SUPERVISOR'S ENDORSEMENT

"I hereby declare that I have read through this report entitle *"Design and Development of Exoskeleton Bionic Hand"* and found that it has complied the partial fulfillment for awarding the degree of Bachelor of Mechatronics Engineering"

Signature : ....

Supervisor's Name : Pn. Norafizah binti Abas

Date : ....

DESIGN AND DEVELOPMENT OF EXOSKELETON BIONIC HAND

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A report submitted in partial fulfillment of the requirements for the degree of BACHELOR OF MECHATRONICS ENGINEERING

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

YEAR 2014

DECLARATION

I declare that this report entitle *"Design and Development of Exoskeleton Bionic Hand"* is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature : ....

Name : Mohamad Fakri Bin Juhari

Date : ....

To my beloved father and mother

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ABSTRACT

Recently, the number of patients with wrist and forearm amputations increased tremendously due to trauma, prolonged constriction, or surgery. The amputees experienced lots of problems, especially in dealings with their daily life activities. Thus, as a solution, a prototype called as bionic hand is designed. Early design of bionic hand comprises of 14 motors with 14 degree of freedom which caused the bionic hand to be costly and complex to control. In this research, design of a bionic hand that has 10 degrees of freedom with 5 motors attached to mechanical linkages is proposed. The bionic hand designs in SolidWorks that resembled the function and size of an actual human hand. It is fabricated using aluminum 6061 as it is light in weight and durable. As for the sensor, V3 muscle sensor is utilized to identify a signal generated from the human muscle and amplified it as the primary control signal to control the movement of the bionic hand. The performance of bionic hand is tested in terms of repeatability and accuracy. Repeatability accuracy test is divided into two phases, the first test is constructed to analyze the repeatability of angular movement for each finger while the second test is constructed to analyze the repeatability of wrist movement. Similarly, the accuracy test is also divided into two phases where the first test is conducted to analyze the accuracy of finger press while the second test is to analyze the accuracy of hand grasp. The results are compared with the natural human force and yielded acceptable results. Finally, the hand is tested in term of canonical hand posture and manage to emulate actual human hand.

ABSTRAK

Baru-baru ini , bilangan pesakit dengan pergelangan tangan dan lengan amputasi meningkat dengan ketara disebabkan oleh trauma , penyempitan yang berpanjangan, atau pembedahan. Pesakit akan mengalami banyak masalah terutama dalam urusan dengan aktiviti kehidupan harian mereka. Oleh itu, sebagai penyelesaian , prototaip yang dipanggil sebagai tangan bionik direka. Reka bentuk awal tangan bionik terdiri daripada 14 motor dengan 14 darjah kebebasan yang menyebabkan tangan bionik menjadi mahal dan kompleks untuk mengawal. Dalam kajian ini, reka bentuk tangan bionik yang mempunyai 10 darjah kebebasan dengan 5 motor dilampirkan kepada hubungan mekanikal adalah dicadangkan . Tangan bionik direka mengunakan Solidworks yang menyerupai fungsi dan saiz tangan manusia sebenar. Ia direka menggunakan aluminium 6061 kerana ia adalah ringan dan tahan lama. Bagi sensor, sensor V3 otot digunakan untuk mengenal pasti isyarat yang dijana daripada otot manusia dan dikuatkan ia sebagai isyarat kawalan utama untuk mengawal pergerakan tangan bionik . Prestasi tangan bionik diuji dari segi kebolehulangan dan ketepatan. Kebolehulangan ujian ketepatan dibahagikan kepada dua fasa, ujian pertama dibina untuk menganalisis kebolehulangan pergerakan sudut untuk setiap jari manakala ujian kedua dibina untuk menganalisis kebolehulangan pergerakan pergelangan tangan. Begitu juga, ujian ketepatan yang juga terbahagi kepada dua fasa di mana ujian pertama dijalankan untuk menganalisis ketepatan akhbar jari manakala ujian kedua adalah untuk menganalisis ketepatan memahami tangan. Hasilnya dibandingkan dengan daya manusia yang semula jadi dan membuahkan hasil yang boleh diterima. Akhir sekali , tangan ini diuji dari segi postur tangan berkanun dan menguruskan untuk mencontohi tangan manusia sebenar.

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CHAPTER 1

INTRODUCTION

Bionic hand is the hand that is designed similar to the human hand. It is produced in order to resemble the work and movement that can be done by humans. With the existence of bionic hand technology, it can help disabled people, especially amputees to carry out their daily activities as usual. However, this technology can be used not only in medicine, but it can also be used in industrial field. For example, Bionic hand can help reduce the risk to workers who are exposed to radiation, where all the works that related to radiation can be managed by using the Bionic hand. The research about bionic hand is started in 1963 at the Princess Margaret Rose Hospital in Edinburgh David Gow. Then, he joined the Bioengineering Center hospitals in 1986 and begun a study on the electronic hand including wrist hand and shoulder. In 1993, he manages to develop his own partial hand and in 1998 he gained recognition when he develops his first shoulder electric power installations. David Gow then join the company called Touch Bionics where in 2007 the company has launched Bionic hand named I - LIMB hand. Then the company has launched a new product are designated the I-LIMB hand extends to the research of the I-LIMB 2007. In 2010 and 2011 they launched the I-LIMB Pulse that has good characteristic compare to the previous. So, bionic hand, this is a prelude to the creation of other parts such as Bionic legs, eyes and so on.

1.1 Motivation

Refer to the *Buletin Perangkaan* 2012, the table shows 359 203 the total of the numbers disabled people registered under the Social Welfare Department and the total amount of 123 346 that which were registered under the handicapped people with physical disabilities catagories. This included the record like, paralyzed, maimed limbs.

Table 1.1: Statistical Bulletin Social Welfare Department [1]

Negeri *State*	Penglihatan *Visually impaired*	Pendengaran *Hearing*	Fizikal [a] *Physical*	Masalah pembelajaran *Learning disability*	Pertuturan *Speech*	Mental	Lain-lain *Others*	Jumlah *Total*
Malaysia	**31,924**	**43,788**	**123,346**	**134,659**	**725**	**8,927**	**15,834**	**359,203**
Johor	3,094	4,732	13,191	19,396	100	1,436	1,661	43,610
Kedah	2,823	3,070	9,395	9,449	66	623	1,403	26,829
Kelantan	3,570	4,612	10,315	8,720	124	678	3,592	31,611
Melaka	1,126	2024	6,270	7,828	37	511	529	18,325
Negeri Sembilan	1,259	1,689	6,867	7,321	30	469	537	18,172
Pahang	1,469	2,092	7,457	6,973	86	696	1,049	19,822
Perak	2,765	3,779	12,305	13,567	30	1,018	1,166	34,630
Perlis	605	564	2,041	2,003	16	143	215	5,587
Pulau Pinang	1,908	3,042	8,832	8,104	19	494	784	23,183
Sabah	2,123	2,805	6,105	7,206	26	190	1,481	19,936
Sarawak	1,950	2,459	5,699	6,883	69	542	434	18,036
Selangor	3,709	6,271	19,059	19,171	92	1,213	1,723	51,238
Terengganu	2,351	2,644	6,704	8,413	22	439	825	21,398
W. P. Kuala Lumpur [b]	3,117	3,918	8,827	9,193	3	462	420	25,940
W. P. Labuan	55	87	279	432	5	13	15	886

The Table 1.1 shows that Selangor recorded the highest reading in the category of disabled people with physical disabilities. For patients that facing this problem of maimed hands, their daily activities become stunted and difficult to adapt to the daily environment. This is because, by losing all five fingers, it will be difficult for them to perform basic movements such as grasps and hanging the object. Therefore, the prototype called bionic hand is implemented to assist and perform their daily activities.

1.2 Problem Statement

Bionic hand is the human hand modelled as a set of links connected by joints. Using the method of robotics, the motion of finger described as a serial robot. However to resemble human movement in daily activities, bionic hand shape and feature need to construct like a human hand, some of the characteristics must be considered before it can be built. Bionic hand must be able to assist the user to grasp and moving the entire finger.

One product that has been produced is the I-limb Ultra which has been designed by Touch Bionics' Company, but by using 14 Degree of Freedom (DOF) the system of this bionic hand become more complex and it's difficult to control. For the mechanical part of the bionic hand, it's hard to implement because having degrees of freedom. It is because by having a lot of degree of freedom the bionic hand will have more joint and more part that need to assemble together.

