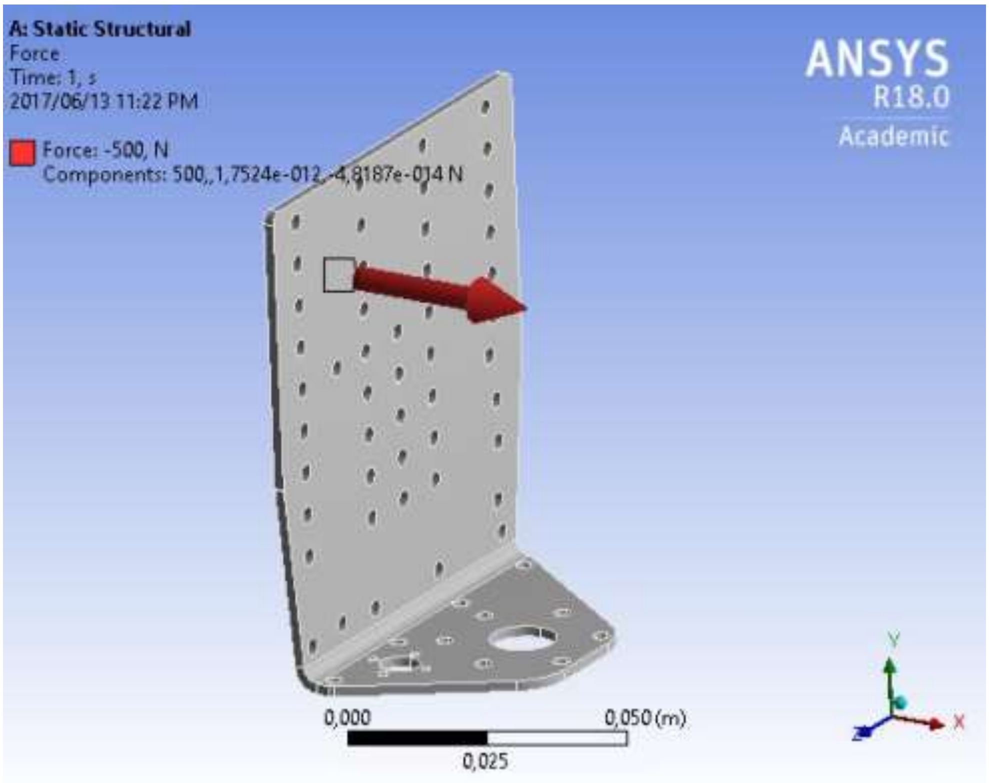


Figure 4-33. Loading of stainless steel chassis with 500 N.

Figure 4-34 shows the deformation caused by the loading. This is less than 12 mm in the maximum case. The loading is an exaggeration of the loads that would be used with this hand.

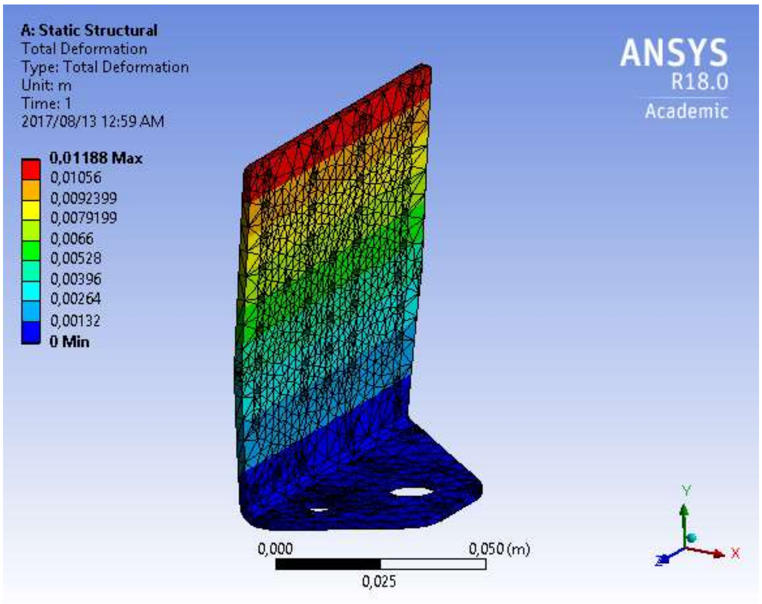


Figure 4-34. Deformation caused by static loading on 2 mm Stainless steel chassis.

A static stress distribution result of the loading can be seen in Figure 4-35, the stresses are at a maximum where the chassis is supported.

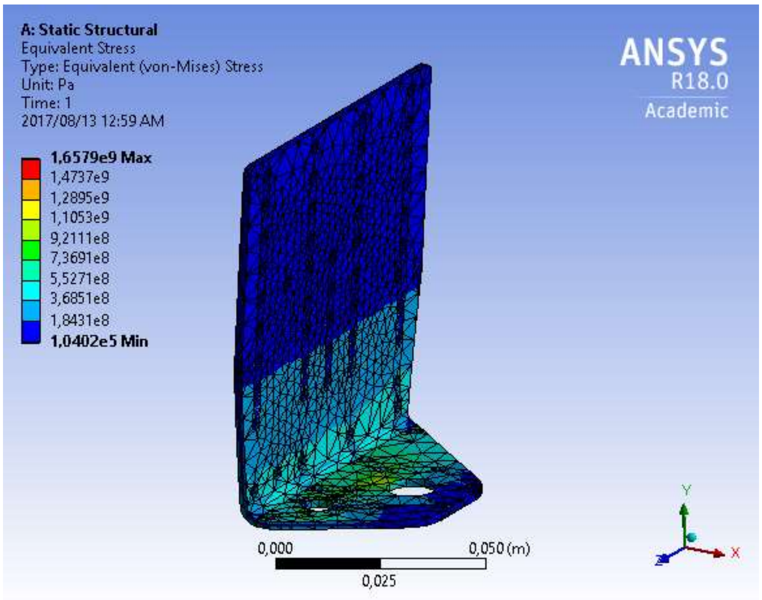


Figure 4-35. Stress distribution caused by static loading on 2 mm stainless steel chassis.

4.3.3.1 Finger stress analysis

Figures 4-36 to 4-40 show the final finger design more clearly and the stress analysis on the fingers if one were pinned at one and loaded with 15 kg individually. Here it was taken that the second hinge joint was also fixed allowing one to see the overall effect of loading on Von-Mises shear stress and displacement. One can see that the maximum Von-Mises stress is below the stress of the material with this loading condition, also the deflection is quite low at 4 mm at the tip in Figure 4-38 but this could cause slight damage. The effect on the safety factor is shown in Figures 4-39 and 4-40 with the minimum being at the pin joint – this is where the design is most likely to fail although in reality much of the load would be carried by the linkage whose effect is cancelled out in this setup.

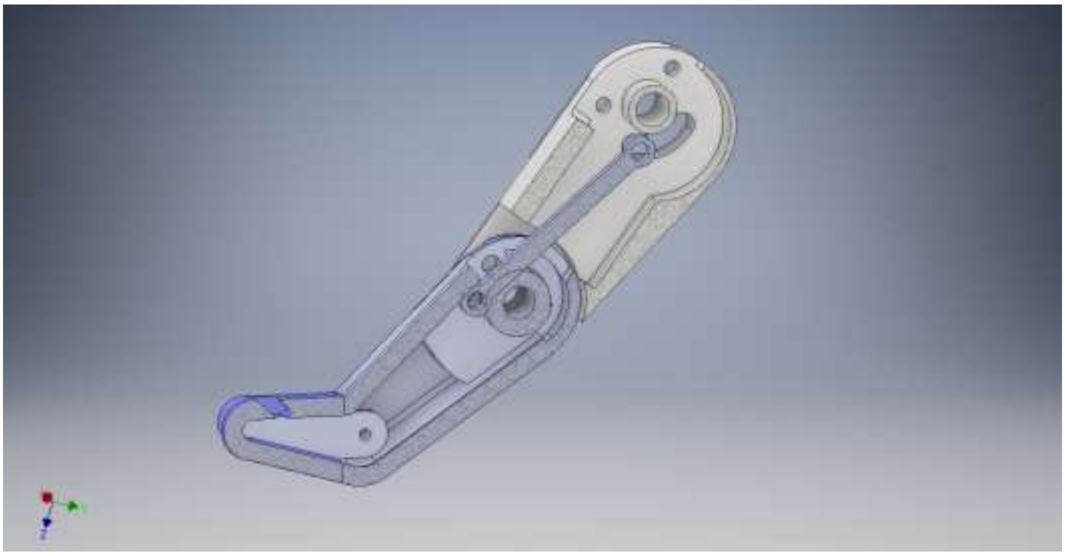


Figure 4-36. Cut away of finger.

The finger is meshed with the mesh settings as shown in Figure 4-37. One can also see how the fingertip is loaded with the force of 150 N on the fingertip extremity.

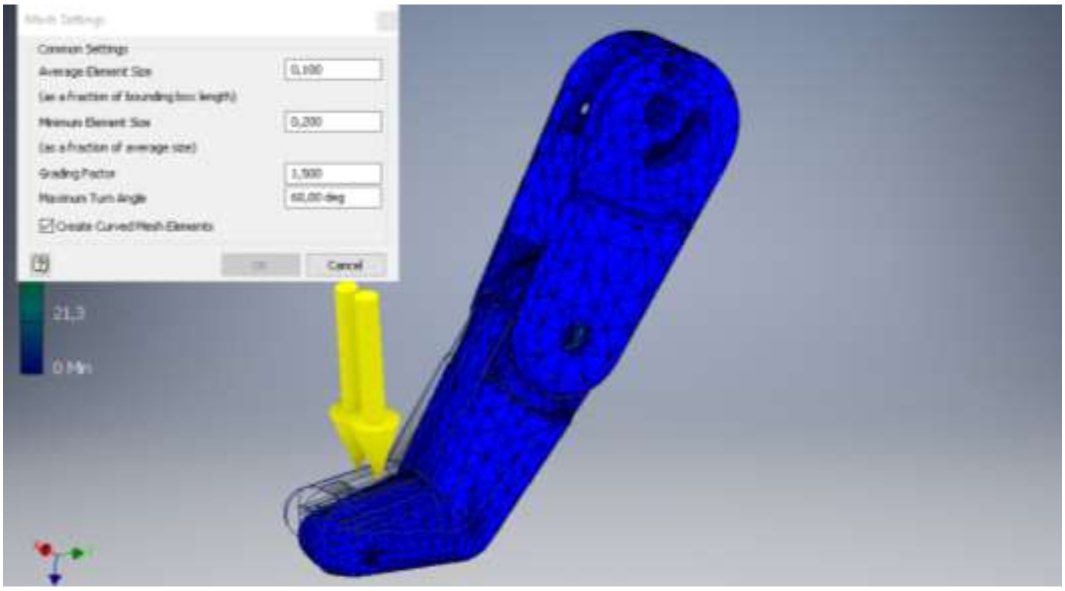


Figure 4-37. Finger mesh analysis.

Figure 4-38 shows a stress distribution cut away of the finger – the stress distribution is at a maximum around the pin joint of around 21,3 MPa for the loading of 150 N, the pin joint is made of steel so this should be safe, failure will occur in the ABS plastic if the stress is greater than 40 MPa or so, this represents a safety factor of around 2.

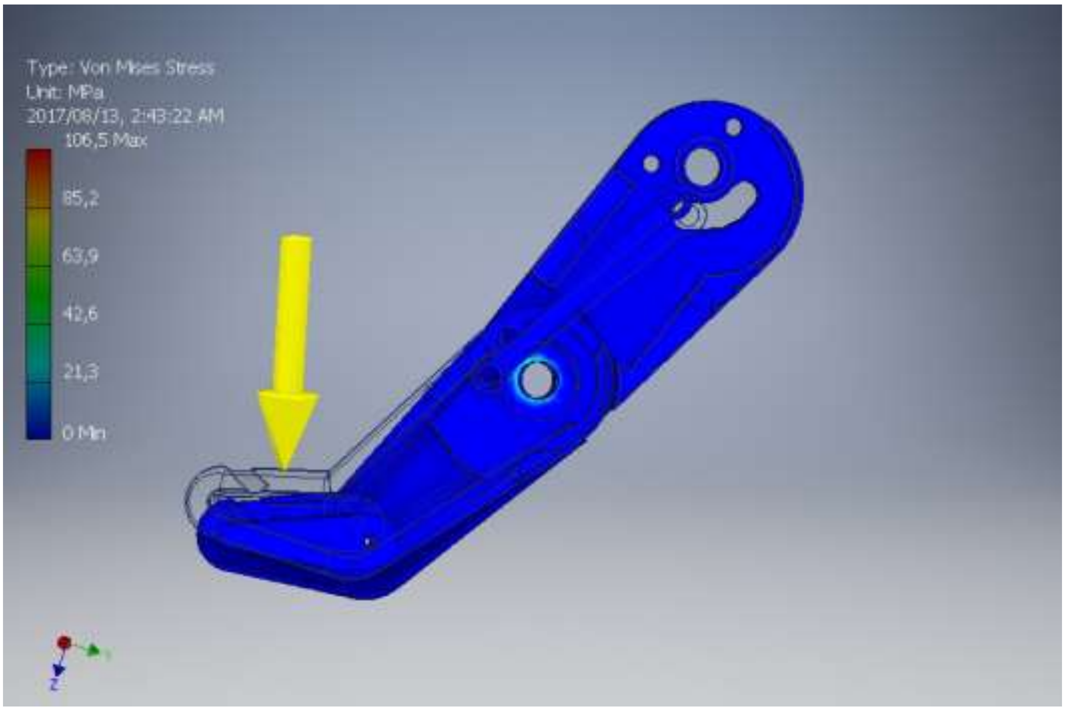


Figure 4-38. Finger Von-Mises stress analysis (loaded with 150 N).

Figure 4-39 shows the displacement on the finger being a maximum at the fingertip – where it is loaded. The setup here should allow for flexion up to a point with the ABS plastic, it is a maximum of 4,406 mm at the fingertip.

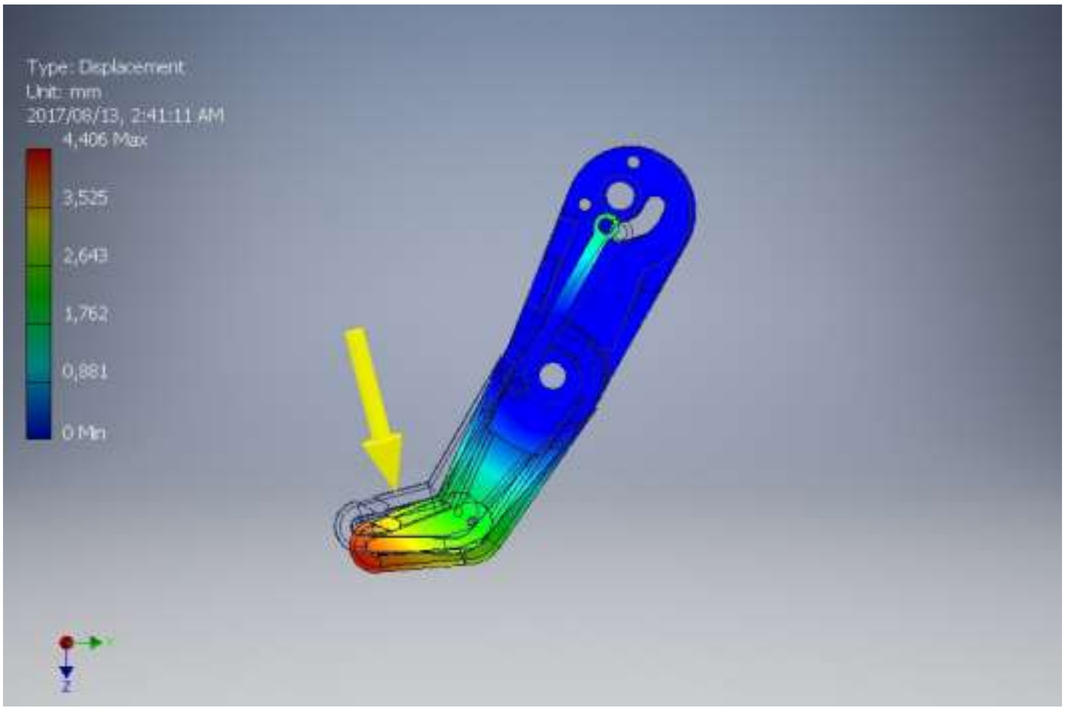


Figure 4-39. Finger displacement (loaded with 150 N).

Figure 4-40 shows the safety factor distribution for the loaded finger.

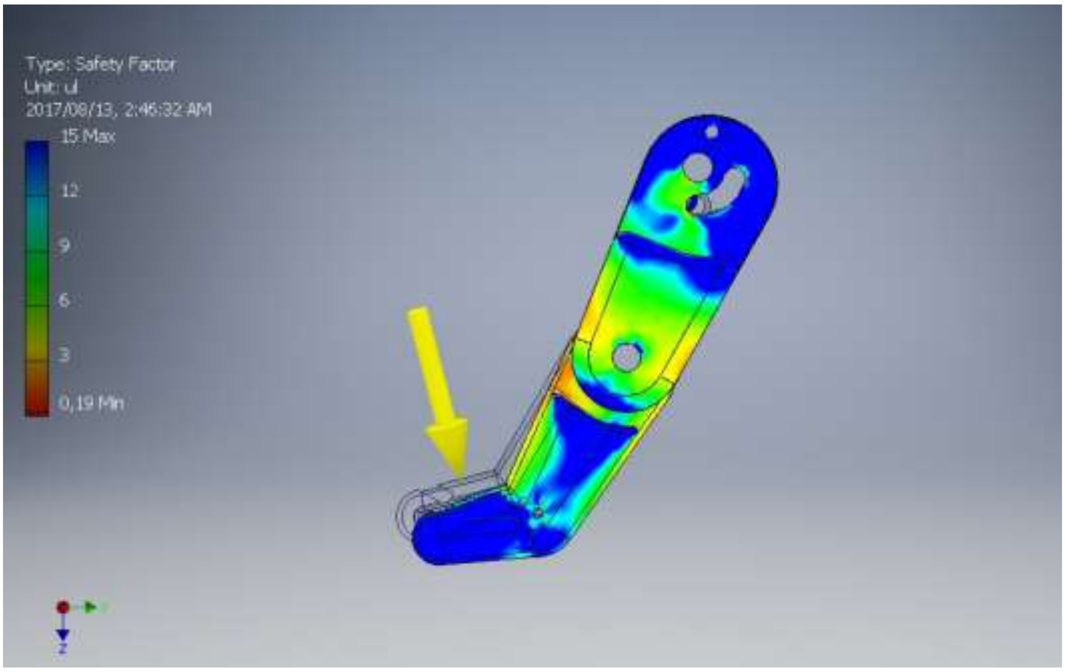


Figure 4-40. Finger safety factors (loaded with 150 N).