Thus, the design of new bionic hand with 10 Degree of Freedom is proposed by using five linear motors and mechanical linkages to generate the movement of the finger. By reducing the number of motor and degree of freedom, the cost of construction of bionic hand can be reduced. At the same time by reducing the total number of motors, the weight of bionic hand also can be reduced. Beside to make the Bionic Hand more durable and easy to construct this project purpose to use the aluminium seven series so it this bionic hand will lighter and better compare to previous bionic hand.

1.3 Objective

i. To design bionic hand that resembles the real human hand.
ii. To fabricate the design bionic hand.
iii. To analyze the performance of the bionic hand in term of repeatability and accuracy.

1.4 Scope

1. The bionic hand is designed by using Solid works Software.
2. The bionic hand focused to 10 Degree of Freedom (DOF).
3. Each of finger has 2 Degree of Freedom (DOF).
4. The bionic hand is actuated using a combination of five Linera DC motors and mechanical linkages.
5. Each the finger of bionic hand actuated between 0° to 90° degree.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this section, the research about bionic hand is conducted. The research focuses more on the mechanism, degree of freedom (DOF), actuator and as well as the material that used to develop the prototype following the K Chart that already develop referring to the Appendix A. There is some concept that must be considered before constructed the bionic hand, the first concept that must be considered, it's the type of mechanism that used to actuate each Degree of Freedom (DOF) for each finger. There are several mechanisms which are applied in the previous experiment to actuate the movement of the Proximal Phalanx (PP), Middle Phalanx (MP) and Distal Phalanx (DP). The second aspect that is considered from the previous research is the number of Degree OF Freedom (DOF). Degree of Freedom (DOF) is the number of movements that can be made by robots. A lot of Degree of Freedom (DOF) will help the robot to do the task better and easier, so if the robot has a lot of number Degree of Freedom (DOF) more work can be done by robots. Bionic hand also needs to be constructed with Degree of Freedom (DOF) where each of finger must have at least two or three Degree of Freedom (DOF) to actuate the Metacapophalangeal joint (MCP), Proxima Interphalangeal joint (PIP) and Distal Interphalangeal joint (DIP). The third aspect is selection of motor to generate the good movement and in accordance with the requirement. A Fourth aspect that is considered in this research is the selection of material. A Material that used must be durable, light, easy to find and also low cost.

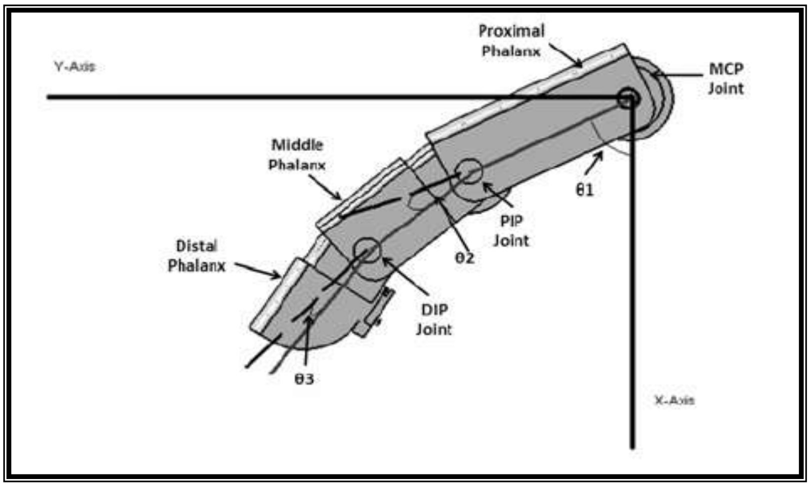


Figure 2.1: Type of Phalange [2]

2.2 Design Concept

Ahmed Jaafar *et al.* (2011) introduce the multifingered anthropomorphic robotic hands that have fourteen degree of freedom (DOF) [2]. The objective of this journal is to mimic the functionality of the biological hand, especially in handling complex object [2]. The bionic hand consists of five fingers where each finger has three different phalanxes it is proximal, middle and distal phalanxes. These three phalanxes were separated by two joints that called the Interphalangeal joint. The design of this bionic hand is done by using CATIA and the fabricated of this prototype is done by using InVision XT-3D Modeler. In this paper the material that is choosed to fabricate this is Acrylic Plastic with the tensile modulus and tensile strength are 1772MPa and 34MPa.

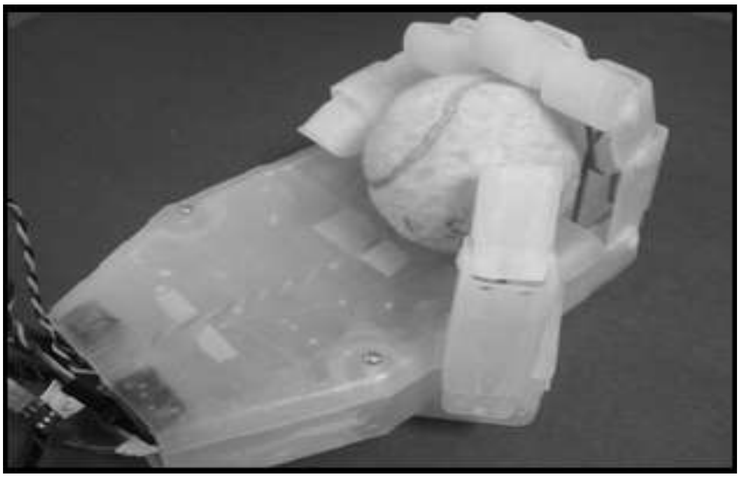


Figure 2.2: Design of bionic hand by Ahmed Jaafar [2]

Whereas in M.C Carrozza *et al.* (2001) the design consists of the 2 degrees of freedom (DOF) for each of the fingers where these bionic hand equipped with three fingers. These papers represent the design and fabrication of novel prosthetic hand base on a “biomechatronics" and cybernetic approach. The objective of this journal is to develop an upper limp prosthesis that can be fielded as a part of the body by the amputee. The prototype fabricated by using Fused Deposition Modeling (FDM) process while acrylonitrile/butadiene/styrene (ABS) plastic is used to construct the body structure for this prototype

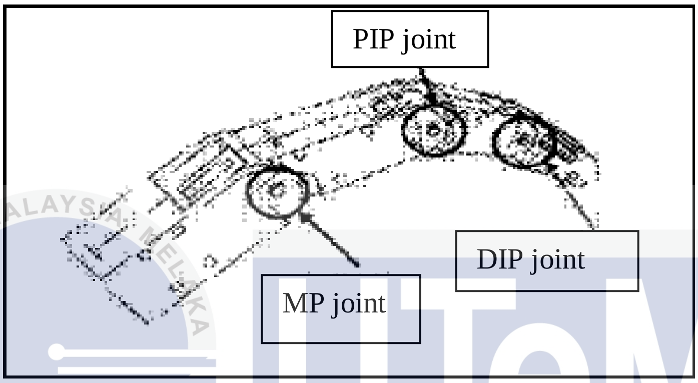


Figure 2.3: Design of bionic hand by M.C Carrozza [3]

According to the Loredano Zallow *et al.* (2007), the biomechatronic approach is used for the design of an anthropomorphic artificial hand. The objective of this journal is to mimic the motion of the human finger [4]. The design of bionic hand consists of (thump, index and middle) with 3 of freedom (DOF) for each finger and 1 degree of freedom (DOF) for ubanation. ProEngineer is used to design and modeling the prototype, where the prototype is constructed by using aluminum alloy while each of the fingers is a shell by carbon fiber. Totally this prototype has ten degrees of freedom (DOF) and 4 degrees of movement.

Figure 2.4: Design of bionic hand by Loredano Zallow [4]

In paper done by W. Widhiada *et al.* (2011) presents how a three fingered gripper can be designed and simulate to provide both gross motion and fine motion of the finger [5]. The objective of this journal is to copy the human hand in term of dexterity and adaptive capabilities to function as either a manipulator or as a prosthetic device [5]. This bionic hand develops with three finger (thump, middle, and index) and seven degrees of freedom (DOF) where all the part is assembling by using SolidWorks program.

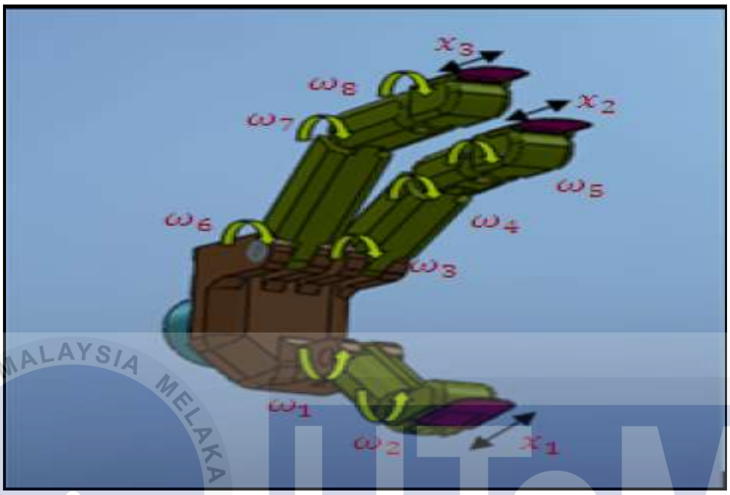


Figure 2.5: Design of bionic hand by W. Widhiada [5]

The design in paper Skyler A. Dalley *et al.* (2010) done by using SolidWorks application to get the true dimensions of design. In this paper, to purpose high strength material, nickel coated thermoplastic are using to create the structure of the bionic hand. In this paper the author represents the design of multi-degree-of-freedom, anthormarphic hand for transradial amputees [6]. The objective of this paper is to provide eight canonical grasp postures [6].

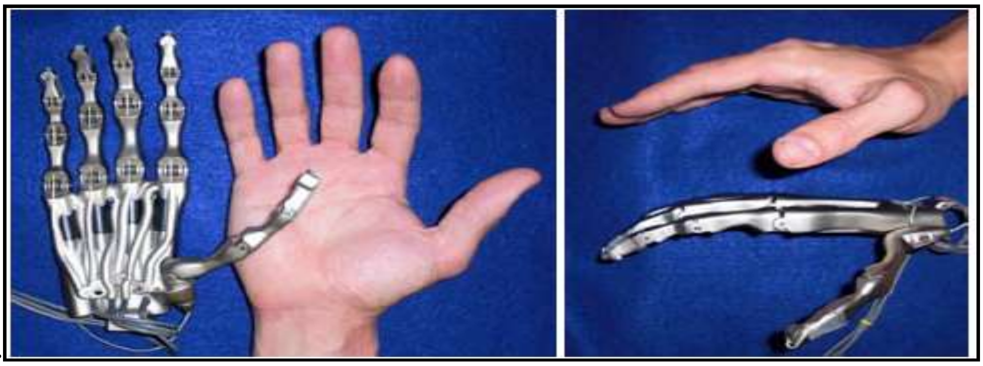


Figure 2.6: Design of bionic hand by Skyler A. Dalley [6]

Preliminary assessment of the ability to perform the activities of daily life living while using the MMC to control a multigrasp prosthesis is proposed by Skyler A. Delly *et al.* (2012) [7]. The objective of this paper is to present a preliminary characterization of the efficiency of the prosthesis during manipulation, capture in the characterization, physical interaction with the environment and demonstrate interdependence between the hand and affected limb [7]. In this paper construction of bionic hand consists of using nine degrees of freedom (DOF) where each of the fingers consists of tree phalange.

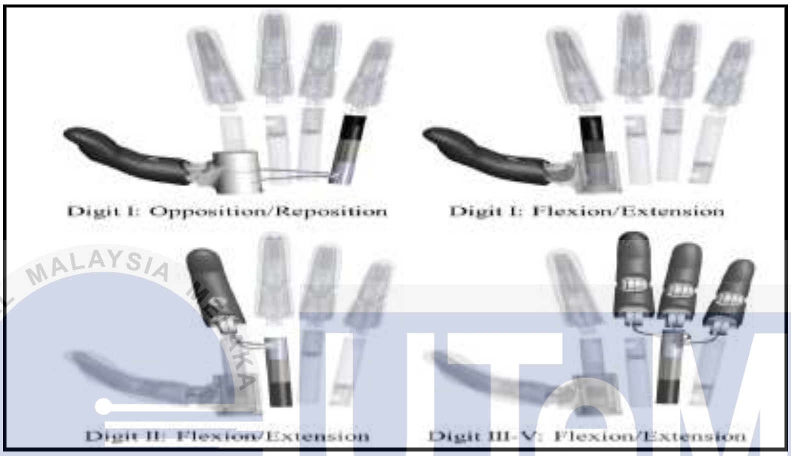


Figure 2.7: Design of bionic hand by Skyler A. Delly [7]

Whereas Praveen Lakkar Srinivasa *et al.* (2013) represent the development of a bionic hand, which perform hand opposition and reposition action (clasp and release) base of the real EMG signal from a below elbow amputee [8]. The objective of this paper is to develop human hand like prosthetic which can provide natural haptic functionality [8]. In this paper the bionic hand is developed by having two degrees of freedom (DOF) below elbow amputee.

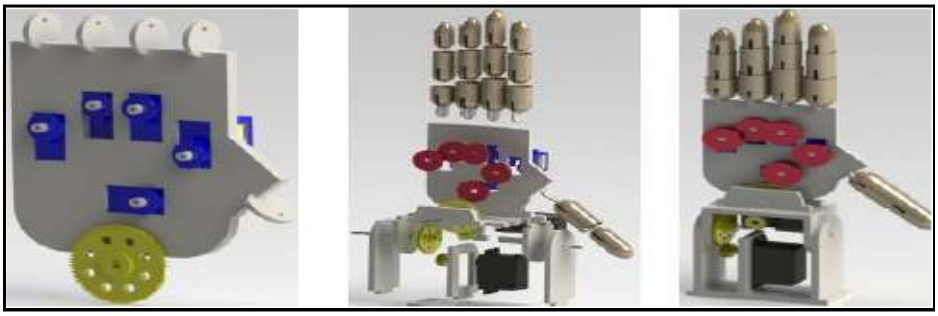


Figure 2.8: Design of bionic hand by Praveen Lakkar Srinivasa [8]

2.3 Actuation Mechanical Design

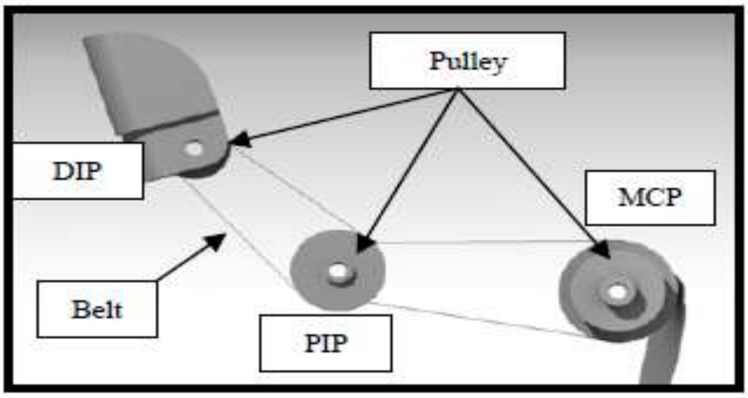


Figure 2.9: Actuation Mechanical Design by Ahmed Jaafar [2]

Jaafar *et al.* (2011) introduce a combination of pulley and belt is used to be the mechanism to transmit the power from the motor to the phalange of a finger. The movement of bionic hand is generated by the micro servo motor where it easy to control and setting the angle of movement.