Figure 4-41 shows a cut away of the finger with the safety factors at a minimum around the pin joint. The pin joint was constrained in this setup hence it is the most likely place for the finger to fail.

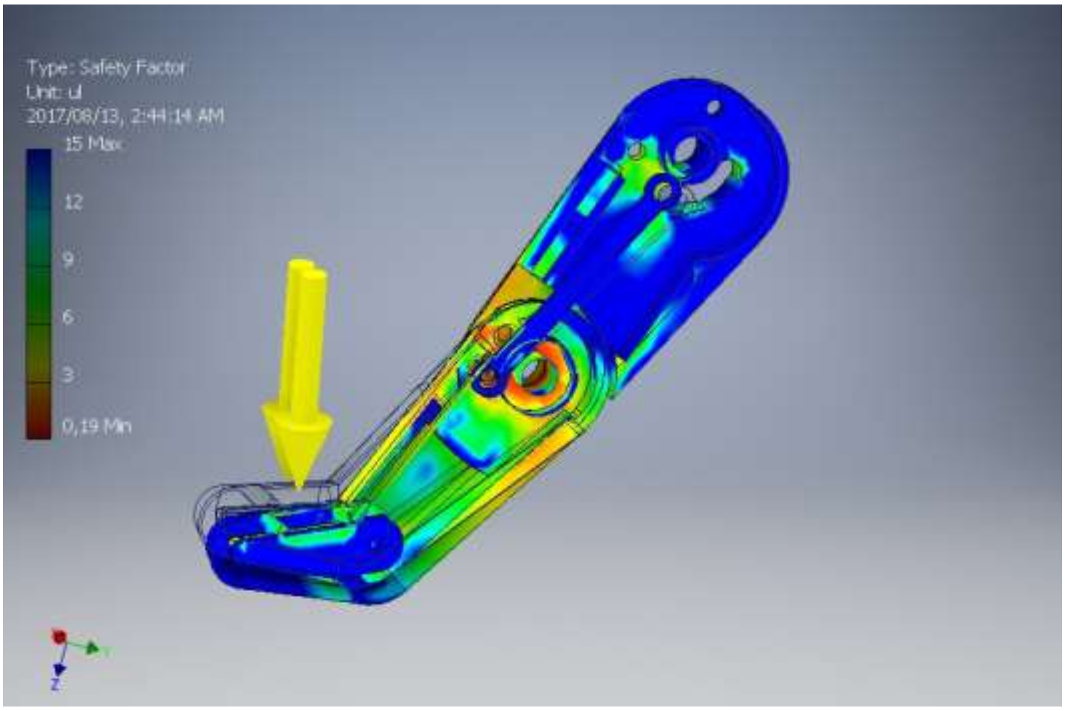


Figure 4-41. Finger cut away safety factors (loaded with 150 N).

4.4 FINAL MECHATRONIC DESIGN

The final mechatronic design would incorporate the electronic control system (motor and Arduino board), chassis, motors, finger brackets, thumb, and covers.

4.4.1 Electronics and control system

For the final design it was decided to go with separate EMG board coupled with Arduino M0 microcontroller external to the hand, with a motor control board coupled to Arduino M0 microcontroller built into the hand. The idea to separate EMG and its microcontroller and motors and their microcontroller makes sense as the processing for the EMG signals can be done externally and fed into the hand as it is done in reality with the processing being done in the human mind fed to the muscles of the human hand. This posed design constraints as the motors as well as motor control board and microcontroller needed to be designed into the hand unit along with the motors driving the fingers and thumb.

Sensory system: The hand has been designed to incorporate pressure and temperature sensors in the finger tips with a cut out in the finger tips although these were not tested in the final testing.

4.4.2 Final design assembly

Throughout the design process testing was carried out on the hand and was quite crucial to determining for example the positioning of the actuator connection points on the fingers. Although this could be done in the CAD system there was some discrepancy when opening and closing This is an advantage of 3D printing in that a model can be fairly rapidly printed and prototyping can be performed, and allows for trial and error testing. To give an example, to determine the position of actuation holes could be drilled and the position tested by moving the actuator.   This was also done to determine the position of the linkage to allow the fingers to close correctly at 90 degrees to their final resting position with the tips on the palm of the hand. This was finally worked out in the CAD software though, with the position being determined on the design placing the finger in its final position and modifying the geometry around that, to have the finger length consistent with the linkage final position.

Experimental testing was performed before making final components of the hand such as the cover, the thumb position was also determined based on testing as well as CAD design to determine the optimum position relative to closing of the index finger. This affects the grip of the hand, how the hand will close and what can be gripped. The final position was determined thus.

The benefit of a modular hand is thus seen in the experimental process as parts can be swapped out thanks to the drillings on the chassis, much like on a Meccano set parts can be interchanged. An exploded view of both hands can be seen in Appendix C. During the experimental testing assembly of the final design the process can be explained as follows:

Finger assembly

1. Bolt stainless steel finger hinge joints to hand main aluminium chassis.
2. Bolt actuator to finger proximal phalanx.
3. Assemble distal finger section and fingertip and connect stainless steel linkage.

4. Connect this assembly to finger proximal phalanx with 15 mm bush (screw each side).
5. Pin proximal phalanx to hinge joint via M4 countersunk screws each end.
6. Connect linkage to hinge joint via M3 x20 mm countersunk screw and M3 locknut.
7. Connect PQ12 linear actuator to chassis using connecting bracket bolted to the chassis using M3 locknut.
8. Complete this for each finger starting from one end of the chassis.

Thumb assembly
1. Connect distal thumb part to actuator using M3 x 15 mm countersunk screw in bolt hole provided.
2. Pass actuator through the space provided in the proximal thumb part.
3. Connect thumb proximal part and actuator using M3 x 20 countersunk screw though the bracket.

Wrist motor assembly:
1. Connect Faulhauber DC motor to chassis using M1,6 mm x 10 mm screws, 4 off.
2. Connect 32 tooth gear to gear support and prosthetic wrist bracket.
3. Press bearing into bearing support and fasten this to the underside of the chassis in the 8 holes provided with M3 x 15 mm countersunk screws.
4. Insert brass tube through bearing and gear, and slide this whole assembly through the chassis plate.
5. Connect gear onto motor via 3 mm grub screw such that the motor presses up against the gear holding the chassis in place.

Motor control assembly
Connect the Arduino microcontroller board to the motor control board and fasten these to the aluminium chassis using the holes provided and the 3D printed 21 mm standoffs.

Figure 4-42 shows the final design model in CAD and Figure 4-43 shows the final model used for testing.

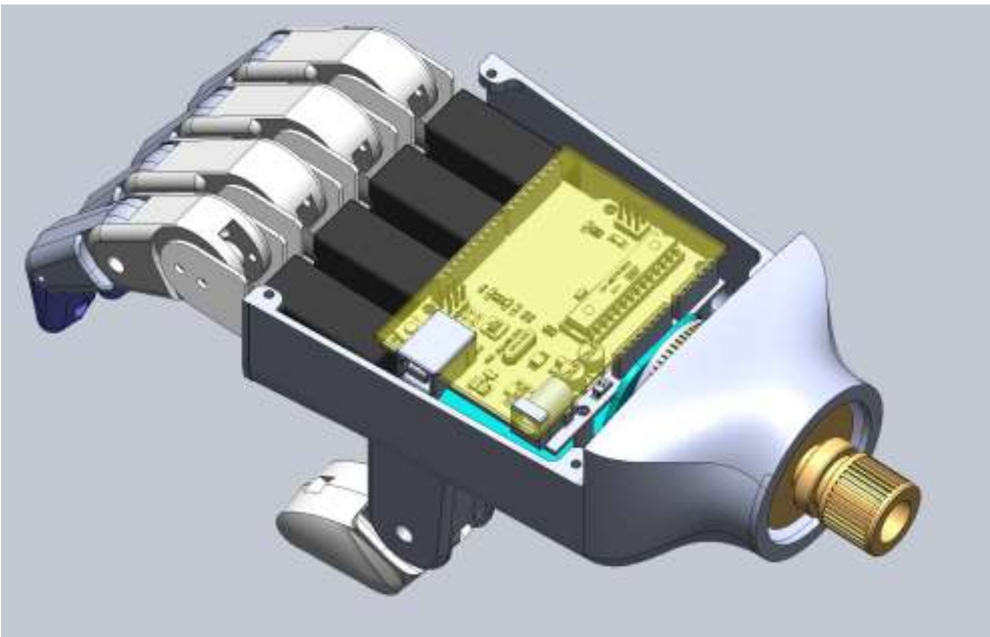


Figure 4-42. Final mechatronic design layout.

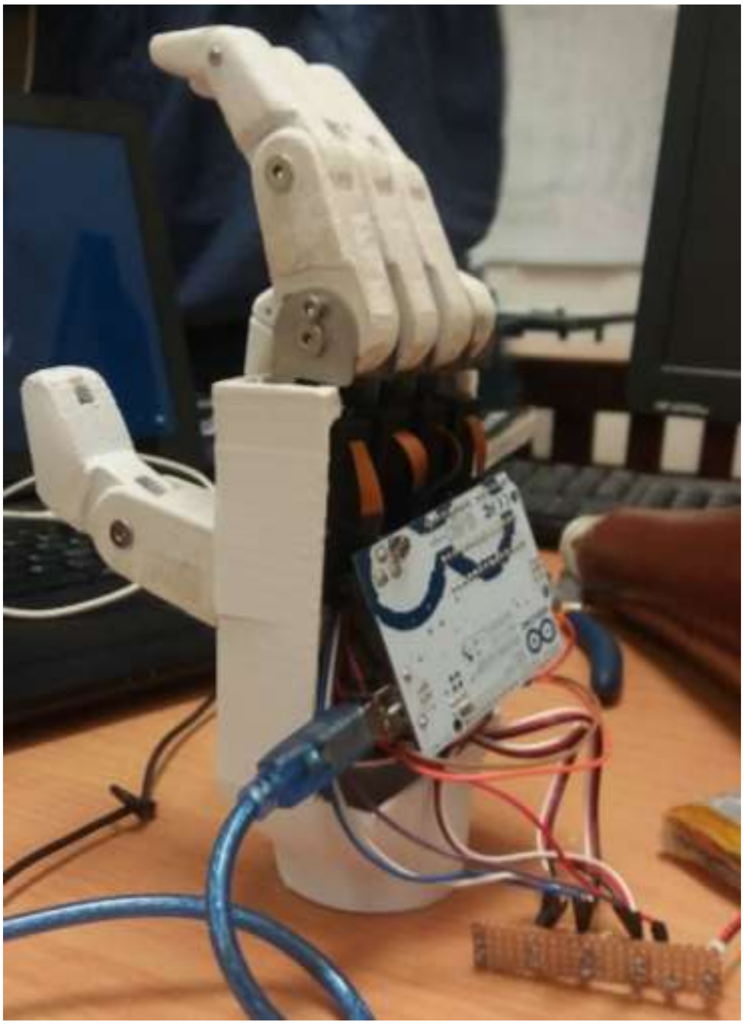


Figure 4-43. View of final mechatronic design test setup.

4.5 CHAPTER SUMMARY

The final generic shell design for the touch hand 3 which can be interchanged for mechanical and mechatronic hands has been described in this chapter. The mechanical design has been documented including spring calculations, FEA stress analysis on parts, and mechanical design on the fingers and final design drawings and models have been documented here. The design has been finalised for testing.

5 BIOMECHANICS AND KINEMATICS

Biomechanics or mechanics is the science that deals with forces and their effects as applied to biological systems. Statics looks at the study of bodies at rest while dynamics is involved with bodies in motion. Newton's laws are applied in a study of the forces involved in magnitude, application and direction.

5.1 BIOMECHANICS OF THE HAND AND FINGERS

The arm can be simplified as a simple lever. A lever is a machine that consists of a rigid body that is capable of rotating about a point on itself referred to as a hinge or fulcrum. It amplifies force, with the ratio of output force to input force being known as the mechanical advantage of a lever. The human hand uses hinge, condyloid and saddle joints.

5.1.1 Static pulley tendon models

In the static tendon pulley models developed by Landsmeer (1960, 1962) tendon joint relationships are determined by spatial relationships between each other assuming the tendon is held securely against the articular surface of the proximal bone of the joint, this is a useful method of describing extensor muscles.

5.1.1.1 Model 1:

The tendon displacement is given by

$$x = r\theta \quad \text{(5.1)}$$

Where
x is the tendon displacement;
r is distance from joint centre to tendon;
θ is the joint rotation angle.

5.1.1.2 Model 2:

If the tendon is not held secure it may be displaced from the joint when the joint is flexed, useful in intrinsic muscles.

$$x = 2r \sin\frac{\theta}{2} \quad \text{(5.2)}$$

5.1.1.3 Model 3:

The tendon runs through a tendon sheath held securely against the bone allowing the tendon to curve smoothly around the joint.

$$x = \left[y + \frac{1}{2}\theta\left(\frac{d-y}{tan\frac{1}{2}\theta}\right)\right] \quad \text{(5.3)}$$

Where:
y is the tendon length to joint axis measured along long axis of bone;
d is distance of tendon to long axis of bone.

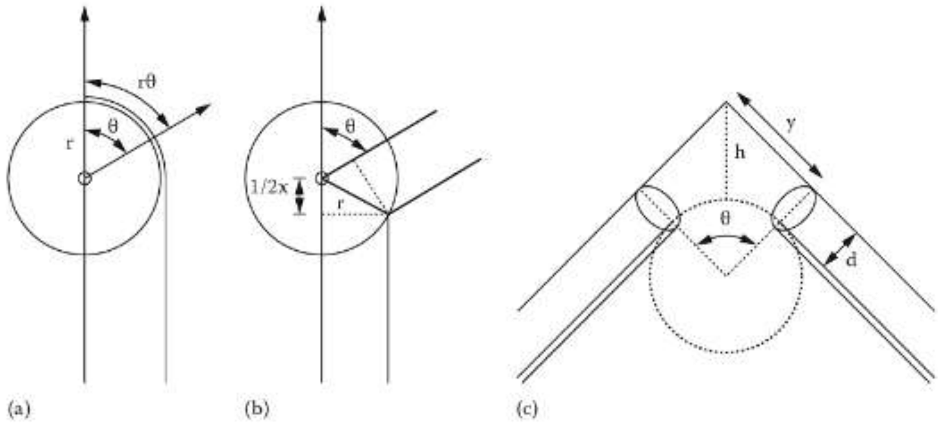


Figure 5-1. Landsmeer's tendon models (a) Model I (b) Model II (c) Model III.

Armstrong and Chaffin (1979) proposed a static model for the wrist based on Landsmeer's tendon model 1 and LeVeaus (1977) pulley friction models finding that when the wrist is flexed the flexor tendons are supported on the volar side of the carpal tunnel. When it is extended the wrist flexor tendons are supported by the carpal bones. The deviation of the wrist from the neutral position causes the tendons to be displaced against the walls of the carpal tunnel. Assuming the tendon sliding over a curved surface is similar to the friction forces involved in pulley wrap around the radial reaction force on the ligament or carpal bones, the radial reaction force can be described as:

$$F_R = 2F_T e^{\mu\theta} \sin\frac{\theta}{2} \quad \text{……………………………………………(5.4)}$$

Where
F_R is the radial reaction force;
F_T is the tendon force or belt tension;
μ is the coefficient of friction between tendon and supporting tissues, and
θ is the wrist deviation angle in radians.

The resulting normal forces are:

$$F_N = \frac{2F_T e^{\mu\theta} \sin\frac{\theta}{2}}{r\theta} \quad \text{…………………………………………(5.5)}$$

Where
F_N is the normal force exerted on a tendon, and
R is the radius of curvature around supporting tissues.

For small coefficients of friction this reduces to:

$$F_N = \frac{F_T}{r} \quad \text{…………………………………………(5.6)}$$

Therefore F_N is a function only of tendon force and radius of curvature. As the tendon force increases or radius of curvature decreases the normal force increases. This gives a basic understanding of the normal supporting force that can be calculated for the hand.

5.1.2 Dynamic tendon pulley models

A dynamic model (Schoenmarklin and Marras, 1990) extends the static model to include angular acceleration looking at a two dimensional study of flexion and extension. It looks at the resultant force exerted by finger bones on tendons at maximum angular acceleration. This looks at wrist motion but gives an indication of finger grip. Simply put the equation is:

$$F_t \times R = (M \times A_T + M \times A_C) \times D + I \times \ddot{\theta}$$

……………………………………(5.7)

Where
M is the mass;
A_T is the tangential acceleration;
A_C is centripetal acceleration;
F is the tendon force;
I is the moment of inertia of the of the hand in flexion and extension, and
$\ddot{\theta}$ is the angular acceleration.