Whereas in paper M.C Carrozza *et al.* (2001) using 2 brushless motors to generate the movement of 2 degrees of freedom (DOF) for each of the fingers where this bionic hand equipped with three fingers. Lead screw transmission is used to be a mechanism to convert the rotational movement from motor the linear finger movement. Three DC motors are placed in the lower forearm in the paper

The combination motor and pin joint and worm wheel transmission is used Loredano Zallow *et al.* (2007) to generate the movement of this prototype, the bionic hand can be actuated to grasp the object like human hands. According to the paper W. Widhiada *et al.* (2011) the actuator that is chosen is DC motor because it provides the precise rotational. Using the combination of motor with rack and pinion, the extension and retraction of this prototype can be actuated by using the DC motor. In Skyler A. Dalley *et al.* (2010) the series spring is used as a mechanism that is placed in six tandems to transmit the force form motor to each phalange. The special brushless DC servo is constructed with a combination of planetary gear head, brushless motor, two way clutch, tandem pulley and angular sensing via Hall Effect is used in this paper

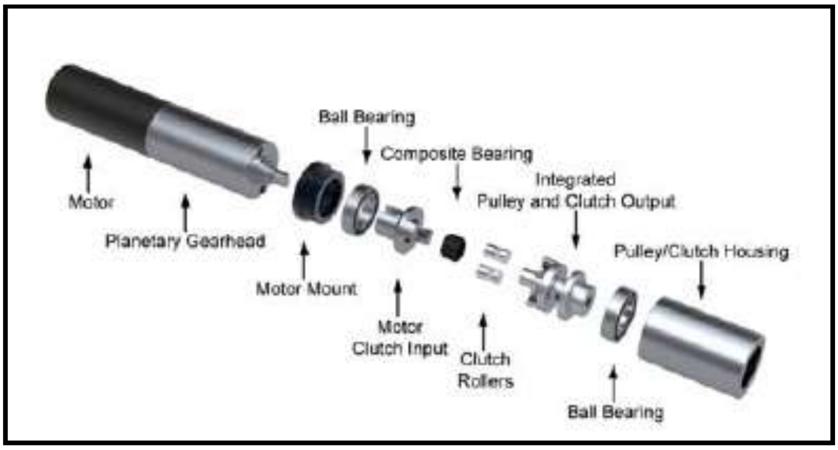


Figure 2.10: Actuation Mechanical Design Skyler A. Dalley [5]

The movement of bionic hand in paper Skyler A. Dalley *et al.* (2010) and Skyler A. Delly *et al.* (2012) generated by using a DC brushless motor as an actuator. The mechanism that is used in this paper is a pulley that fixed in the shaft of the brushless motor. The control method of this ionic hand, represent by using MMC (Multifinger Myoelectric controller). This controller consists of event driven, finite state controller, two-side myoelectric interface where the user needs to determine his hand to open or close. Using five servo motors as an actuator that is attached at the hand of robot Praveen Lakkar Srinivasa *et al*. (2013), the movement of the bionic hand is generated.

2.4 Control Method

Denavit-Hartenbeg method is used in paper Ahmed Jaafar *et al.* (2011) to determine the relationship of rotation and orientation of a fingertip. In this paper also the author used three types of controllers to control the finger movement. The first method is by using Graphical User Interface (GUI) where the combination of the Visual Basic and programming is used to control the movement of a finger. The second method is by using programmings that download to the microcontroller and the last method to control the finger movement by using manual control for the test, the bionic hand is analyzed in term of several grasp with different objects. The kinematic analysis in paper M.C Carrozza *et al.* (2001) is used to determine the relationship of rotation and orientation of the finger movement. The pressure sensor is used in this experiment to analyze the performance of the pressing force from bionic hand. CCS00001 Controller (RMb CH) is used to control the movement for each motor.

According to paper Loredano Zallow *et al.* (2007) the joint space and slide space is controlled by using the P-D controller to purpose the movement of each finger. In paper done by W. Widhiada *et al.* (2011) by using the combination of motor with rack and pinion, the extension and retraction of this prototype can be controlled by using P-D controller. . Skyler A.Delly *et al.* (2012) present the control method of this bionic hand, represent by using MMC (Multifinger Myoelectric controller). Whereas Praveen Lakkar Srinivasa *et al*. (2013) shown using Electromyogram (EMG) the signal of a muscle can be collected at the skin surface in wave form, the wave can be taken by using MyoScan-pro v2 SEMG and the signal is amplified before it can used to control the movement of a finger. The signal that is captured will process in three steps, the three steps that need to complete is feature extraction, feature reduction and signal classification. The signal after that saved in text format and using the MATLAB software the signal would be processed to control the movement of the bionic hand.

2.5 Summary of Literature Review

From the literature that has been made, all the method that used to construct the bionic hand is summarized in a table. Below is the table that shows the comparison of methods that will help the construction of the project.

Table 2.1: Comparison of mechanism, degree of freedom and actuator

Article	Writer	Mechanics	Degree of Freedom (DOF)	Actuator
Design and Control of a Multifingered Anthropomorphic Robotic Hand (2011)	Ahmad Jaafar M.Saiful Bahari Cheng Yee Low	Combination of belt and pulley	14 (5 finger)	DC servo motor
The Development of a Novel Biomechatronic Hand – Ongoing Research and Preliminary Result (2011)	M.C Carrazza S. Micera B. Mass R. Lazzarimi N. Carella P. Dario	Lead screw Transmission	2 (1 finger)	DC brushless motor
Boimechatonics Design and Control of an Anthropomorphic Artificial Hand for Prosthetic and Robotic Application (2007)	Leradana Zollo Stefono Rocella Eugerio Gugliemelli M. Chiara Corrozza Paola Daria	Pin joint and wheel transmission	10 (3 finger)	DC motor

Design and Control of Three Finger Motion for Dexterous Assembly of Compliant Element (2011)	W. Widniad S.S Douglas I.D Jenkinson J.B Gomm	Rack and pinion	7 (3 finger)	DC servo motor
A Multigrasp Hand Prosthesis for Transradial Amputees (2010)	Skyler A Dalley Taumas E Wister Huseyin Atatan Voral Michael Goldfard	-Serial spring	16 (5 finger)	DC servo motor
Preliminary Functional Assessment of a Multigrasp Myoelectric Prosthesis (2012)	Skyler A Dolley Baneal A. Bennett Michael Goldfard	-Serial spring	9 (5 finger)	DC brushless motor
Development of Two Degree of Freedom (DOF) Bionic Hand for Elbow Amputees(2013) .	Pravcen Lakkur Srinirasa Nigananda S.N Govint R. kandambi Hariharan .R Pree Shankpal Shankpal S.R	-	2 (1 finger)	DC brushless motor

Table 2.2: Comparison of material selection, and software that used to design bionic hand

Article	Writer	Material	Modeling by using
Design and Control of a Multifingered Anthropomorphic Robotic Hand (2011)	Ahmad Jaafar M.Saiful Bahari Cheng Yee Low	Acrylic plastic	CATIA
The Development of a Novel Biomechatronic Hand – Ongoing Research and Preliminary Result (2011)	M.C Carrazza S. Micera B. Mass R. Lazzarimi N. Carella P. Dario	Acrylonitrile/butadiene/styrene (ABS)	-
Boimechatonics Design and Control of an Anthropomorphic Artificial Hand for Prosthetic and Robotic Application (2007)	Leradana Zollo Stefono Rocella Eugerio Gugliemelli M. Chiara Corrozza Paola Daria	Aluminum alloy	ProEngineer Software
Design and Control of Three Finger Motion For Dexterous Assembly of Compliant Element(2011)	W. Widniad S.S Douglas I.D Jenkinson J.B Gomm	Solve silicon steeve	SolidWorks

A Multigrasp Hand Prosthesis for Transradial Amputees (2010)	Skyler A Dalley Taumas E Wister Huseyin Atatan Voral Michael Goldfard	Nickels coated thermoplastic	-
Development of Two Degree of Freedom (DOF) Bionic Hand for Elbow Amputees(2013)	Pravcen Lakkur Srinirasa Nigananda S.N Govint R. kandambi Hariharan .R Pree Shankpal Shankpal S.R	Nylon plastic	SolidWorks

Table 2.3: Comparison of Controller

Article	Writer	Control Method
Design and Control of a Multifingered Anthropomorphic Robotic Hand (2011)	Ahmad Jaafar M.Saiful Bahari Cheng Yee Low	-Graphical User Interface (GUI) -Programming -Manual controller
The Development of a Novel Biomechatronic Hand – Ongoing Research and Preliminary Result (2011)	M.C Carrazza S. Micera B. Mass R. Lazzarimi N. Carella P. Dario	-CCS00001 Controller (RMB. CH)
Boimechatonics Design and Control of an Anthropomorphic Artificial Hand for Prosthetic and Robotic Application (2007)	Leradana Zollo Stefono Rocella Eugerio Gugliemelli M. Chiara Corrozza Paola Daria	-P-D controller
Design and Control of Three Finger Motion For Dexterous Assembly of Compliant Element(2011)	W. Widniad S.S Douglas I.D Jenkinson J.B Gomm	-P-D controller

A Multigrasp Hand Prosthesis for Transradial Amputees (2010)	Skyler A Dalley Taumas E Wister Huseyin Atatan Voral Michael Goldfard	-Humusoft 624 DAQ and integrated hall effect
Preliminary Functional Assessment of a Multigrasp Myoelectric Prosthesis (2012)	Skyler A Dolley Baneal A. Bennett Michael Goldfard	-eletromyogram EMG

From result of study studies on literature reviews, the bionic hand is constructed by using the linear motors to generate movement of each finger of my bionic hand referring to the video on the internet. By using a combination of mechanical linkages and motors, each finger can be actuate resemble to the motion like a human finger. Each part of bionic hand is designed by using SolidWorks program where each part can be measured with a more precise dimension. The bionic hand had 10 degrees of freedom where each of fingers will have 2 degrees of freedom.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology used in this project is based on step how to develop this project base on how to achieve the objective. With the activities that have been planned, the idea to solve the design and analysis can be done with more detail and it is also able to guide whatever in doing this project. With these methods, it can help to prepare documentation on this project. The documentation will include the first phase until the last phase before the presentation. In addition, with this method, it can help to make the project goes smooth and able to identify the error is done when doing this project. Therefore, all the error can be easily corrected by return to the previous phase only.

In this methodology section, all the development of bionic hand for this project is discussed in detail referring to the objective. At the early stage on this section shown the step how to design the bionic hand that can resemble the real human hand. The second section will discuss about how to construct the design bionic hand, emulate the human hand shape and the last section will discuss about how to analyze the performance of the bionic hand in term of performance of repeatability and accuracy. Flow chart below shows the step how this project can achieve the entire objective in this methodology.

3.1.1 Flow Chart

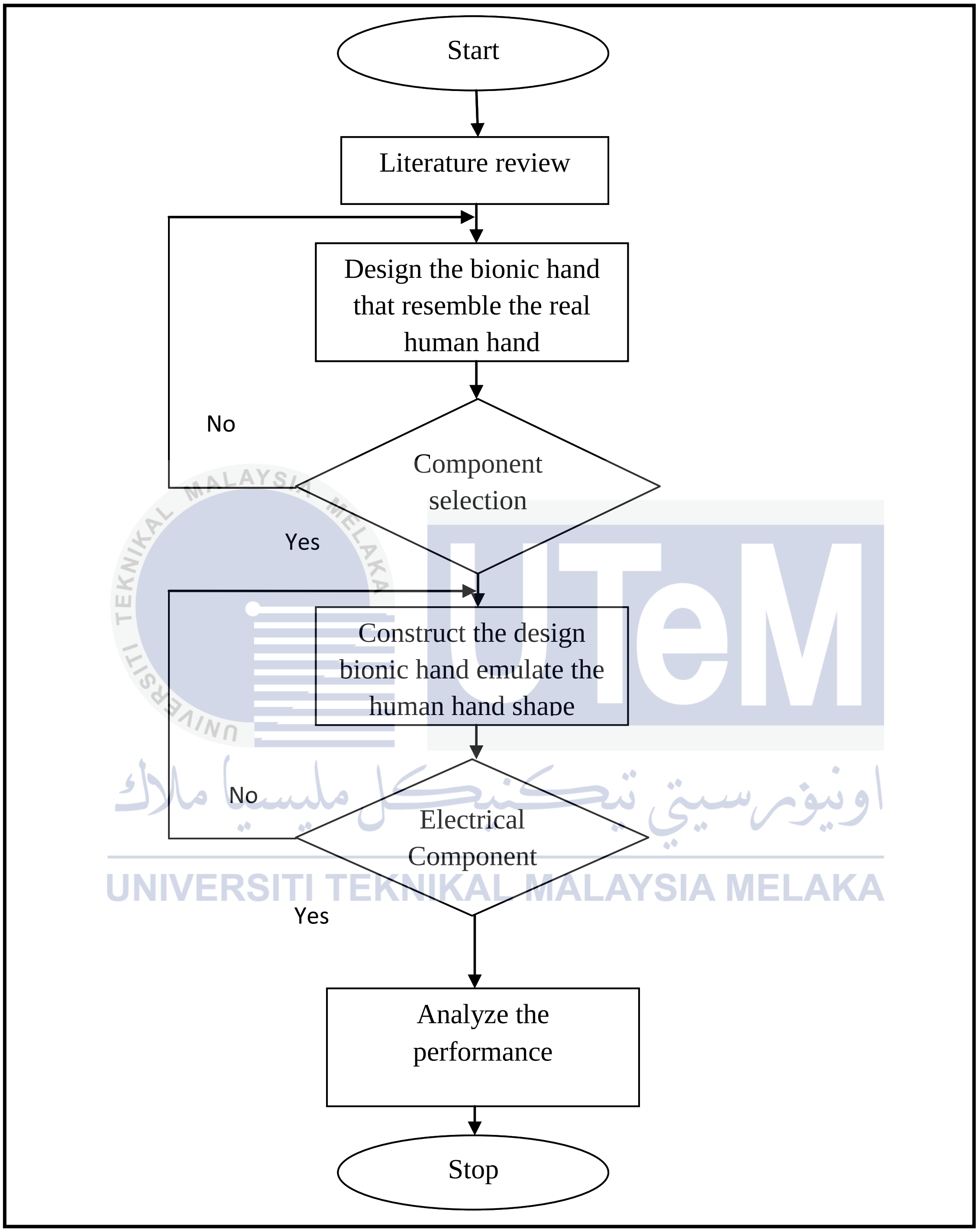


Figure 3.1: Flow chart of methodology

Based on the Figure 3.1, the development of bionic hand can be divided into three significant sections. Each section is discussed in detail to highlight its methodology.

3.2 Design of Bionic Hand

The first objective is to design the bionic hand that resembles the real human hand. This section comprises of two phases, where the first phase discussed about mechanical design while the second phase discussed about the component. Both of section are important to discuss because the component that selected will influence the design of bionic hand. Accordingly, to achieve this objective, the prototype of the bionic hand is designed referring to the human hand characteristic.

3.2.1 Mechanical Design

The mechanical design for this bionic hand is done by using the SolidWorks 2014 software. The bionic hand is designed following the characteristic of the human hand. The natural human hand has set, of which include palm and fingers. There are five fingers each hand where each of finger consists of Proximal, Middle and Distal Phalanx. Figure 3.2 showed the combination of the human phalanx for each of the fingers.

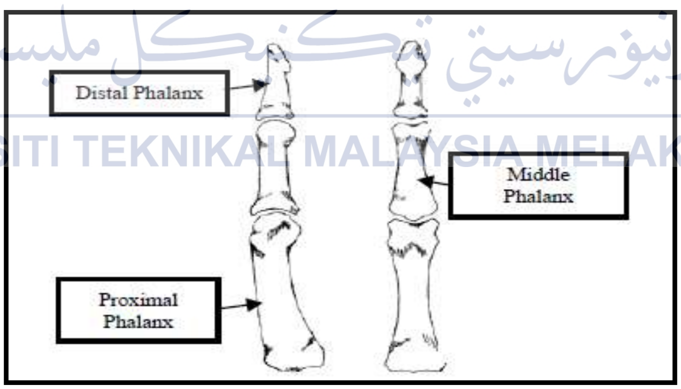


Figure 3.2: Human Finger Stucture [2]

Referring to the figure above these three phalanxes are linked with three joint that call Interphalangeal Joint, Metacarpal Joint and Proximal Joint. Interphalangeal Joint situated between Distal and Middle phalanx, where Metacarpal Joint is situated between Middle and Proximal Phalanx whereas Proximal Joint is situated between Proximal Phalanx and hand palm.