Angular velocity is zero with the hand accelerating from a stationary position, resulting in a zero centripetal force, simplifying to

$$F_T = \frac{(M \times D^2 + I) \times \ddot{\theta}}{R}$$

……………………………………(5.8)

With

$$F_R = 2 \times \left(\frac{(M \times D^2 + I) \times \ddot{\theta}}{R}\right) \times sin\left(\frac{\theta}{2}\right)$$

……………………………………......(5.9)

Where
R is the radius of curvature of the tendon;
D is the distance between centre of mass of the wrist;
M is the weight of the hand;
θ is the wrist deviation angle.

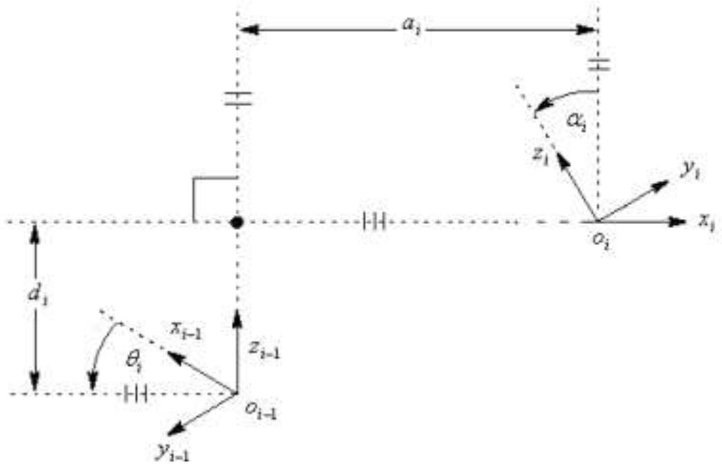
This equation for the resultant force shows that exertions of great angular acceleration and wrist angle results in greater resultant forces on tendons.

5.1.3 Hand finger kinematics

Dynamics is the study of forces and torques and their effect on motion whereas kinematics studies the motion of objects. A kinematic study of the finger joints allows one to calculate the exact position of the finger joints throughout their motion with respect to each other in reference frame at any instant. The finger represents a kinematic chain with 3 links and four degrees of freedom. The thumb was also modelled as a chain with 3 links and 4 degrees of freedom. Forward kinematics is a study mainly in robotics applications that is used to describe the end effector position or orientation given the joint co-ordinates.

5.1.3.1 Description of link and joint parameters

The Denavit-Hartenberg parameters are used to describe the four base parameters in the kinematic analysis of such finger systems, with two of the parameters defining the links and the two others describing their relation to other links. Each link has 2 directions of translation and 2 axes of rotation known as the link parameters. A frame of motion is attached to the end effector and the open chain is analysed individually using matrix notation.



Link

Figure 5-2. Denavit- Hartenberg linkage parameters.

Looking at Figure 5-3 we can define the link parameters as follows:
a_i is the distance masured along the common normal to both axes called link length;
$\propto_i$ is the twist angle , the angle between both joint axes measured orthogonally between I and (i+1) axes;
θ_i is the rotation about the joint axis know as the joint angle, and
d_i is the link offset or displacement along the same axis.

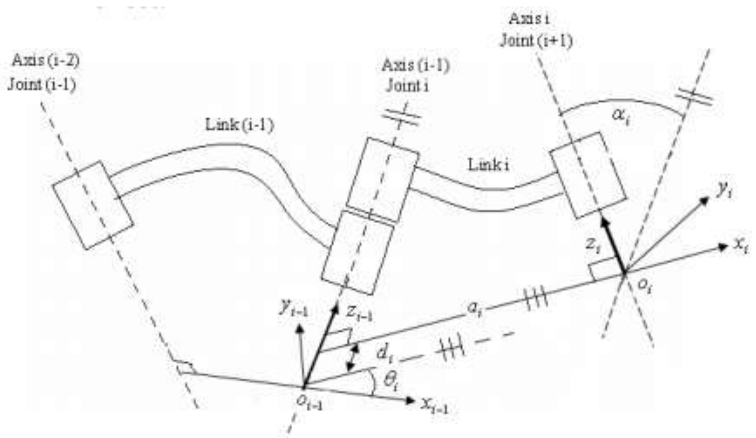


Figure 5-3. Denavit-Hartenberg joint parameters.

Link 1 is connected to two other links (i-1) and (i+1), links keep a fixed configuration between thejoints characterised by a_i (shortest distance along x axis) and $\propto_i$ (angle between joint axes z_{i-1} and z_i measured about x_i axis. d_i and θ_i are called distance and angle between adjacent joints and determine the relative position of neighbouring links.

The Denavit-Hartenberg convention is commonly used for selecting frames of reference in linkage applications. In this convention the position and orientation of the end effector are given by

$$H = Tn = T1^1T2^3T3^{n-1}Tn$$

……………………………...…………….(5.10)

^{1-i}Ti describes the finite motion from link i-1 to link 1
The frame transformation $^{i-1}T_i$ is expressed as

1. Rotation θ about z_{i-1};
2. Translation di along the z_{i-1}axis;
3. Translation a_i along x_i;
4. Rotation $\propto_i$ about x_i.

$$^{1-i}T_i = R(z_{i-1}\theta_i)T(z_{i-1}, di)R(x, a_i)T(x_i\alpha_i)$$

………..…………..(5.11)

The transformation matrix reduces to:

$$\begin{bmatrix} cos\theta_i & -cos\theta_i sin\theta_i & sin\alpha_i sin\theta_i & a_i cos\theta_i \\ sin\theta_i & cos\alpha_i cos\theta_i & -sin\alpha_i cos\theta_i & a_i sin\theta_i \\ 0 & sin\alpha_i & cos\alpha_i & di \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

………...….(5.12)

For a finger joint the Denavit- Hartenberg table denotes as below:

Table 5-1. Denavit-Hartenberg finger parameters table.

Link, i	a_i	α_i	d_i	θ_i
1	L1	0	0	θ_1
2	L2	0	0	θ_2
3	L3	0	0	θ_3

For the thumb joint it is simplified to two links as below in the neutral position

Table 5-2. Denavit-Hartenberg table parameters table.

Link, i	a_i	α_i	d_i	θ_i
1	L1	$\frac{\pi}{2}$	0	θ_1
2	L2	0	0	θ_2

5.2 KINEMATIC ANALYSIS

ADAMS Kinematic analysis was performed on the finger motion using ADAMS View 2016 to simulate the effects of the actuator force on the finger and also to better understand the kinematics of the design. Graphed outputs of various parameters can be viewed to see the various parameters through the finger motion. Figure 5-4 shows the geometric constraint setup in ADAMS where the forces, pinned joints and rotating joints were all setup. Accelerations were added in order to simulate the finger motion.

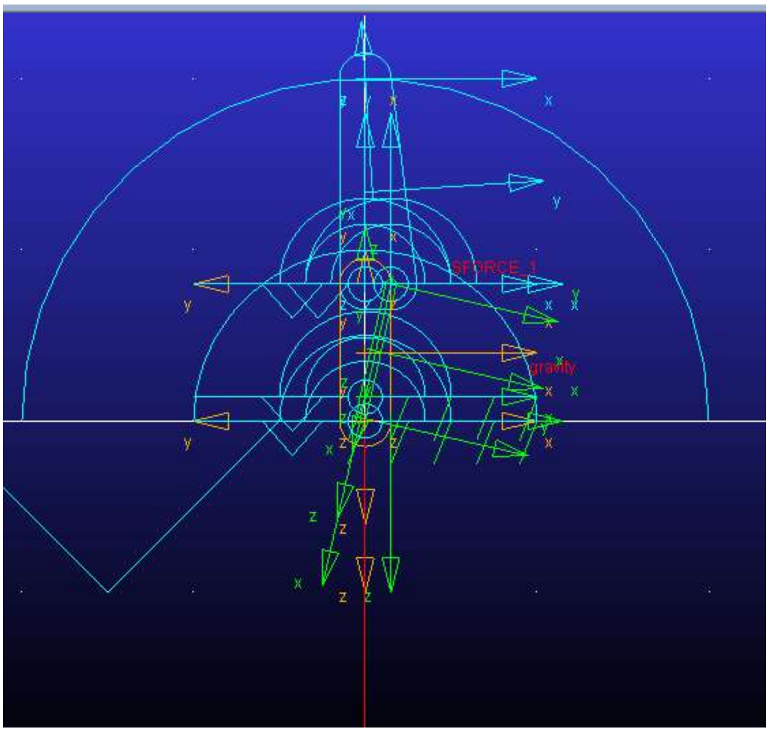


Figure 5-4. Finger constraint setup.

Figure 5-5 shows the result of the modelling, a graph shows the variables of angular velocity with respect to force (y axis) and time (x axis).

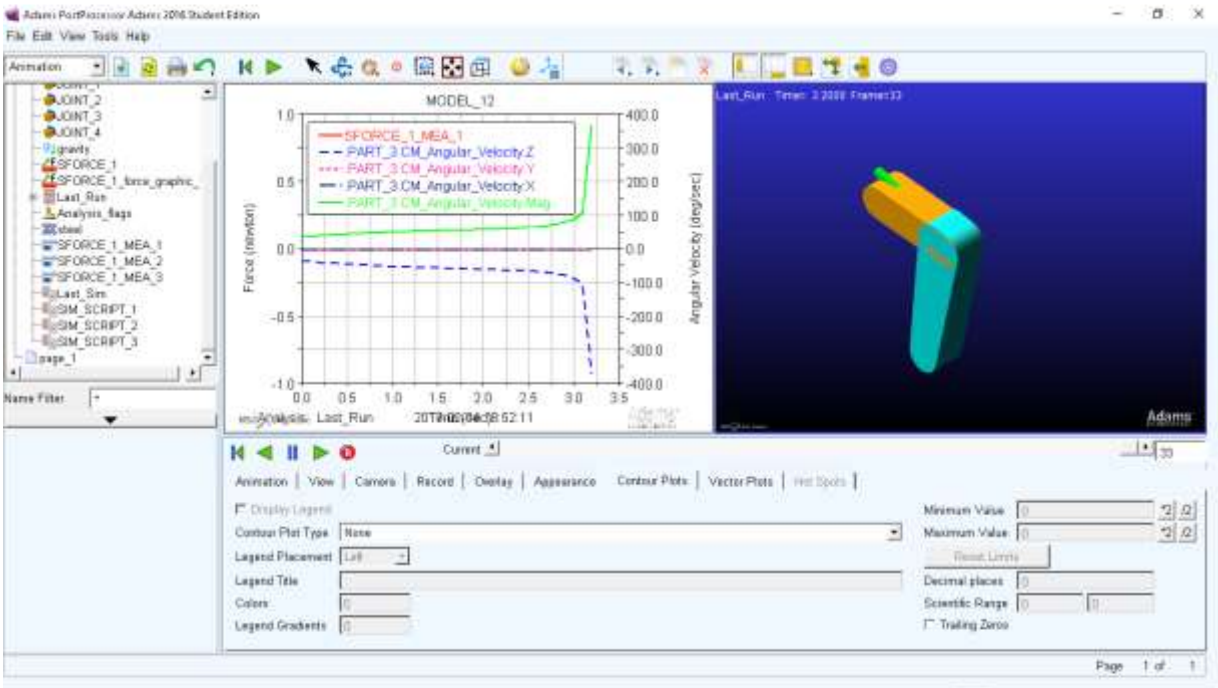


Figure 5-5. Finger range of motion modelling (ADAMS).

Figure 5-6 has added force and kinetic energy to the graphs and one can see for example how the kinetic energy of the fingertip is at its maximum close to the end of the finger motion, also at a maximum exerted force. ADAMS analysis allows for various parameters to be setup and measured and gives a realistic simulation of real world outcomes.

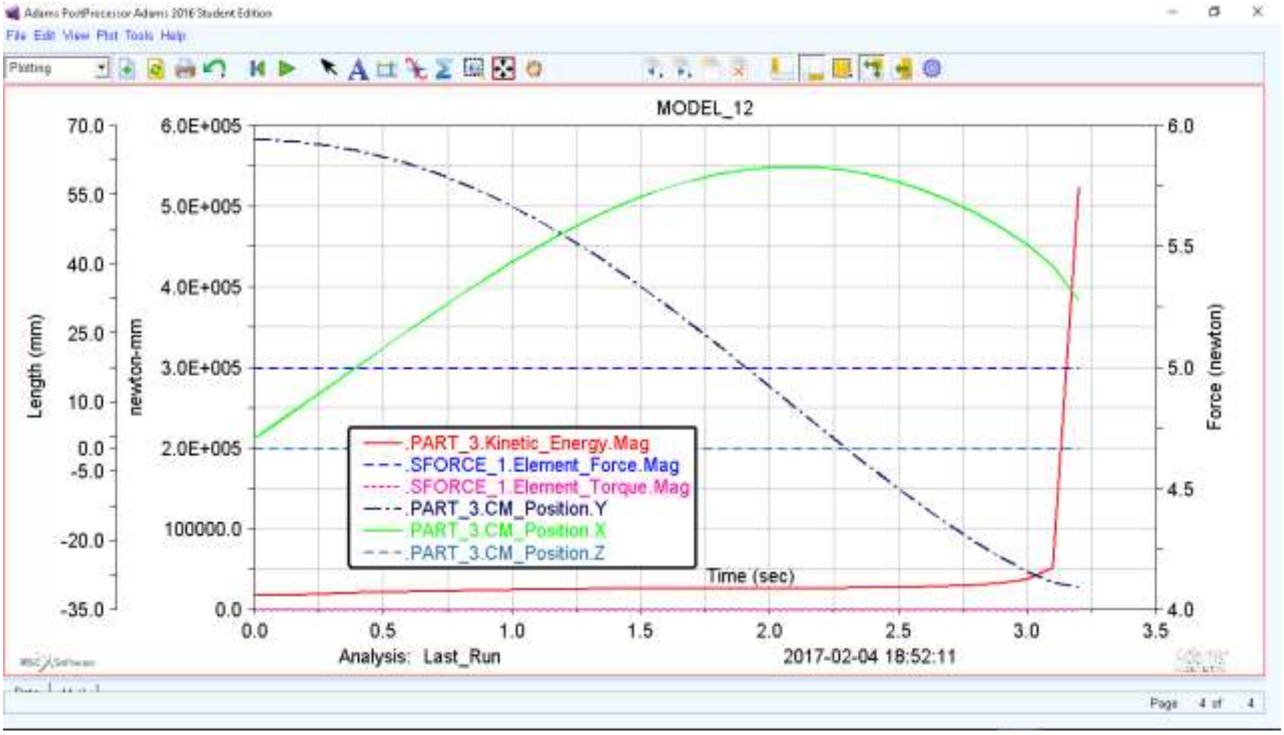


Figure 5-6. Finger plot: Displacement, force, and torque versus time for contraction (ADAMS).

Figure 5-7 is a screenshot in ADAMS showing the model of the finger next to the graphs of motion. One is able to view an animation of the finger motion while seeing the result of the graph for each moving element.

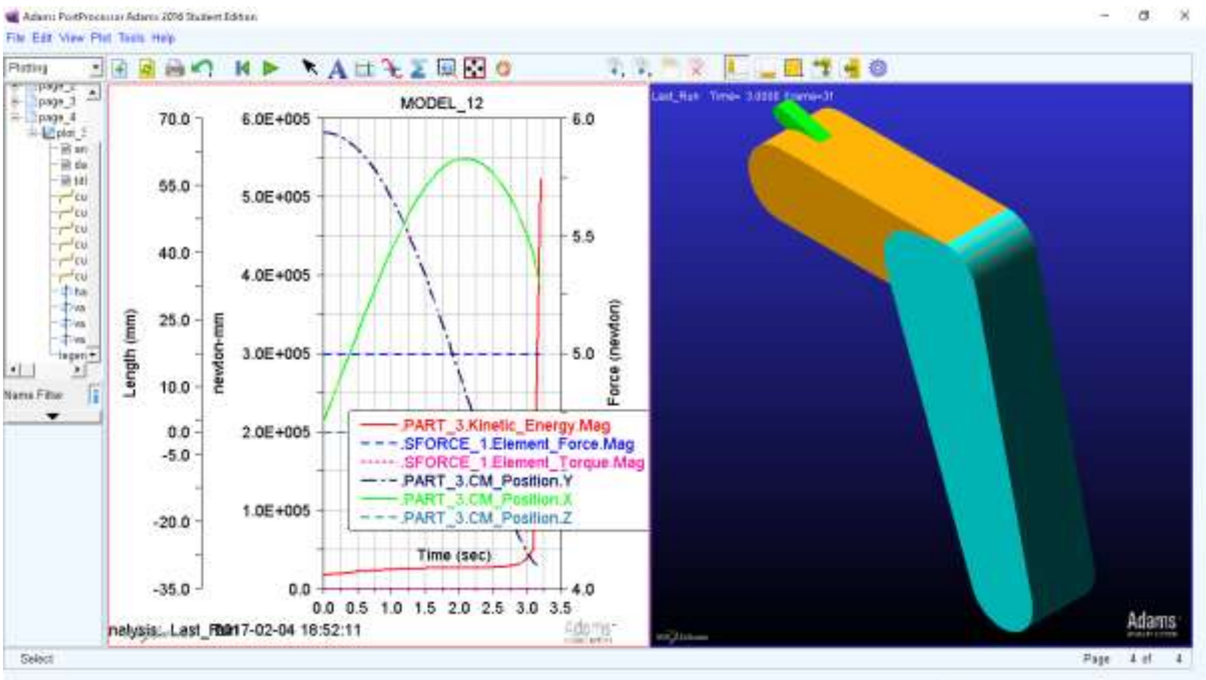


Figure 5-7. Finger displacement plots.

5.3 CHAPTER SUMMARY

This chapter has looked at both the biomechanical and kinematic analysis of the hand, mainly with and analysis of finger motion. Mathematical tendon models as well as kinematic ADAMS modelling have been looked at. Denavit – Hartenberg analysis has been done describing finger motion in matrix form. ADAMS kinematic analysis shows the results of the finger motion from which one is able to view the results of the different components of force, velocity and position for different moving components.

6 TESTS AND RESULTS

This chapter looks at the final deigns tests and their results. In order to test the hand it needs to be tested against a recognised test that human hands as well as prosthetic hands can be graded on. In this case the Yale Open hand tests and SHAP object tests seem to be sufficient for testing the hand.

6.1 INITIAL TESTS

To test the prosthetic hand a basic test has been compiled. It is not as comprehensive as the SHAP test but basic elements have been retained so that results can be compared between different prosthetic hands on the market and also such that the Touch hand 3 can be compared to the previous two Touch hands and similarly to the prototype.

Tests developed and measurements taken were also similar to those taken from the IEEE Spectrum Robotics and Automation Magazine, Vol. 24 No.1 March 2017 ISSN 1070-9932 http://www.ieee-ras.org/publications/ram, Yale Open hand Project: Optimising Open- Source Hand designs for Ease of Fabrication and Adoption, pgs. 34-40. The Yale Open hand is a simple open source hand with 3 actuated "fingers" that has been made available for research purposes. In this paper rudimental tests were performed using a few household items following an open-loop grasping evaluation whereby the hands were tested in order to compare results. In the case of this research this is done without the use of a robotic manipulator but follows the same basic procedure. In each test the hand is initialized with its palm directed downward at the table and oriented such that it was aligned with the objects principle axis. The hand was then lowered towards the object until the palm enclosed the object or the fingers were obstructed by the table during grasping closure. The hand then was given the instruction by EMG or manually to close and then attempt to lift the object. After lifting, if the object remained in the grasp the hand was reoriented 90 degrees such that its palm axis now pointed downwards. The hand was then rotated back 180 degrees to determine the grasp quality and its ability to hold the object in different orientations.

6.1.1 Designing tests for a prosthetic hand

The true test of a prosthetic hand is that it is able to manipulate basic everyday objects in the same way that a human hand would. There have been some tests developed to assess the functionality of the human hand, one being the Southampton Hand Assessment Protocol (SHAP). This is a clinically validated hand function test developed by Colin Light, Paul Chappell and Peter Kyberd in 2002 at the University of Southampton which was originally developed to assess the effectiveness of upper limb prostheses. The SHAP test is a timed test that looks at the manipulation of 6 abstract objects and 14 Activities of Daily Living (ADL). In the SHAP test the person is required to time themselves performing the various tests. A normalised result of the times taken to perform the various activities is used to compare and rate the user's performance. Figure 6-1 shows the different grip types used in the SHAP tests.

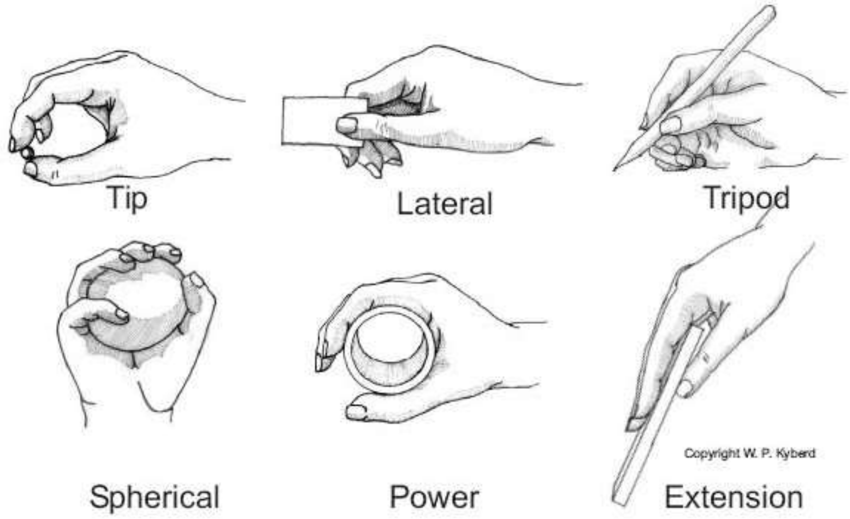


Figure 6-1. Grip patterns as identified in the Southampton Hand Assessment Procedure (SHAP).

A participant should complete the basic abstract objects test first before proceeding to the everyday objects tests. Simply put the abstract objects tests test the basic ability of the hand to manoeuvre basic objects and place them in a slot. It tests different grips such as spherical (for example closing the fingers over and gripping a ball), tripod grip (e.g. gripping between the thumb and two fingers), power grip (gripping an object between the fingers and thumb), lateral gip (gripping an object with the thumb and palm), tip (gripping an object between the thumb and index finger) and extension grip (extending the fingers around an object). The different object types are shown in the Figure 6-2.

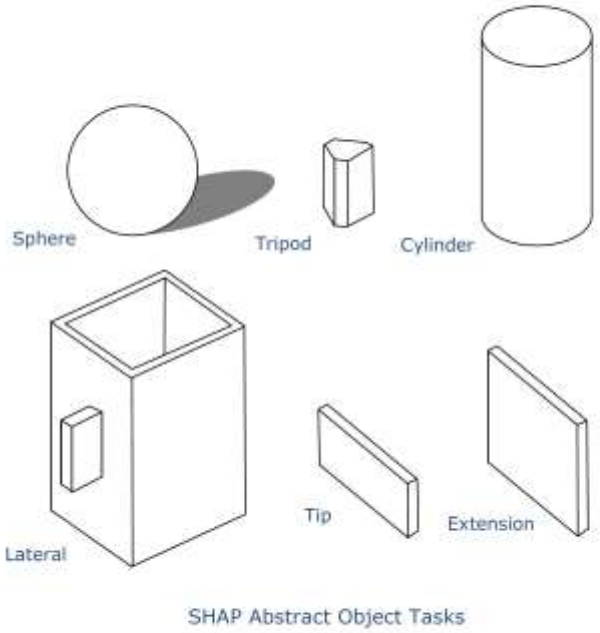


Figure 6-2. Abstract objects as used in the SHAP object tests.

Figure 6-3 A) shows the abstract objects and the form board used in the SHAP tests, where Figure 6-3 B) shows the objects used in the SHAP activities of daily living test.

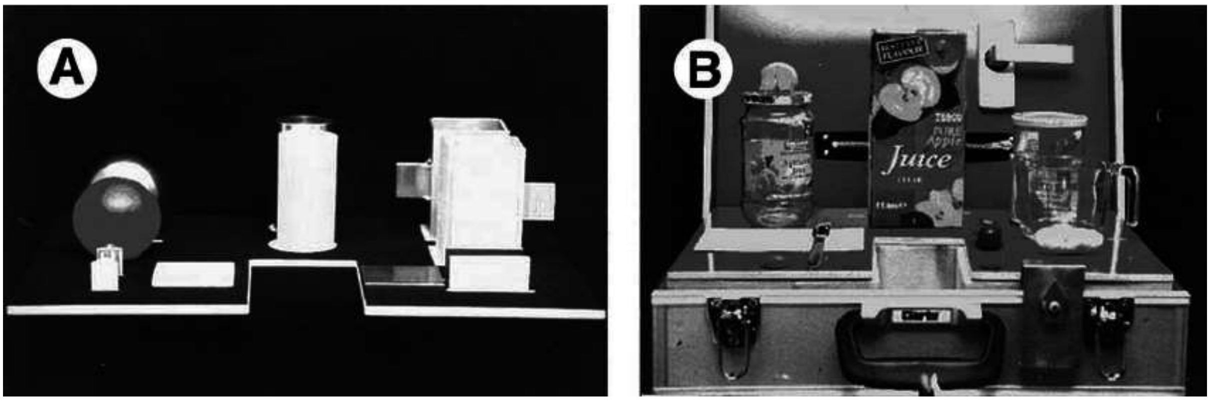


Figure 6-3. (A) SHAP abstract object and form board (B) SHAP activities of daily living.

Table 6-1 gives a summary of the tasks and their grip classification used in the SHAP tests.

Table 6-1. Summary of SHAP tests.

Task Number	Task	Grip Classification
1	Pick up coins	Tip/Tripod
2	Buttons	Tripod
3	Food cutting	Tripod/Power
4	Simulated page turning	Tripod/Extension
5	Remove Jar lid	Spherical
6	Pour water from jug	Tripod/Lateral
7	Pour water from carton	Spherical (flexion)
8	Lift large "heavy" object	Power
9	Lift large "light" object	Power
10	Lift weighted tray	Lateral/Extension
11	Rotate key 90	Lateral
12	Zip	Lateral/Tip
13	Rotate screw 90	Power (with precision grip)
14	Rotate door handle	Power

Other aspects that are looked at in prosthetic testing besides the functional evaluation are usually are the amputees own evaluation, aesthetic or cosmetic evaluation and technical evaluation. In the amputees evaluation the amputees' consideration for type of amputation needs to be considered as well as his own assessment of the prosthetic apparatus in terms of comfort, weight, fit, usability.

In terms of cosmetic evaluation the prosthesis needs to be scored in terms of its rest posture, shape, texture, projection in the glove, these also need to be looked at in a dynamic (when moving) sense when in motion, how it performs aesthetically.

A technical evaluation would look at specifics in terms of the prosthetic hands absolute weight, weight relative to volume, pinching force, maximum opening and closing speed of the hand.

6.2.1 INITIAL RESULTS

To test the final designs of the mechatronic and mechanical hands some basic tests were first setup to see what the hands could do with basic everyday objects. These were the initial tests of the designs.

6.2.1.1 Mechatronic hand initial test

Video analysis was performed for the initial testing of the mechatronic hand, these results were performed using objects as used in the Yale Open hand tests (IEEE Spectrum and Robotics Magazine Vol. 24 No. 1 March 2017). Results were tabulated and compared as in the IEEE report. Five runs were done with the objects similarly manipulated although the initial results were just pick, rotate approximately 180 degrees and place. Figure 6-4 below shows the electronic test setup for the mechatronic hand. The four motors driving the fingers were connected in parallel as can be seen in Figure 6-4. An Arduino Uno with a simple programming code was used to drive the fingers, opening and closing the four fingers, with the thumb remaining stationary. The fingers were set to open/close for four second intervals allowing enough time to grasp an object, and then four seconds to release the object. This provided an ample setup arrangement with which to test the hands grasping ability with various objects. Figure 6-4 shows the electronic setup to run the 4 finger motors.

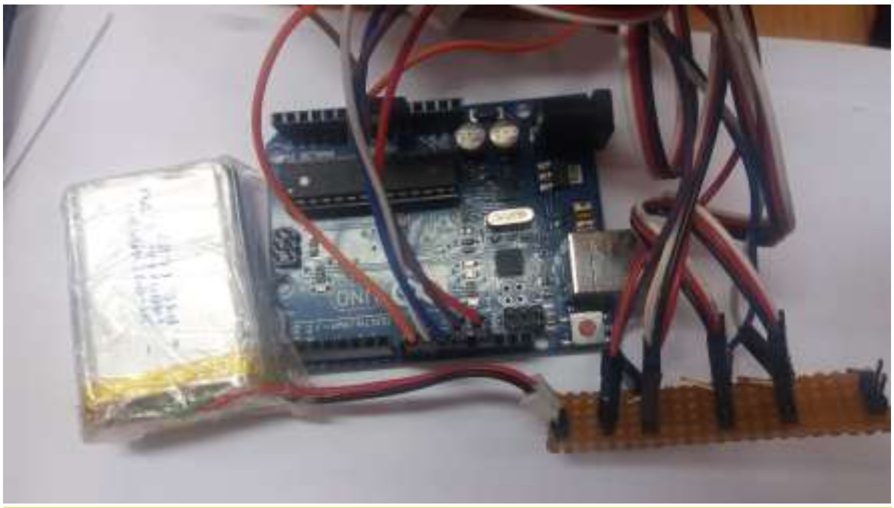


Figure 6-4. Mechatronic hand test setup.

6.2.1.2 Mechatronic hand initial test:

Figures 6-5 to 6-8 show the video analysis of the initial tests carried out on the mechatronic hand with objects based on those used in the Yale Open hand tests. Table 6-2 shows the objects physical properties used in hand grasp analysis tests.

Table 6-2. Objects physical properties in hand grasp analysis test (Yale Open Hand).

Object	Coffee Cup	Mustard bottle (full)	Spatula	Cheeze it box - (Full) - Salticrax box
Weight (g)	118	432	104	453
Size (mm)	89 x 89 x 83	38 x 76 x 178	38 x 102 x 356	64 x 161 x 229

Figure 6-5 shows a test run of the mechatronic hand picking up a coffee cup.

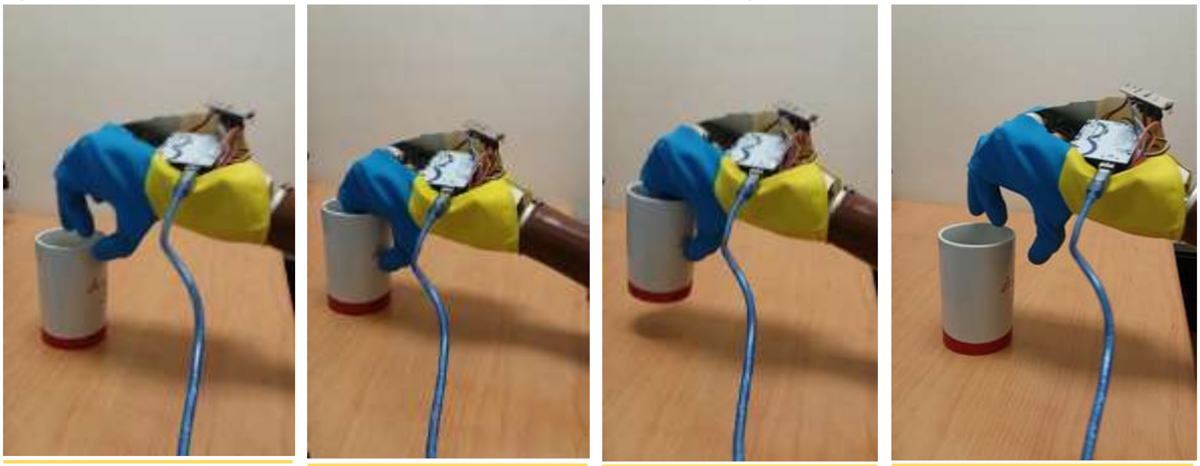


Figure 6-5. Testing mechatronic hand picking up a coffee cup.

Figure 6-6 shows the mechatronic hand picking up a mustard bottle of 432 grams with ease.

Figure 6-6. Testing mechatronic hand picking up a mustard bottle

Figure 6-7 shows the mechatronic hand picking up a medium size biscuit box.

Figure 6-7 Testing mechatronic hand picking up a medium size biscuit box

Figure 6-8 shows the mechatronic hand lifting large biscuit box.

Figure 6-8. Testing mechatronic hand picking up a large biscuit box.

6.2.1.3 Mechanical hand initial test:

The same initial tests were carried out for the mechanical hand. Figures 6-9 to 6-12 show the tests on the mechanical hand design based on the Yale Open hand tests. These were the initial tests done on the final design of the mechanical hand.

In Figure 6-9 one can see the mechanical hand lifting a coffee cup of weight 118 grams.

Figure 6-9. Testing mechanical hand picking up a coffee cup.

Figure 6-10 is of the final mechanical hand picking up a mustard bottle with ease.

Figure 6-10. Testing mechanical hand picking up a mustard bottle.

A medium sized biscuit box is being picked up by the mechanical hand in Figure 6-11.

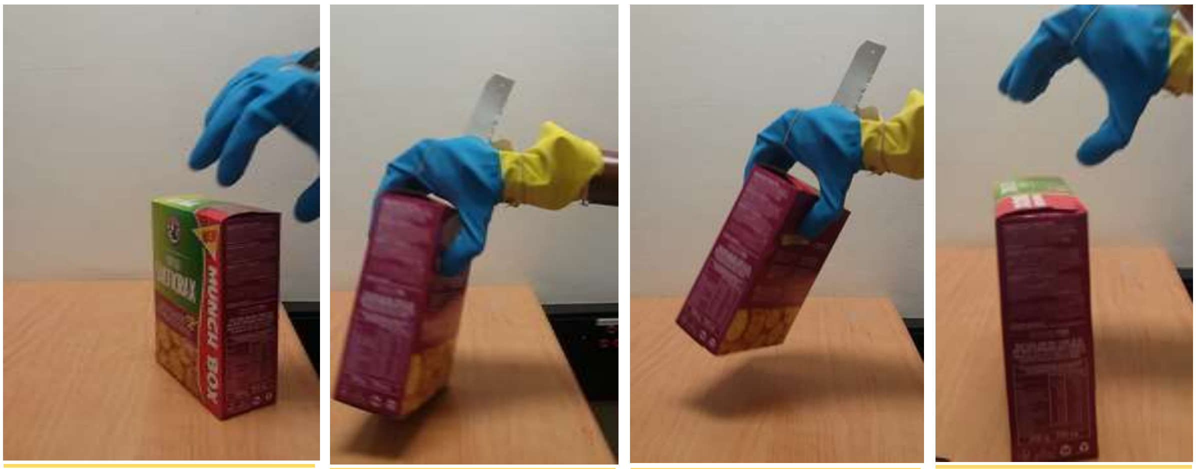


Figure 6-11. Testing mechanical hand picking up a medium size biscuit box.

The mechanical hand was able to grasp and lift a large biscuit box in Figure 6-12.

Figure 6-12 Testing mechanical hand picking up a large size biscuit box.

Hand grasp analysis was performed based on the Yale open hand tests initially to establish the ability of the prosthetic hands.

6.2.1.4 Mechatronic hand grasp acquisition tests (initial) results

The mechatronic hand grasp acquisition test results can be seen in Table 6-3.

Table 6-3. Mechatronic hand grasp analysis test results.