From the information of human hand characteristic, the bionic hand is designed to have five fingers called thumb, index, middle, ring and pinkie. The bionic hand has reduced the degree of freedom by ignoring the Interphalangeal Joint where the Distal and Middle Phalanx is combined together. Using this SolidWorks software, the designs start with designing each of the fingers. Each finger has a different of dimension except the index and ring finger that have the same dimension of the Proximal Phalanx (PP).

Overall, to the design of the bionic hand is subject to change in order to get the suitable shape movement. The size also will be depending on the actuator available in the market.

3.2.2 Component Selection

Component selection the most important during design the bionic hand, it is because each of component that going to be used will influence the structure of bionic hand. In this section the all the component consist of material, actuator and mechanism that is used during the fabrication of bionic hand is discussed in detail. Referring to the previous literature review that is conducted before, linkages and linear DC motor is decided to use as a mechanism and actuator to generate the movement of bionic hand, whereas for the material, aluminum alloy 6061 is used to be the structure of bionic hand during fabrication.

3.2.2.1 Material of Fabrication

Aluminum Alloy 6061 is the one most extensively used in the 6000 series aluminum alloy. It is very versatile heat treatable extruded alloy with medium to high strength capabilities. There are some typical properties of alloy 6061 that be a selection factor of this research. This aluminum provides a good surface finish and good toughness. Beside that, it also provides excellent corrosion resistance to atmospheric condition, good workability and widely available.

3.2.2.2 Firgelli L12 – P Linear Actuator

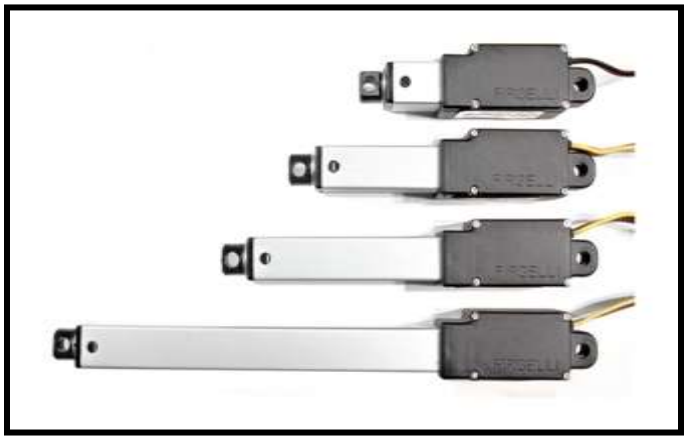


Figure 3.3: Linear motor [8]

. Referring to the design that want to develop, the linear movement is needed to generate the movement each of the fingers. To provide this movement, the linear DC motor is used to generate the motion for each of the fingers. Five linear DC motors are needed during construct this bionic hand and it will be placed inside the hand palm. It will provide the highest torque and low speed movement to each of the fingers. Table 3.1 below show the specification of this linear DC motor.

Table 3.1: Specification of Firgelli L12 – P Linear Actuator

Gearing Option	23N@ 6mm/s
Max Speed (no load)	12 mm/s
Backdrive Force	80N
Weight	34g
Positional Accuracy	02mm
Max Side Force (fully extended)	40N

3.2.2.3 Servo Motor C36R

This servo motor is used to actuate the wrist movement. It placed between the bionic hand, palm and the forearm of bionic hand. The technical parameter and specification of the motor is shown in the Table 3.2.

Figure 3.4: Servo Motor C36R

Table 3.2: Technical Parameter And Specification

RC Servo Code		**C36R**
4.8 V	Speed (s/60˚)	0.16
	Torque(Kg.cm)	3.50
6.0 V	Speed (s/60˚)	0.14
	Torque(Kg.cm)	4.50
Pulse Width Range (ms)	0.5ms to 2.35ms	
Weight (g)	36	

3.2.2.4 Mechanical Linkages

In this project, to make the movement of each finger goes smoothly, mechanical linkage is used as a mechanism to transfer the power that will generate from the linear motor for each of the Proximal Phalanx (PP), Middle Phalanx (MP) and Distal Phalanx (DP) finger. The mechanical linkages are connected to the palm, Proximal Phalanx (PP), Middle Phalanx (MP) and Distal Phalanx (DP) part and motor will generate the movement to retract or extend the entire phalanx.

3.3 Electrical Component

The electrical component is integrated together during the construction process. The selections of electrical components need to do to control this bionic hand. There are many types of electrical component that can be used to control the bionic hand, but in this section the electrical component that is used is discussed in detail.

3.3.1 Electrode

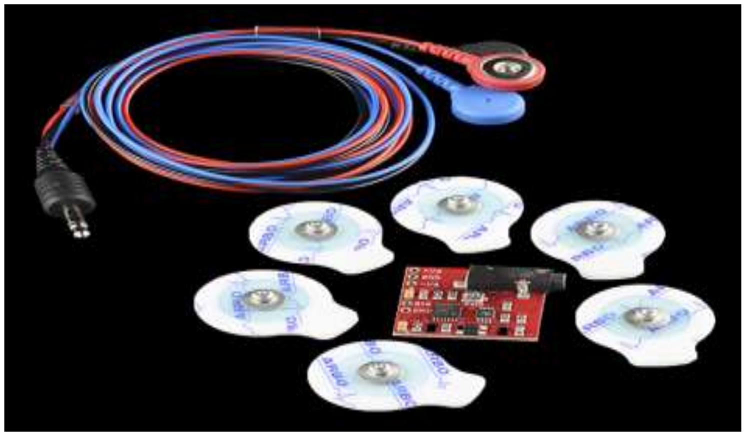


Figure 3.5: Electrode [9]

The electrode is used in this project to detect the electromyogram (EMG) at the surface of human skin. It works like a sensor where each of movement or activities that related to the muscle activities can be captured. This type of sensor is an extension module with V3 kit so all the signal will processed V3 muscle sensor. There have three connections, the blue and red indicate the positive and negative input voltage where the black connection indicates the ground of this sensor.

3.3.2 V3 Muscle Sensor

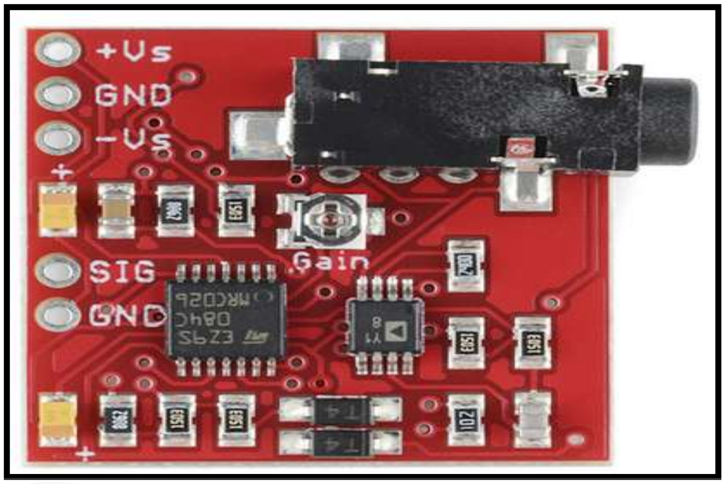


Figure 3.6: V3 Muscle Sensor [9]

The signal from the electrode will amplify by using a V3 muscle sensor. It builds up with small form effect and special design for microcontroller. The gain of this sensor can be adjusted and 3.5mm connector. It can connect to a breadboard and power supply voltage is 3V to 9V. It works like interface between electrode and Arduino. The entire electomyogram signal that is captured by electrode will pattern to a voltage that can be used for Arduino as an input signal.

3.3.3 Arduino Uno13

Figure 3.7: Arduino Uno13 [10]

This bionic hand will control by using Arduino microcontroller Uno R3 that has 14 digital input/output where the pin of number 6 can use as a PWM. It also has 6 analog inputs and 16 MHz ceramic resonator, a USB connection, a power jack, an ICPS header and also reset button. It provides a simply connect simply connection to computer with used cable or power it an AC-to-DC adapter or battery to get started.