Object	Coffee Cup	Mustard bottle (full)	Spatula	Snacktime Assorted crackers (400 g)	Mini Salticrax box (200 g)
Actual Weight (g)	376	582 (582 ml)	88	506	234
Size (mm)	75 x 75 x 120	65 x 55 x 184	30 x 80 x 333	64 x 190 x 209	60 x 132 x 180
Grasp Acquisition test (Hold test)					
time	4s	4s	4s	4s	4s
Run1	yes	yes	yes	yes	yes
Run2	yes	yes	yes	yes	no
Run3	yes	yes	yes	yes	yes
Run4	yes	yes	yes	yes	no
Run5	yes	yes	yes	yes	no
Score	5 of 5	5of5	5 of 5	5of5	3 of 5

6.2.1.5 Mechanical Hand grasp acquisition tests (initial) results

The result of the mechanical hand grasp acquisition can be seen in Table 6-4.

Table 6-4. Mechanical hand grasp analysis test results.

Object	Coffee Cup	Mustard bottle (full)	Spatula	Snacktime Assorted crackers (400 g)	Mini Salticrax box (200 g)
Actual Weight (g)	376	582 (582 ml)	88	506	234
Size (mm)	75 x 75 x 120	65 x 55 x 184	30 x 80 x 333	64 x 190 x 209	60 x 132 x 180
Grasp Acquisition test (Hold test)					
time	5 of 5	4 of 5	5 of 5	5 of 5	5 of 5
Run1	yes	yes	yes	yes	yes
Run2	yes	no	yes	yes	yes
Run3	yes	yes	yes	yes	yes
Run4	yes	yes	yes	yes	yes
Run5	yes	yes	yes	yes	yes
Score	5 of 5	5 of 5	5 of 5	5 of 5	5 of 5

6.2.1.6 Dynamometer tests:

Testing was performed using a dynamometer for both the mechanical and mechatronic hands and the results were compared to typical human hands of some test subjects. A dynamometer measures the amount of force in kilograms that the hand is able to exert in a closed grip. A comparison of the different grip strengths can be seen in the Table 6-5.

Table 6-5. Dynamometer test results.

Test	Touch hand 3 Mechatronic (kg)	Touch Hand 3 Mechanical (kg)	Subject 1: Human hand (kg) (subject1) Age 34	Subject 2: Human hand (kg) (subject 2) Age 26
1	1,5	2,1	38	44,6
2	1,9	1	38,6	38,4
3	1,6	1,4	31,4	34
4	1,4	1,3	33,9	48,1
5	1,8	2,8	40,2	45,9

The hand dynamometer used for the tests is shown in Figure 6-13, measuring a reading of the mechanical hand.

Figure 6-13. Testing the mechanical hand on the dynamometer.

The test results of the dynamometer tests on the mechatronic and mechanical hands versus two human subjects can be seen in Table 6-5. One can see the mechanical hand here outperforming the mechatronic version although the human tests show the human hand is capable of a much greater grip strength.

Figure 6-14 is a line chart showing the results of the dynamometer tests of the two touch hand 3 designs versus those of human hands. The human hands outperform the touch hand 3 by a substantial value.

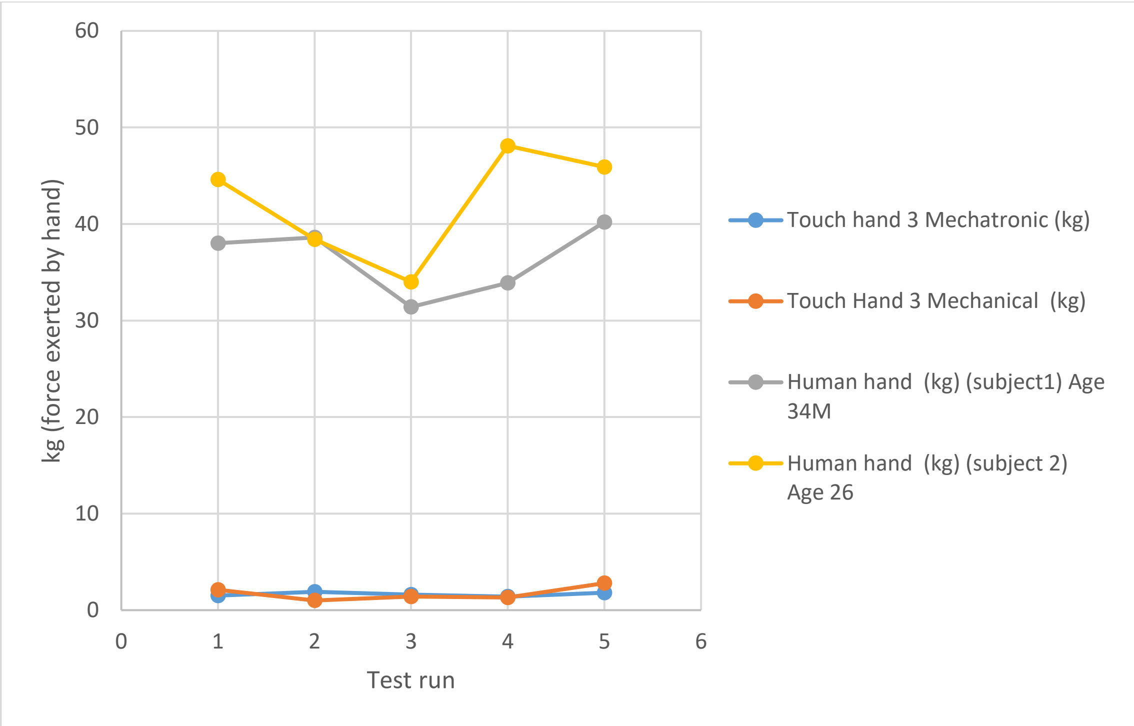


Figure 6-14. Comparing dynamometer test results.

Figure 6-15 shows the line chart of the dynamometer results in kg force of the mechatronic hand versus the mechanical hand for different runs. One can see the hands are quite similar although the mechanical hand looks to outperform the mechatronic hand especially in test run number five.

Figure 6-15. Dynamometer results comparison between mechanical and mechatronic hands.

6.2 SHAP ABSTRACT OBJECT TESTS

In order to test the functionality of the prosthetic hands simplified SHAP tests were run for both the mechanical and mechatronic hands. These tests are in line with the tests run in the Cybathlon Prosthetics Olympics test, although much more simplified. These tests look at the functionality of the hand in the following grips – spherical, tripod, power, lateral, tip and extension. Objects were chosen similar to those used in the SHAP tests to carry out the testing of both hands, the objects and their masses are tabulated in the next table.

Simply to explain the test setup, the timer is started (in this case a cell phone stopwatch is used) and the object relevant to the test is moved 8 cm to a new location and then the timer is stopped with the prosthetic hand. Results are achieved based on the success of moving the object and the times taken to complete the task can be compared to the normative data for each hand. With these results one can get an idea of the quality of the prosthetic hand compared with other prosthetics on the market and also with the human hand.

Spherical	Visual	Actual Object	Mass(g)
			55
Tripod			
			17
Power			
			222

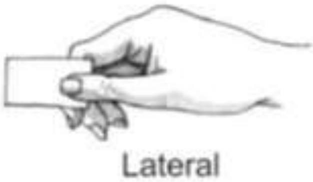
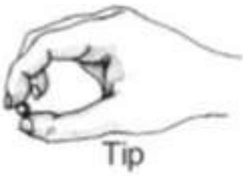
Lateral			
			34
Tip			
			6
Extension			
			272

Figure 6-16. Parts used in SHAP abstract objects tests.

6.2.1 SHAP TEST RESULTS

Video analysis of the SHAP Abstract object tests is shown in the following headings and it gives a graphic of the object moved over the distance of 8 cm. From these images one can grasp the level of difficulty of the grip and how well the hand was able to complete the task.

6.2.1.1 Mechatronic SHAP abstract object test

Figures 6-17 to 6-22 show the video images of the mechatronic hand undergoing SHAP tests. The results are analysed in terms of the performance of the hand in the tests.

One can see the mechatronic hand performing the spherical grip, picking up a tennis ball in Figure 6-17.

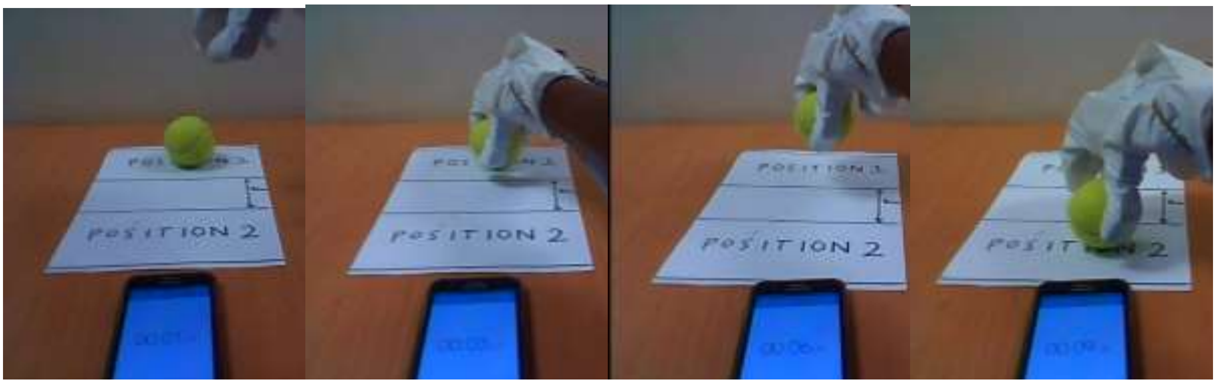


Figure 6-17. Spherical grip - mechatronic hand.

In Figure 6-18 one can see the mechatronic hand performing the cylindrical grip picking up a bottle with ease.

Figure 6-18. Cylindrical grip -mechatronic hand.

Figure 6-19 shows the mechatronic hand picking up and placing a pen using the tripod grip.

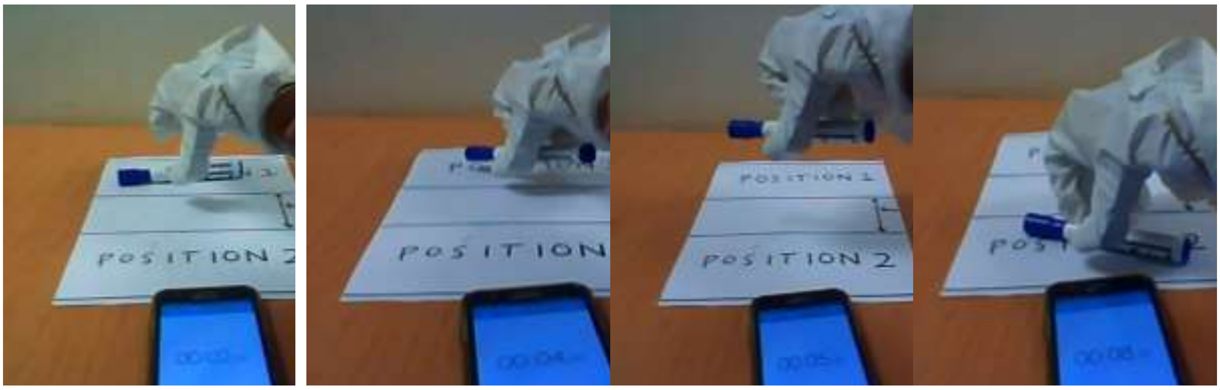


Figure 6-19. Tripod grip - mechatronic hand.

Figure 6-20 shows the mechatronic hand using a lateral grip to pick up and place a small box.

Figure 6-20. Lateral grip - mechatronic hand.

Figure 6-21 shows the mechatronic hand performing the tip grip picking up and placing a small spring using the index and thumb fingers.

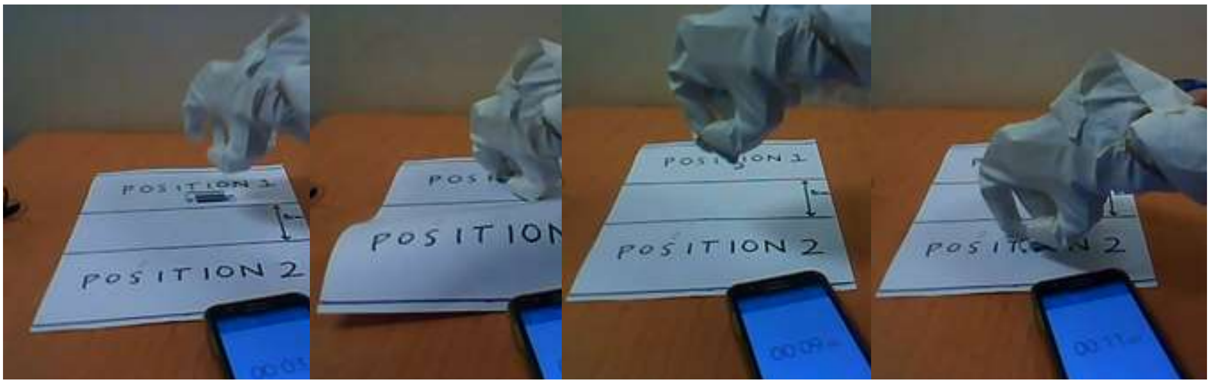


Figure 6-21. Tip grip - mechatronic hand.

The extension grip was carried out with the mechatronic hand where the fingers are kept in extension, applying minimal pressure closing. The object is kept between the extended fingers and the thumb as it is moved from one position to another.

Figure 6-22. Extension grip - mechatronic hand.

In Table 6-6 the results of the SHAP tests for the mechatronic hand are shown with the hand being able to pick up all the objects, the tip grip was the longest to complete at 13 seconds as the spring object used was more difficult for this hand to grasp. All tasks were a success this time showing that the mechatronic version of the hand had strong potential for gripping and manipulating simple fairly lightweight everyday objects.

Table 6-6. Mechatronic hand SHAP abstract object test results.

Grip	Success/Fail	Time (s)
Spherical	Success	9,36
Tripod	Success	9,96
Power	Success	11,35
Lateral	Success	7,56
Tip	Success	13,31
Extension	Success	10,25

6.2.1.2 Mechanical SHAP abstract object test

SHAP abstract object tests were carried out for the mechanical hand for the same objects. In Figure 6-23 one can see the mechanical hand picking up a tennis ball, the fingers close well around the ball and this is an example of a spherical grip. There is no trouble picking up and placing the tennis ball, the ball was not dropped during the movement.

Figure 6-23. Spherical grip - mechanical hand.

In Figure 6-24 one can see the mechanical hand performing a grip similar to the lateral grip on a small box. The hand is able to move the box from one position to another fairly easily and without any problem.

Figure 6-24. Lateral grip - mechanical hand.

The tripod grip is a grip in which the object is held between the index and middle fingers and the thumb. This grip is usually used in holding a pencil. In Figure 6-25 the grip is illustrated with the mechanical hand picking up a pen.

Figure 6-25. Tripod grip - mechanical hand.

The tip grip is a grip that is a grip an object between the index finger and the thumb and is used to pick up fine objects. In Figure 6-26 one can see the mechanical hand picking up a small spring using the tip grip.

Figure 6-26. Tip grip - mechanical hand.

Figure 6-27 shows the mechanical hand using the power grip which is a grip where an object is clamped between the fingers and the palm, the mechanical hand handles this grip.

Figure 6-27. Power grip - mechanical hand.

A test was carried out using the mechanical hand performing the extension grip. The box was too heavy and kept slipping from the hands grip, so the mechanical hand failed this grip type.

Table 6-7 shows the results of the mechanical hand SHAP tests on abstract objects. The hand performed fairly well and was able to pick up most objects, the only failure being the extension grip, this was the heaviest weight and also one of the more difficult grips. The times here are shown and one can see that the hand closes quickly enough to allow for grasping, the tripod grip took the longest with the delay being in grasping the object.

Table 6-7. Mechanical hand SHAP abstract object test results.

Grip	Success/Fail	Time (s)
Spherical	Success	7,42
Tripod	Success	16,51
Power	Success	9,03
Lateral	Success	7,2
Tip	Success	7
Extension	Fail	>20

From the video analysis one can see that the mechanical and mechatronic hands can both perform similar grip patterns with the only grip that wasn’t carried out being the failure of the mechanical hand to perform the extension grip. This was after a few attempts, and can be due to the weight and shape of the object being difficult to grip. Also the spring tension force in the hand can be a detractor to its performance for picking up all objects.

The mechatronic hand on the other hand had good success with picking up all the objects as can be seen in the Figure 6-28. One notable difference between the mechanical and mechatronic hand was the time taken for the hands to grip the objects with the mechatronic hands time being noticeably longer. The delay time for the motors to close was set at 4 seconds in programming the fingers motors closing. This was done as four seconds gave enough time to allow for manipulating the hand to grasp the objects.

The SHAP Abstract object tests are known to give a good representation of hand performance in common activities of daily living (ADL's).The assessment has been shown to be a statistically reliable measure of hand functionality and thus gives a good assessment of both hands designed here. (Skyler A. D., 2012). A comparison of the times taken to perform the various tasks can be seen below, with the advantage in most cases being slightly with the mechanical hand, except for two occurrences.

Figure 6-28 is a bar graph showing a comparison of the times taken to perform different grasps, it gives a good visual comparison of the differences between the two types of hand tested.

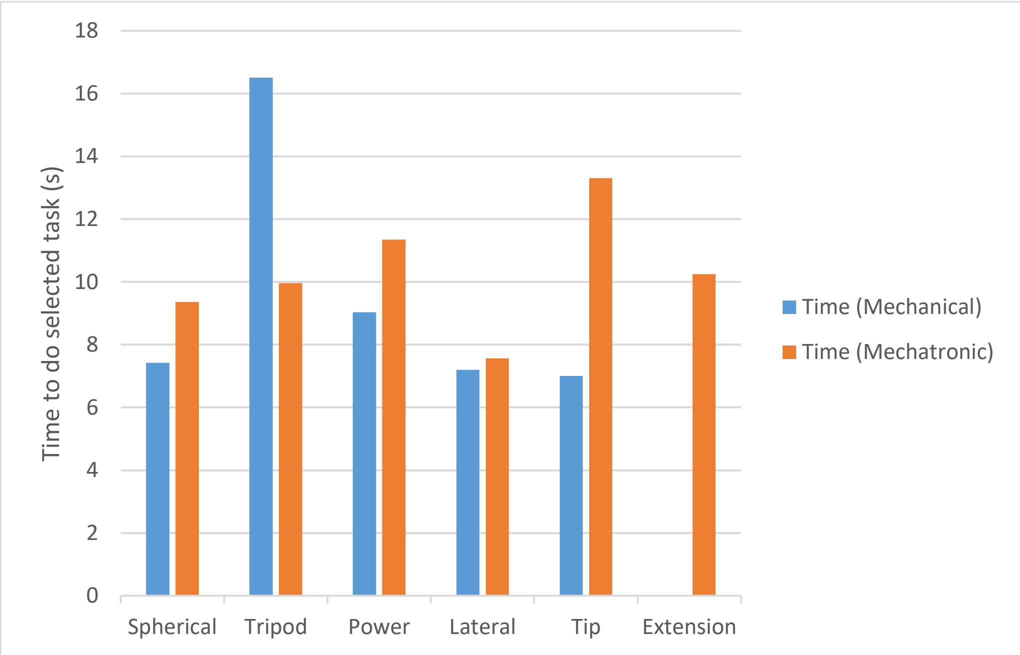


Figure 6-28. Comparison between hands: SHAP abstract object tests.

SHAP was designed to be used with all hands - natural, impaired or prosthetic and emphasises the function of the hand. (Kyberd, P. J., 2017). In this dissertation one has looked at the more basic aspects of the SHAP Abstract object test - i.e. Is the hand able to perform a specific task and how long does it take to perform that task.

6.3 CHAPTER SUMMARY

This chapter has looked at the performance of both final designs, mechatronic and mechanical, in the Yale Open Hand tests and SHAP tests which are designed to test hand function. The results of these tests have been positive and show that both the mechanical and mechatronic versions are able to perform tasks of daily living, from picking up small difficult to handle parts such as the spring, to large heavier parts such as various boxes. The hands have also been analysed with a hand dynamometer and their grip strengths measured. Both hands although still at a research stage are able to perform well and will work as prostheses.

7 CONCLUSION

This study, the mechanical design of a modular prosthetic hand, has looked at the functioning of a human hand in order to design a prosthetic hand to be as lifelike as possible. It has looked at aspects of prosthetic hands on the market past and present, a biological and biomechanical study of the functioning of the human hand, anthropometrics of the human hand have been studied and highlighted, different grip strengths and grip patterns have been looked at, suitable materials as well as the economic aspects of prosthetics have been studied.

In the design part of the project preliminary possible designs have been looked at for both the mechanical and mechatronic hands. Motor selection and mechanical mechanism selection has been done to establish the best way to drive the prosthetic hand. A preliminary prototype design was successfully completed, 3D printed and tested on an amputee. Results of the video analysis have been documented and the prototype design has been analysed.

The electronic system for a prototype and final design of the prosthetic hand has been developed and its specifications documented. The mechatronic design of the hand has been built around the housing of the electronics in the final design of the hand.

The mechanical design of the hand has been optimised to include a generic shell design that is common and can be interchanged between the mechanical and mechatronic hands. The design has been developed to include a modular chassis, modular hinges, and modular interchangeable fingers have been developed. The fingers have been developed with a linkage system allowing them to actuate and grasp various objects. The fingers, thumb, chassis, cover, and hinges were analysed using finite element analysis under various loading situations and found to be able to withstand the forces imposed and optimally designed for the loading conditions. The final designs for both hands were 3D printed, laser cut and assembled.

Biomechanics theory of finger motion has been described and the tendon pulley motions described. The Denavit-Hartenberg notation for finger motion kinematics has been described with matrices that can calculate the position of the end effector. A kinematic study of the finger motion using linkages has been done using ADAMS simulation and components for example acceleration of the finger components is modelled for different finger positions.

Testing methods were established for testing the prosthetic hand. A dynamometer has been used to analyse the grip strength of the prosthetic hand and has been compared to those of two human subjects. Two methods were looked at which have been validated in previous studies. One method being the Yale Open hand test was used for the initial testing of the final design using basic household items of different masses. Testing was carried out on both hands, using another method which is used to test human hand response known as the Southampton Hand Assessment Protocol (SHAP) in which the hands ability to move different objects of with different grip types a set distance are timed.

The results of both tests have been analysed and the hands have been found to be successful in manipulating most everyday objects with the different grip types.

The contributions from the literature study have been met successfully in the final design

- A modular system has allowed for adaptability based on the needs of the amputee depending on what they should require from their device. The mechanical prosthetic hand is therefore upgradable to a mechatronic system.
- The modular system that allows for the selection of a pure mechanical prosthetics hand or and mechatronics system.
- The modular system that allows the mechatronics system to be adaptable to the person's needs and affordability, allowing for the different sensors, actuators and accessories to be added, as they are required.

With the final design being modular as its different systems and components can be added as necessary.

7.1 COMPARASION OF HANDS

In Table 7-1 the Touch hand 3 is compared with other commercially available hands on the market as well as the other 2 hands developed in the department. One can see that the hand fairs well in terms of cost, weight and grip patterns. In terms of grip strength it fairs similarly although slightly better than Touch hand 1.

Table 7-1. Comparison of the three hands produced by the department of Mechanical Engineering, University of KwaZulu/Natal compared to other hands on the market.

Feature	**i-Limb Ultra Revolution (Touch Bionics 2103a)**	**Michaelangelo (Ottobock, 2014)**	**Bebionic 3 (RSL Steeper, 2013b)**	**Touch Hand I (2014)**	**Touch Hand II (2015)**	**Touch Hand III Mechatronic (2016/2017)**	**Touch Hand III Mechanical (2016/2017)**
Power Grip Strength (N)	136	70	140,1	19,5	60,6	18,639	27,468
Lateral Grip Strength (N)	35	60	26,5	3,7	8	4,29678	1,3734
Hook Grip Load (kg) (passive)	90	n/a	45	8	6,175	n/a	n/a
Finger Hook load (kg)	32	n/a	25	n/a	1,54	n/a	n/a
Closing Time (s) Power Grip	1,2	n/a	1	2	0,826	2,5	0,22
Grip Patterns	24	7	14	19+	Depends on control (10 were tested)	6(tested)	6(tested)
Control	2 MES Channels	2 MES Channels	2 MES Channels	2 MES Channels	Myoelectric control to be added (designed as via PC)	2 MES Channels (EMG, Andrew Mangezi 2016)	Mechanical
Weight with wrist (g)	515	600	608	540	486	593	513
Cost ($) (Van der Riet, 2014; Jones 2015)	40000	75000	35000	1000 (materials)	1244 (direct manufacturing costs)	1042,24 (materials)	81,76 (materials)

To compare the Touch hand 3 mechanical and mechatronic versions then, one can see from Table 7-1 that the hand did not perform as well as the other hands and scored significantly lower when comparing the grip strengths. Touch hand 3 compared favourably with Touch hand 1 in grip strengths and is similar in cost and better at gripping objects for the different grip types. In terms of cost Touch hand 3 cost less than Touch hand 2.

In conclusion then extensive successful testing of the final designs of both the mechanical and mechatronic hands has been carried out with positive results. Both hands have been analysed according to the Open Yale Hand tests and SHAP tests and found to be successful.

In order to assess the final designs one would need to go back to the original design criteria laid out initially to see if they have been met. A review of the hands performance versus the initial specifications is given next followed by a comparison of the hands.

Finger forces and Kinematics - the final finger forces and finger kinematics for both hands are life like in their design, although not as strong as a human hand the fingers open and close the same way and are able to grip various objects.

Grip strength and grip patterns – Although the grip strength for both hands (1.8 kg – mechatronic; 2.7 kg –mechanical) is not as strong as the human hand (55 kg maximum) the hands are both able to perform daily activities.

Finger design and hand design – In both design modularity was incorporated, this can be seen in the finger brackets which bolt onto the main chassis, and the fingers themselves which incorporate the same linkages, pins, fasteners etc. These can be interchanged, except for the links and main proximal phalanx of the pinkie finger and are also interchangeable between both the mechanical and mechatronic hands.

Thumb positions – the final design of the thumb was decided to be a static (non-actuated) thumb although the thumb tip could be manually positioned for different grips. The design of the thumb like this allowed for nearly all grip types without the complexity of actuation and also incorporated a modular design.

Hand tests – both hands have been tested for various grip types under different test setups and found to be successful at manipulating most objects. The results obtained are similar to those sought after in theory.

Weight - in the next section the final weights are compared, mechatronic – 593 g (final weight based on test setup), mechanical – 513 g. This is including the wrist so is below the maximum desired weight and is in a similar range as other modern prosthetic hands on the market.

Cost - the cost of the mechatronic hand ($1042.24) and cost of mechanical hand ($ 81.76) , calculation of which can be seen in part B of the Appendices. This fairs well lower than the cost of commercial prostheses and makes the hand available to more of the public.

7.2 FUTURE WORK

In order to improve on the design of this prosthetic hand some suggestions need to be made on what can be done to improve on the design in future.

7.2.1 Mechatronic option:

One can see that the Touch hand 3 mechatronic hand is not quite at the level of the Touch hand 2 in term of grip strength and finger strength aspects but these could be improved upon in the design, one could try to lessen the amount of friction in the fingers by using brass bushes reducing sliding friction. One could also keep the linkage system, but introduce a pulley system that makes use of mechanical advantage to increase the grip strength of the fingers. A better actuation system for the fingers could be developed to increase the grip strength of the capable and functional finger design.

7.2.2 Mechanical option:

Further work could be done to improve the mechanical design, stronger springs could be incorporated into the fingers and more testing could be carried out. Also the design of the chassis could be changed to make it more lightweight and robust. A different system could be developed to allow for more mechanical advantage, making the user not have to strain as much to get the required force to open the hand.

One advantage of the Touch hand 3 over the Touch hand 2 and other hands is that this hand is more robust incorporating a stainless steel chassis and more modular system of assembly. Other aspects having a mechanical and mechatronic option make it more flexible to the user's requirements.

7.3 CHAPTER SUMMARY

This chapter has looked at a summary of the project, looking at the specifications and strengths and weaknesses of both hands and comparing them to the previous designs. The designs have been summarised and the advantages and disadvantages noted. Future work has noted improvements that can be made to the designs to possibly get the designs to a commercial level.

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9 APPENDIX A

MOTOR AND GEARBOX SELECTION AND DATASHEETS

Miniature Linear Motion Series · PQ12

Firgelli Technologies' unique line of Miniature Linear Actuators enables a new generation of motion-enabled product designs, with capabilities that have never before been combined in a device of this size. These tiny linear actuators are a superior alternative to designing your own push/pull mechanisms. Their low cost and easy availability make them attractive to hobbyists and OEM designers alike.

The PQ12 actuators are complete, self contained linear motion devices with position feedback for sophisticated position control capabilities, or end of stroke limit switches for simple two position automation. Driving them couldn't be easier, simply apply a DC voltage to extend the actuator, and reverse the polarity to retract it. Several gear ratios and voltage options are available to give you varied speed/force configurations.

PQ12 Actual Size

Benefits

- → Compact miniature size
- → Precise position feedback
- → Limit switches
- → Simple control
- → Low voltage
- → Equal push/pull force
- → Easy mounting

Applications

- → Robotics
- → Consumer appliances
- → Toys
- → RC vehicles
- → Automotive
- → Industrial Automation

PQ12 Specifications

Gearing Option	30:1	63:1	100:1
Peak Power Point	15N@15mm/s	30N @ 8mm/s	40N @ 6mm/s
Peak Efficiency Point	8N @ 20mm/s	12N@12mm/s	20N @ 8mm/s
Max Speed (no load)	28mm/s	15mm/s	10mm/s
Max Force (lifted)	18N	45N	50N
Max Side Load	5N	10N	10N
Back Drive Force	9N	25N	35N
Stroke		20 mm	
Input Voltage		6 or 12 VDC	
Stall Current		550mA @ 6V, 210mA @ 12V	
Mass		15g	
Operating Temperature		-10°C to +50°C	
Positional Repeatability		±0.1mm	
Mechanical Backlash		0.25 mm	
Audible Noise		55dB @ 45cm	
Ingress Protection		IP-54	
Feedback Potentiometer		5kΩ±50%	
Limit Switches		Max. Current Leakage: 8uA	
Maximum Duty Cycle		20%	

Basis of Operation

The PQ12 is designed to push or pull a load along its full stroke length. The speed of travel is determined by the load applied(see load curves). When power is removed the actuator will hold its position, unless the applied load exceeds the back drive force. Repeated stalling of the actuator against a fixed load will shorten the life of the actuator. Since application conditions (Environmental, loading, duty cycle, vibration, etc) vary so widely, we advise application specific testing to determine the expected life of the actuator.

Ordering

Small quantity orders can be placed directly online at www.firgelli.com. Each actuator ships with two mounting brackets, M3 mounting hardware, and one FPC ribbon cable connector. To extend the length of the ribbon cable you can purchase one of our PQ12 cable adapters and extension cable, or solder wires directly to the ribbon cable. Contact sales@firgelli.com for volume quotes and customization options for OEM's.

Firgelli

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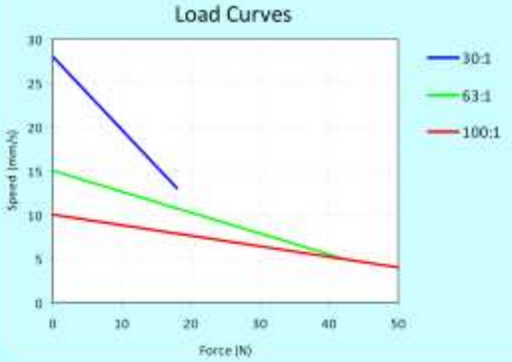
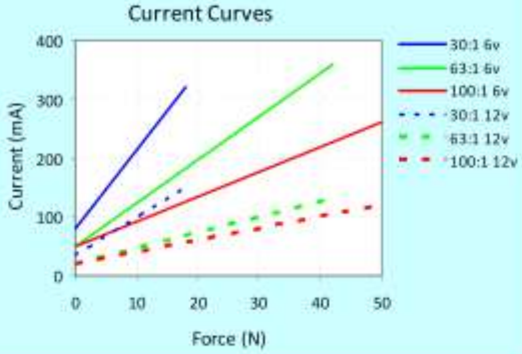
sales@firgelli.com
www.firgelli.com

Rev B

Figure A-1. Firgelli PQ12 datasheet.

PQ12 Specifications





Model Selection

The PQ12 has 3 configuration choices: Gear Ratio, Voltage and Controller. PQ12 options are identified according to the following scheme:

PQ12-GG-VV-C

feature	*options*
GG: Gear reduction ratio (refer to load curves above)	**30, 63, 100** (lower ratios are faster but push less force, and vice versa)
VV: Voltage	**6, 12** (DC volts)
C: Controller	**P** Potentiometer Feedback **S** Limit Switches **R** RC Linear Servo (6V Only)

PQ12 Controller Options

Option S – End of Stroke Limit Switches

WIRING: (see next page for pin numbering)
1- Limit Switch Detection (Optional)
2- Actuator Motor Power
3- Actuator Motor Power
4- Not Connected
5- Not Connected

The –S actuators have limit switches that will turn off power to the motor when the actuator reaches within 1mm of the end of stroke. Internal diodes allow the actuator to reverse away from the limit switch. The limit switches cannot be moved. While voltage is applied to the motor power pins (2 & 3) the actuator extends. Reverse the polarity and the actuator retracts. This can be accomplished manually with a DPDT switch or relay, or using an H-Bridge circuit. The –S model cannot be used with the LAC control board. Pin #1 can be used to sense when the actuator has reached the end limits. See our FAQ page for a simple schematic to light an LED when the limits are reached.

Option P – Potentiometer Position Feedback

WIRING: (see next page for pin numbering)
1 – Feedback Potentiometer negative reference rail
2 – Actuator Motor Power
3 – Actuator Motor Power
4 – Feedback Potentiometer positive reference rail
5 – Feedback Potentiometer wiper

The –P actuators have no built in controller, but do provide analog position feedback. While voltage is applied to the motor power pins (2 & 3) the actuator extends. Reverse the polarity and the actuator retracts. Position of the actuator stroke can be monitored using the internal linear potentiometer. Provide any stable low and high reference voltage on pins 1 & 4, then read the position signal on pin 5. The voltage on pin 5 will vary linearly between the two reference voltages in proportion to the position of the actuator stroke. Connect to an LAC board for easy interface with any of the following control signals: Analog 0-5V or 4-20mA, or Digital 0-5V PWM, 1-2ms Standard RC, or USB.

Option R – RC Linear Servo

WIRING: (see last page for pin numbering)
1 - RC input signal (RC-servo compatible)
2 - Power (+6 VDC)
3 - Ground

Note: Reversing polarity on pins 2 and 3 may cause damage

-R actuators are ideally suited to use in robotics and radio control models. The –R actuators or 'linear servos' are a direct replacement for regular radio controlled hobby servos. The desired actuator position is input to the actuator on lead 1 as a positive 5 Volt pulse width signal. A 2.0 ms pulse commands the controller to fully retract the actuator, and a 1.0 ms pulse signals it to fully extend. If the motion of the actuator, or of other servos in your system, seems erratic, place a 1–4Ω resistor in series with the actuator's red V+ lead wire. The PQ12–R Linear Servos are designed to work with typical RC receivers and battery packs. Consequently they also are compatible with Arduino control boards, VEX Microcontrollers and many other similar boards designed for robotics.

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Rev B

Figure A-2. Firgelli PQ12 datasheet.