3.3.4 Firgelly Linear Actuator Controller

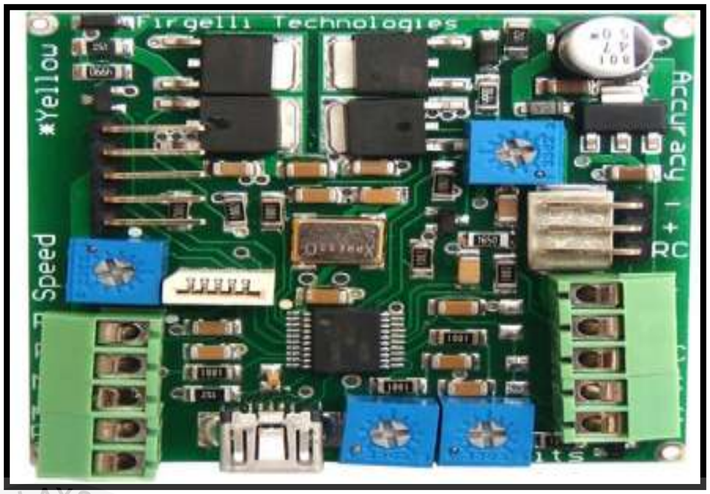


Figure 3.8: Firgelly Linear Actuator controller (LAC) [11]

The liner actuator board as close-loop control board specifically designed for Fergelli "P". It's saving development time, cost and processor overhead associated with direct control motor. One digital or analog is required for position control. LAC can operate as both an interface board, or stand alone with the additional of an external potentiometer and power supply. LAC just can control 1 linear actuator and will require an external potential power supply rates for the actuator

3.3.5 Electrical Circuit Design

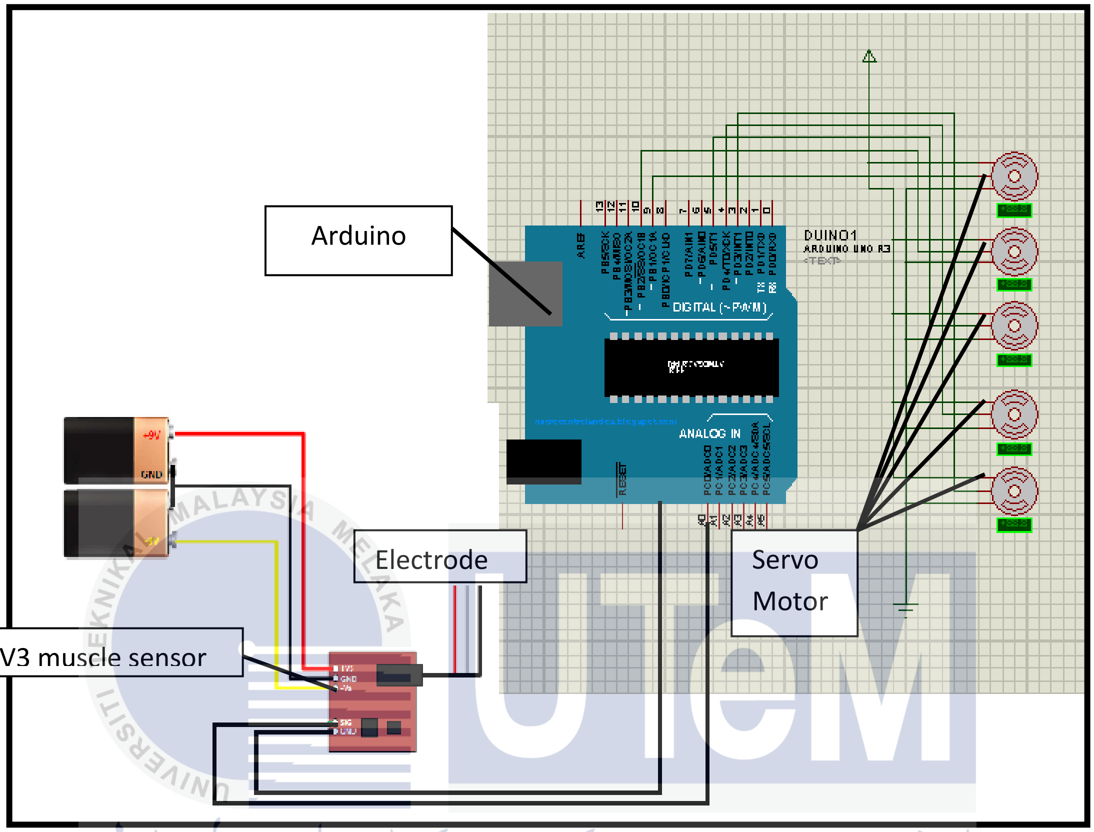


Figure 3.9: Connection of Elctrical Component

The electrical design is the wiring between Arduino Uno R3, DC servomotor, electrode, V3 muscle sensor and other component. Figure 3.9 shows the design circuit that used for the exoskeleton bionic hand. The function of electrode in the design is to capture the signal from muscle sensor. Servo motor And V3 muscle sensor is attached with external power supply. The simulation of the component is tested by using Proteus 7 before all the component can be connected to each other. The Figure 3.10 below shows the block diagram of the bionic hand system

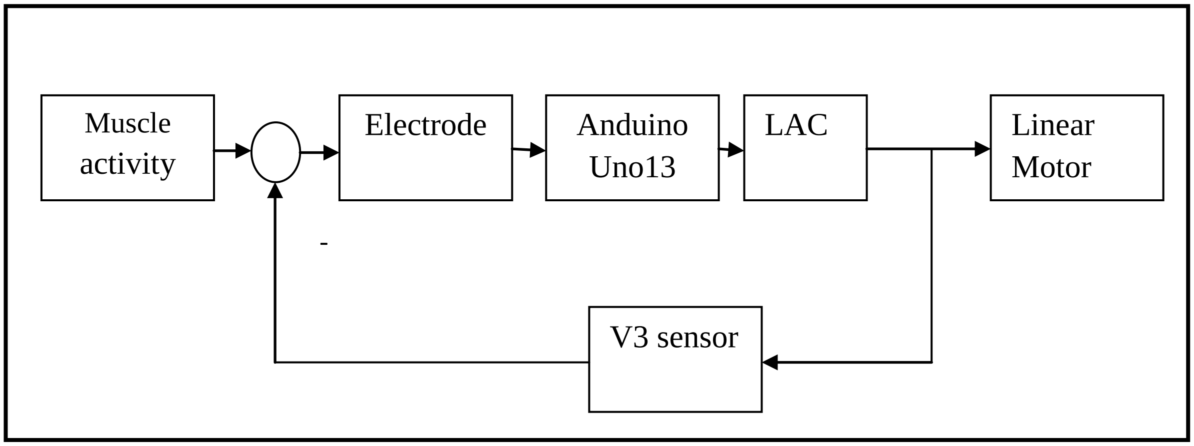


Figure 3.10: Block Diagram of Control System

3.4 Analysis of Performance

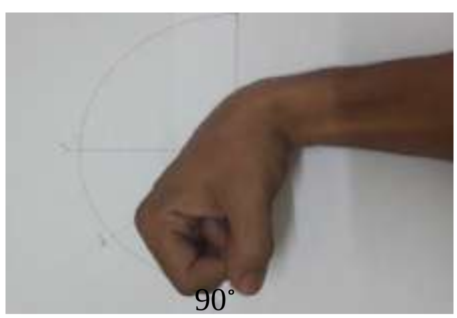
Three types of experiment to analyze the performance of bionic hand is conducted. The first experiment is to analyze the repeatability of joint angle for each finger and wrist movement. Second experiment is to analyze the accuracy of bionic hand on the press and grasp test. The canonical hand postures of bionic hand have be the experiment to analyze the performance of canonical bionic posture. Before the experiment setup, bionic hand is tested to actuate by using signals from muscle. By using the V3 muscle sensor is tested to find the range of analog digital converter value to actiated the bionic hand.

Bionic hand is connected to the electrical component so that it can function. Some test is made to move the bionic hand by using V3 Muscle sensor. These tests are conducted to identify the range of electromyogram before it can be used to program the Arduino, so the linear DC motor can be actuated by using the range of electromyogram. The range of electromyogram just can be taken by making some of the posture of the human hand. Table 3.3 below the posture of the human hand that is made to find the analog digital converter range before it can be used to actuate the bionic hand. Referring to the posture of natural human hand like platform or grasp, the value of elecromyogram different range will give a different reading. The table below has the shown posture of natural human hand that made to find the range of analog digital convert using V3 muscle sensor.