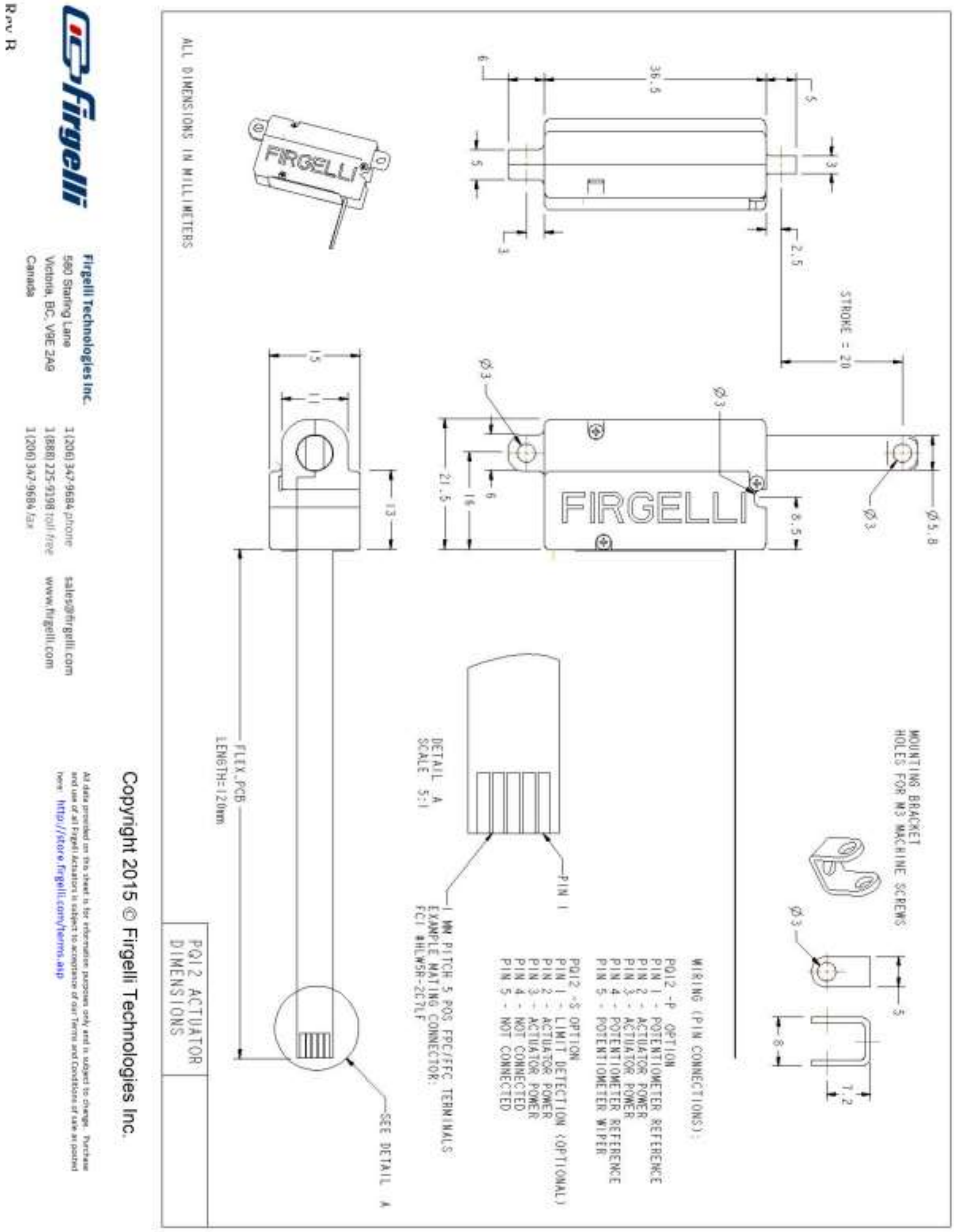

Figure A-3. Faulhauber motor datasheet.

10 APPENDIX B

COST ESTIMATIONS

Table B-1. Cost Estimate comparison mechatronic and mechanical touch hand 3.

Item name	Cost per item(ZAR)	No. of items (Mechanical)	No. of items (Mechatronic)	Cost(Mechanical)	Cost (Mechatronic)
Mechanical Hand					
ABS Plastic (3D Printing Material)	R400,00	1	1	400	400
Laser cut material				0	0
Chassis (1,2 mm ALU) ea	R30,84		1	0	30,84
Chassis(2 mm 304 Stainless steel) ea	R50,99	1		50,99	0
Linkages (estimate for all lengths – 35 mm and 29 mm)	R2,05	8	0	16,4	0
Finger hinge brackets (Stainless steel)	R15,20	5	4	76	60,8
Lever (Stainless steel)(mechanical)	R8,52	2		17,04	0
Fasteners				0	0
M4 Tapped 5 mm bush	R5,00	10	9	50	45
M4x5 Countersunk SS bolts	R0,47	20	18	9,4	8,46
M3 threaded rod	R19,30	1	1	19,3	19,3
M3 x25 SS bolts	R0,83	20	20	16,6	16,6
M3 x 20 SS bolts	R0,50	20	20	10	10
M3 locknuts	R0,50	6	6	3	3
diameter 13 mm brass tube	R100,00	1	1	100	100
Bearing ID 13 mm OD	R85,00	1	1	85	85
Springs	R15,00	4	1	60	15
Pinion Gear	R145,00	1	1	145	145
Mechatronic Components					
Firgelli PQ 12 Linear actuator	R1 046,00		4	0	4184
Faulhauber DC Motor (1717A006SR + 15A 152:1)	R1 089,00		1	0	1089
Arduino M0 Pro	R693,20		2	0	1386,4
Electronic components (estimate from Andrew Mangezi's Dissertation)	R3 748,60		1	0	3748,6
Batteries	R100,00		3	0	300
EMG Sensors (Myoware)	R925,00		2	0	1850
TOTAL COST (ZAR)				R1 058,73	R13 497,00
TOTAL COST (US $) (1 US$ = R12.95 ZAR) 11/06/2017				$81,76	$1 042,24

11 APPENDIX C

FINAL DRAWINGS

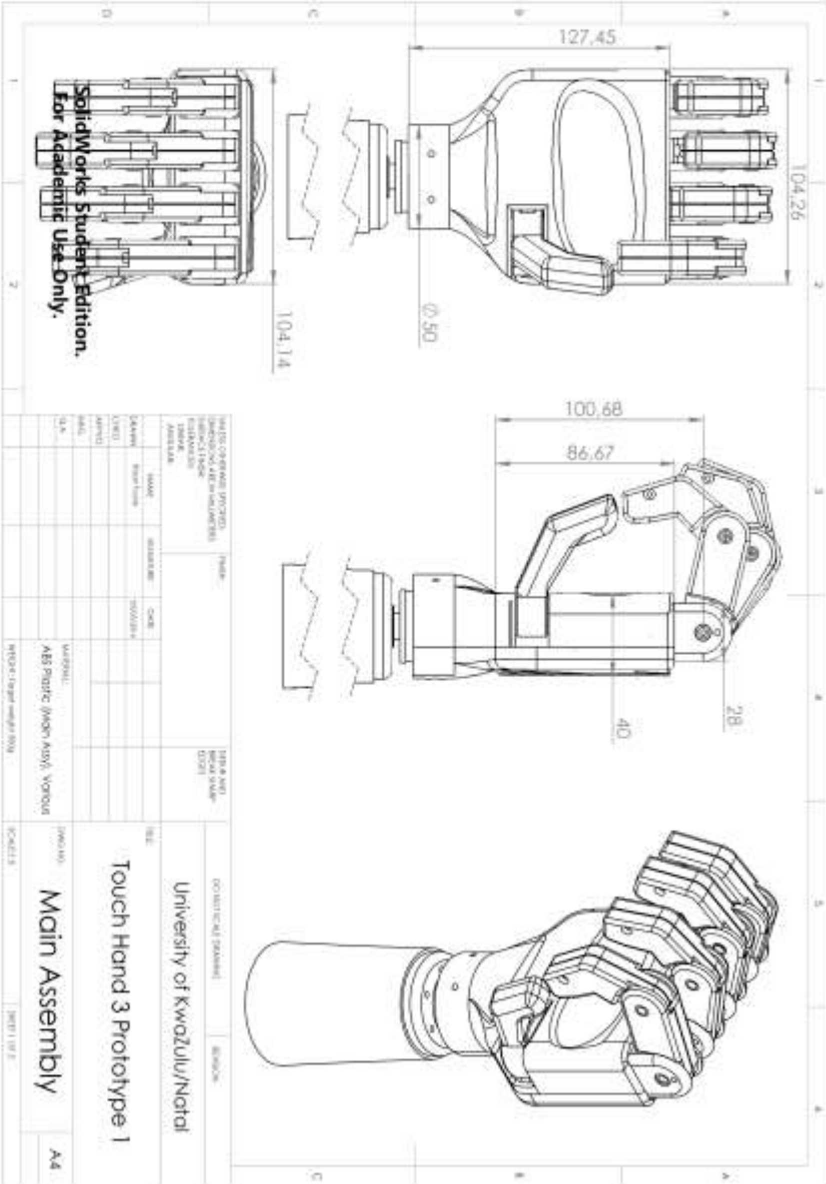

Figure C -1. Prototype drawing.

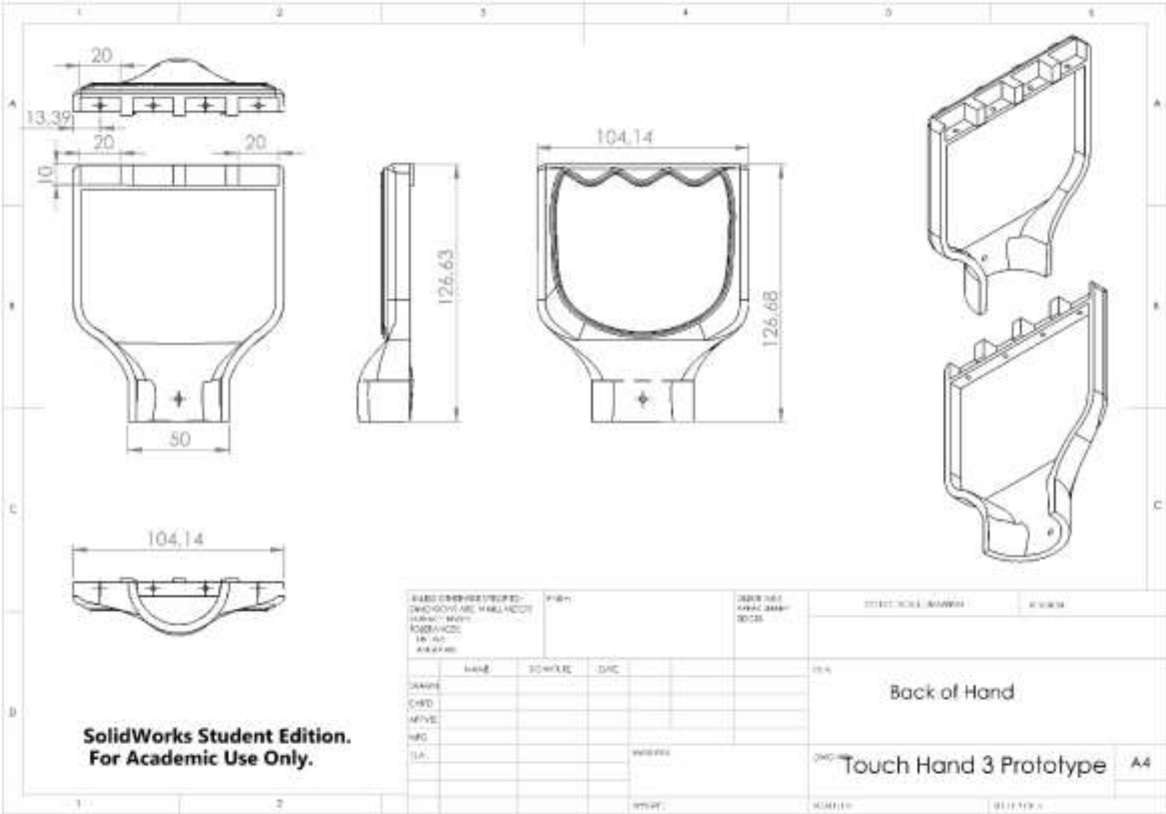

Figure C -2. Prototype cover.

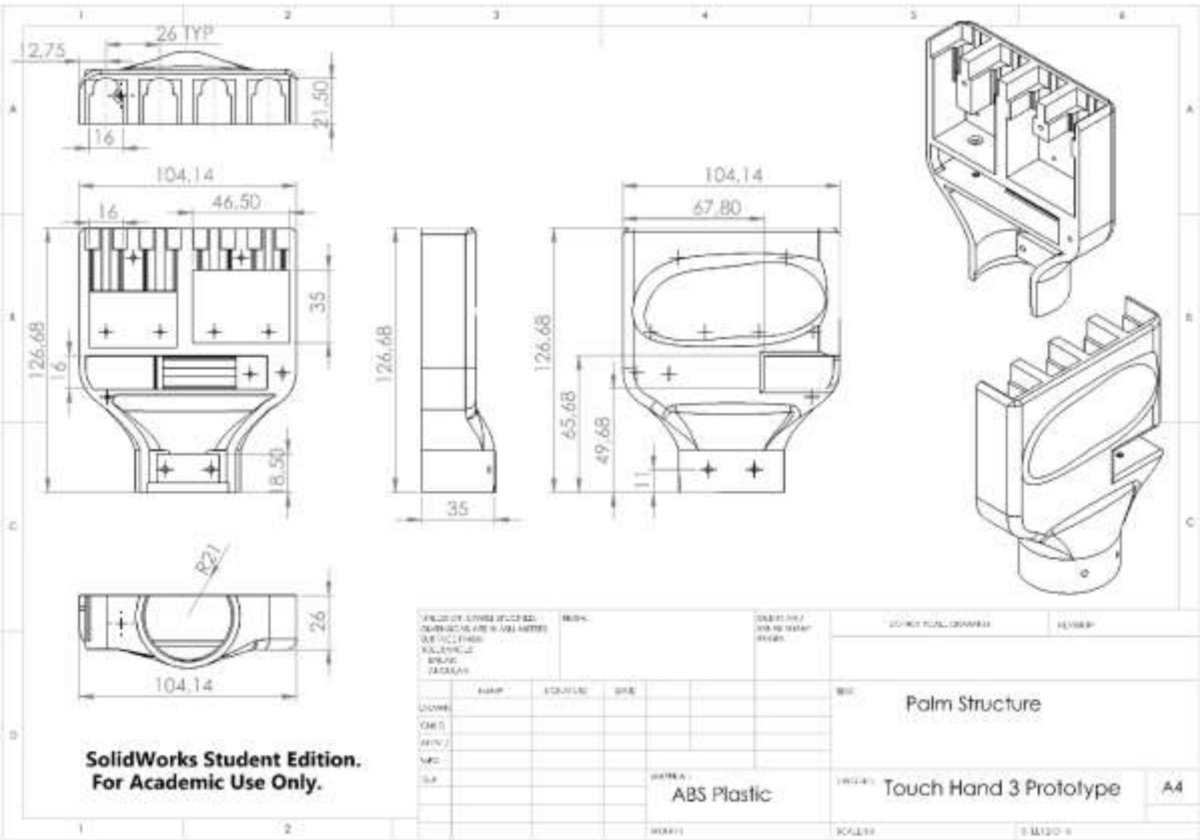

Figure C -3. Prototype back.

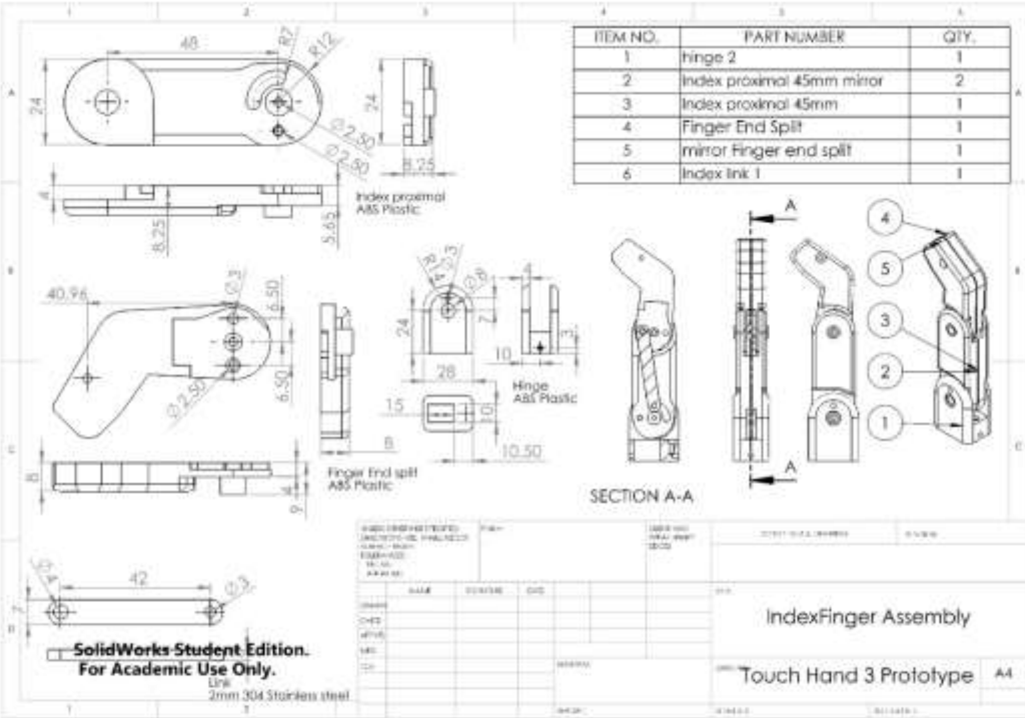

Figure C -4. Prototype finger.

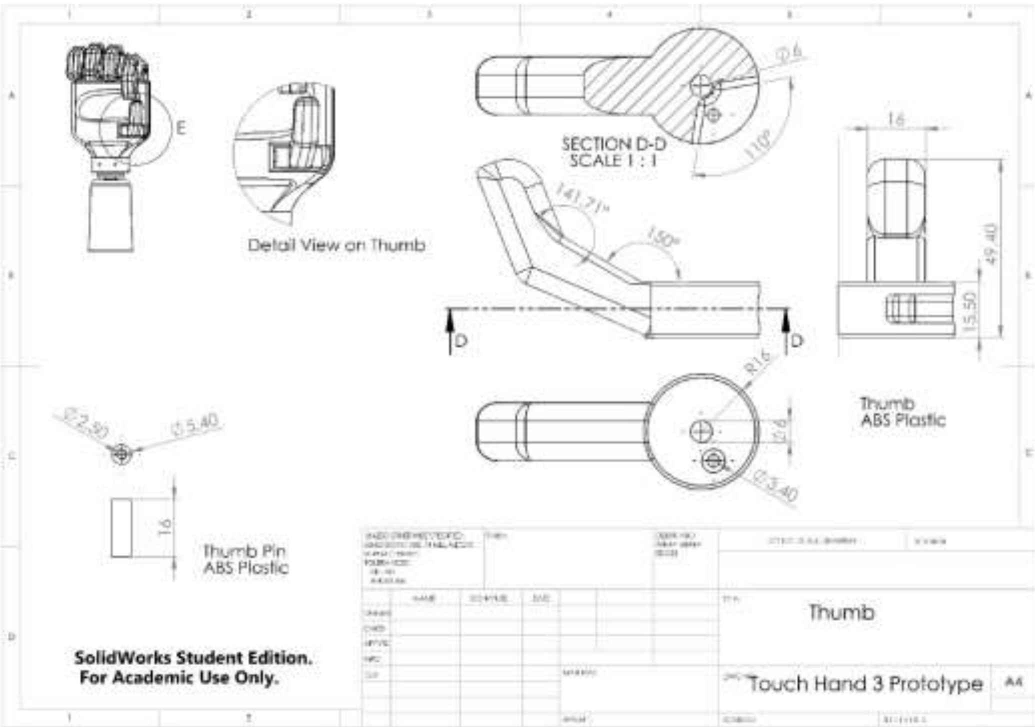

Figure C -115. Prototype thumb.

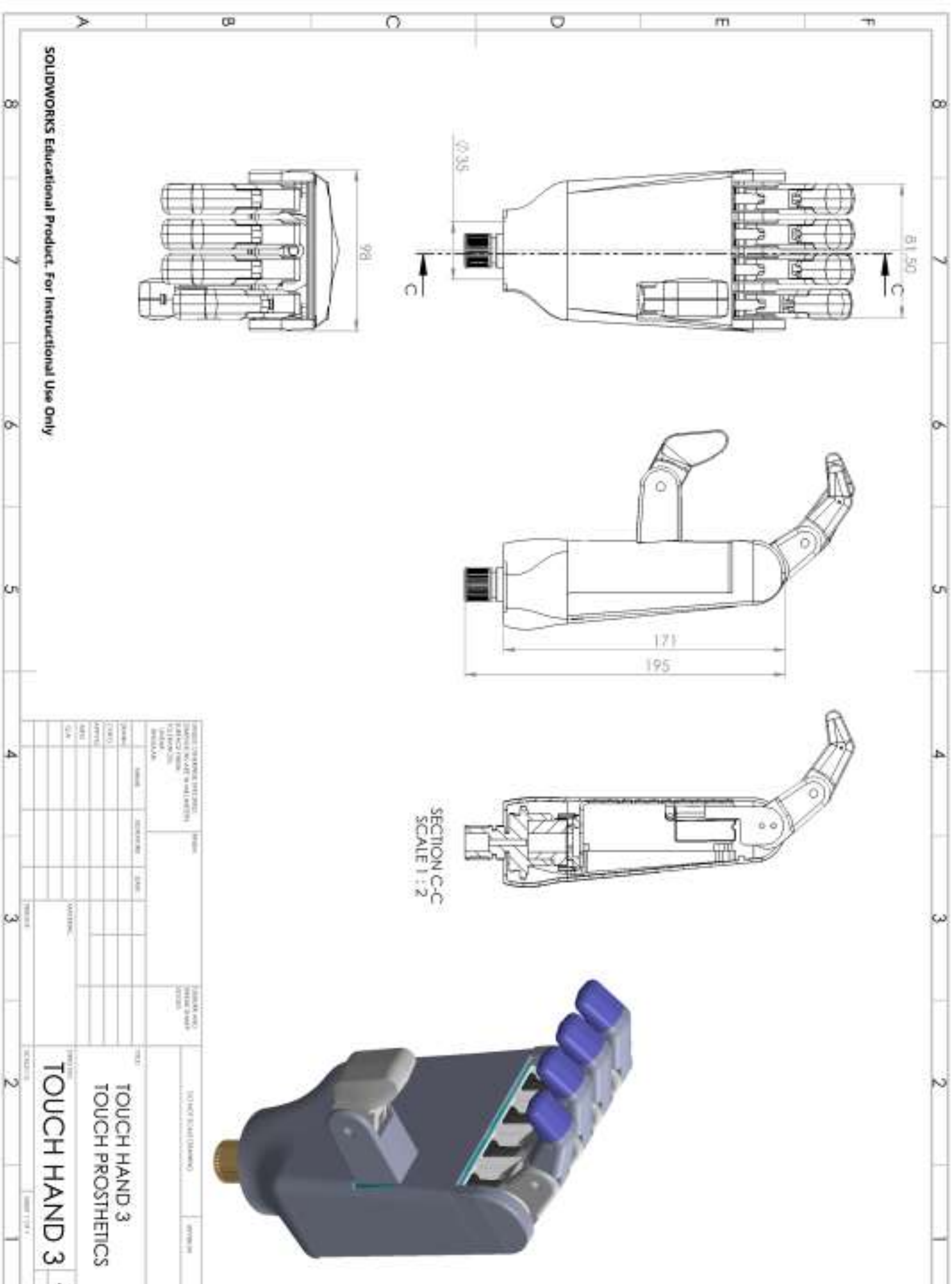

Figure C -6. Final mechatronic assembly drawing.

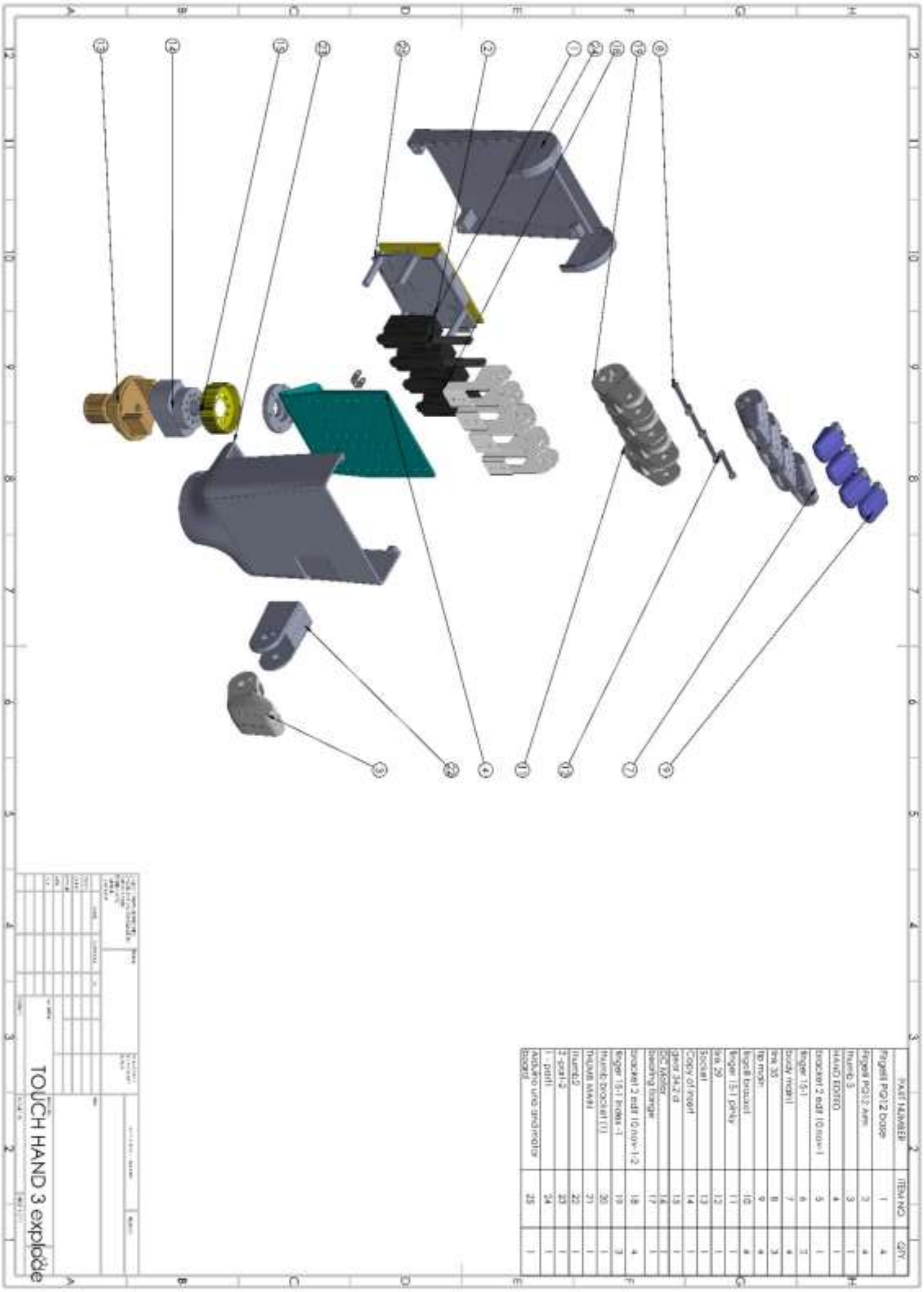

Figure C -7. Touch hand 3-mechatronic exploded drawing.

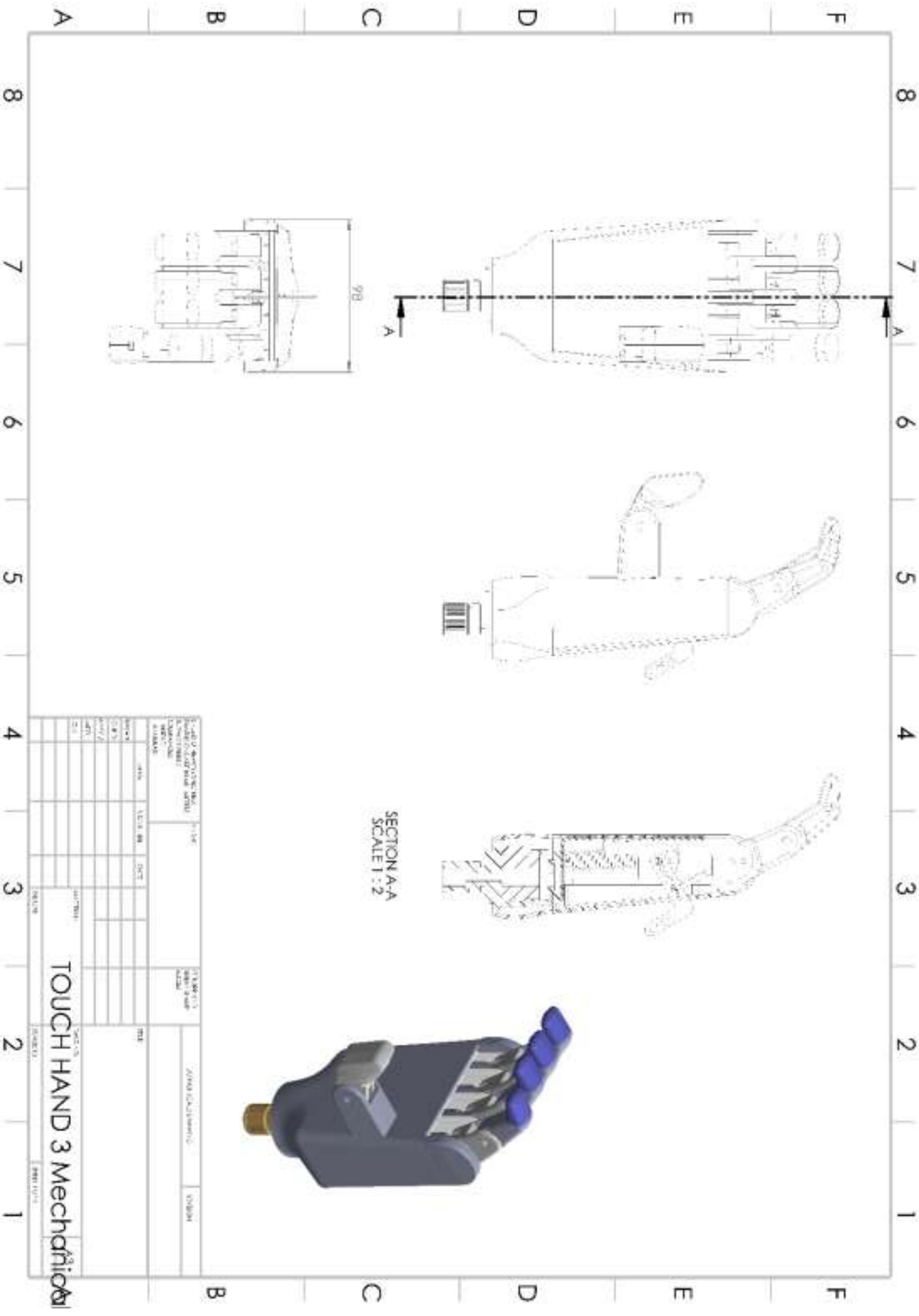

Figure C -8. Touch hand 3 mechanical hand assembly drawing

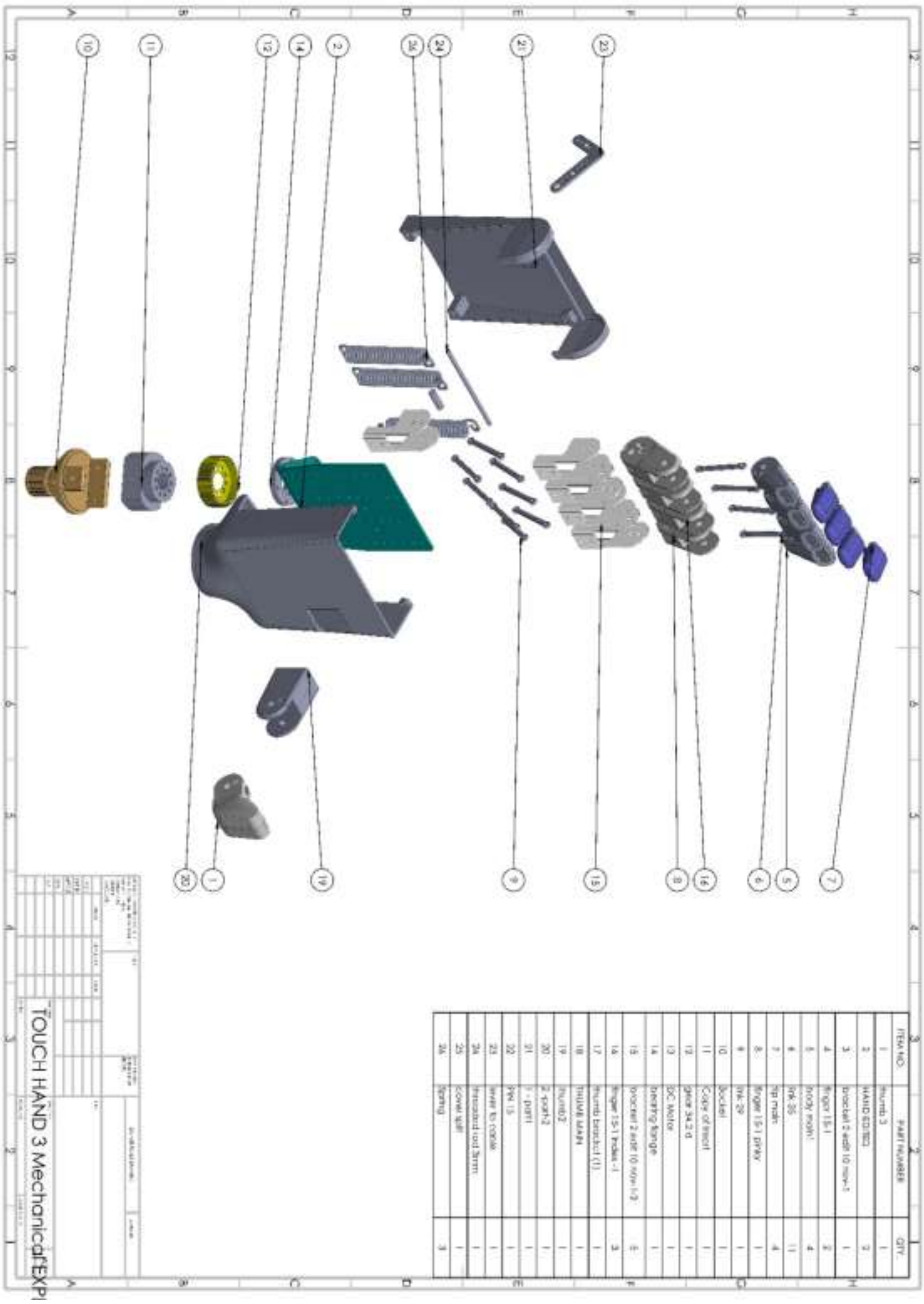

Figure C -9. Touch hand 3 mechanical hand exploded drawing.