Table 3.3 : Movement of Human Hand To Generate Electomyogram Signal

Human Hand Posture





3.4.1 Experiment of Repeatability

In the experiment the digital camera used to capture the frame for each of joint angle where the tripod to make sure the stabilizing of the camera during the experiment. Figure 3.11 showed the equipment that used during the experiment.

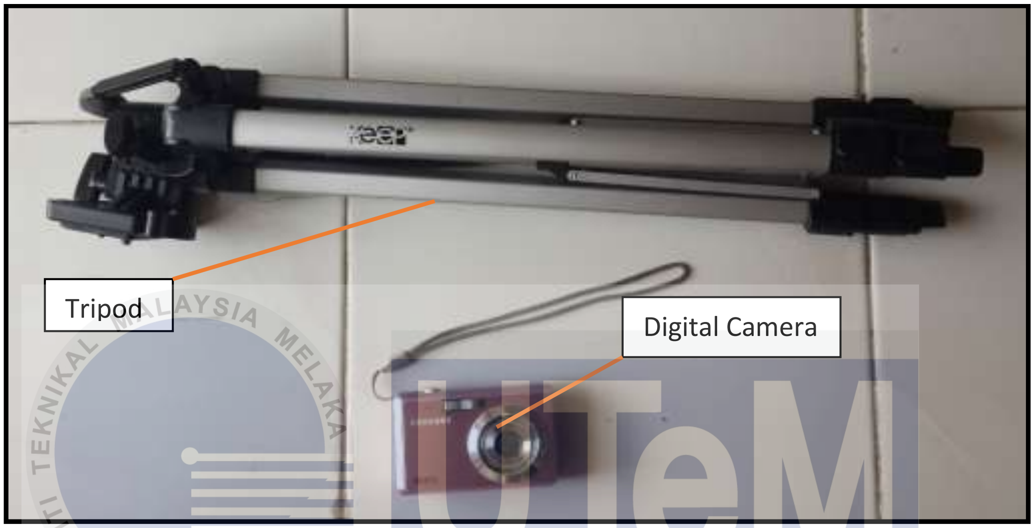


Figure 3.11: Digital Camera and Tripod

Two tests were conducted during this experiment.

I. Repeatability of angle for finger movement

II. Repeatability of angle for wrist movement

The 80 different frame ware acquired during this test, 50 frames are acquired from each finger movement and the other 30 frames are acquired from wrist movement. During this experiment, the digital multimeter is used to obtain the voltage supply to the bionic hand. It is important because the angle of the finger and wrist is related to the voltage supplied. The relative position of joint is measured by using protector. For the first experiment the angle of flexion and extension is taken and the data are tabulated in the table. From the experimental data, one graph is constructed to evaluate the analysis of repeatability. The same step is used to analysis the repeatability of the second experiment.

3.4.1.1 Repeatability of Angle for Finger Movement

A digital camera is mounted on a tripod in order to obtain the stable position perpendicular to the plane of movement of the finger which is fixed in vertical.

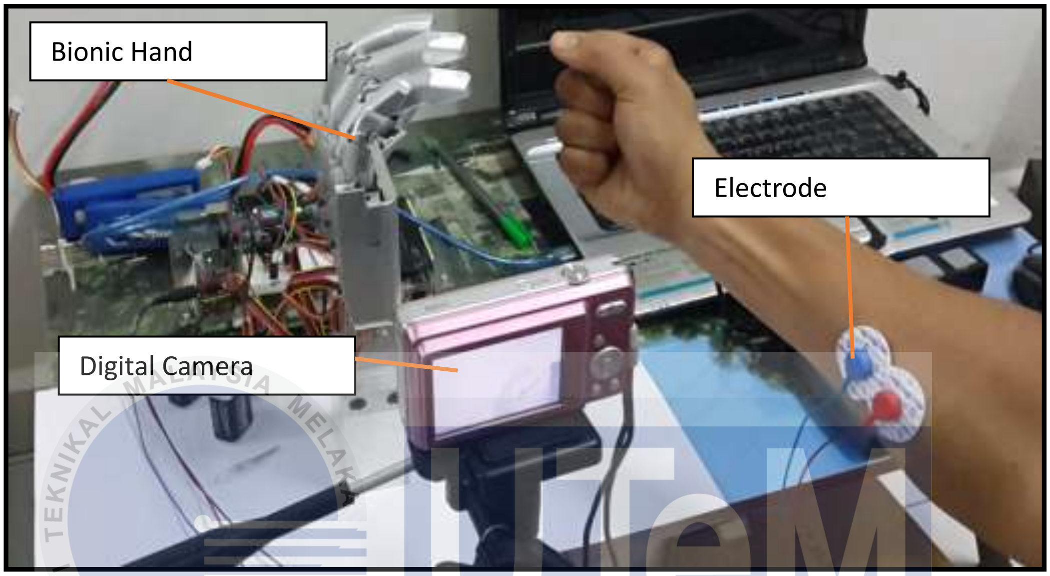


Figure 3.12: Experiment of Finger Repeatability

Figure 3.12 showed the electrode is used to supply the electromyogram signal to the bionic hand. Using the signal from electrode one by one finger is tested to determine the angle of repeatability of joint angle for extension and flexion angle. The experiment started when the electromyogram is supplied from electrode to the bionic hand until the finger move from open position to fully closed. After the position of the fingers is identified, the frame of finger is captured by using a digital camera. The process is repeated until 10 times for each finger and wrist to using the same procedure.

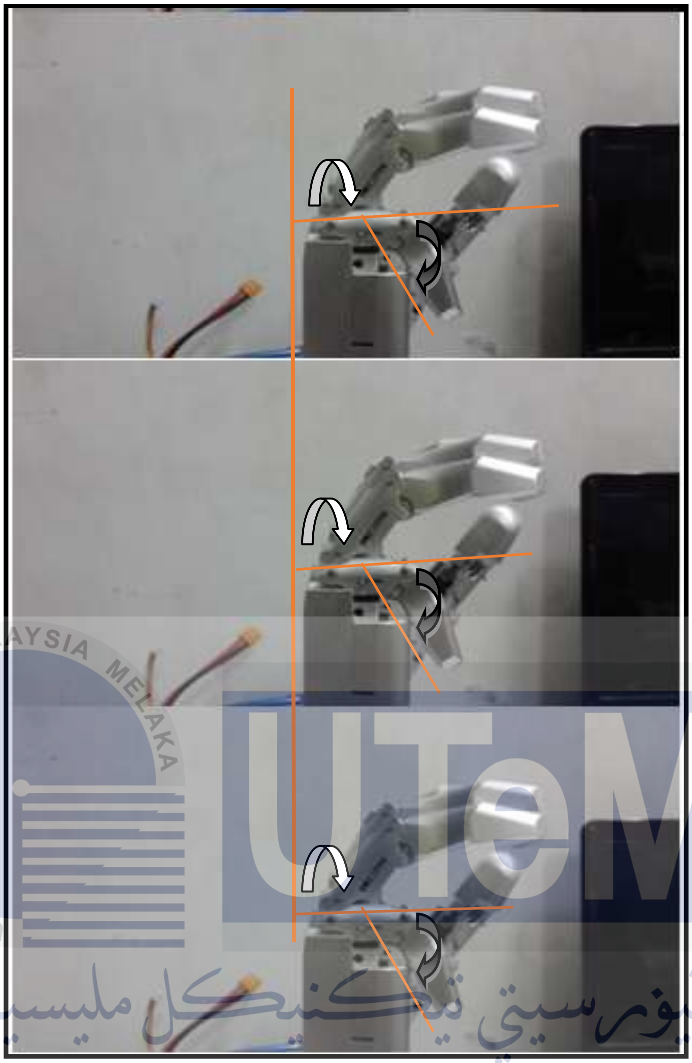


Figure 3.13: Example of Result For Repeatability of Pinkie Finger (for extension and flexion angle movement)

Based on Figure 3.13 above which indicate the three samples of result for a repeatability test conducted to observe the extension and flexion of angle movement for pinkie finger. The relative position of joint for flexion and extension are measured by using protector the data from the measurement are constructed into the table. From the data that is recorded, one graph is constructed to evaluate the analysis of repeatability.

3.4.1.2 Experiment of Repeatability for Angle Wrist Movement

The same step is used to analysis the repeatability of the second experiment. The Electrode is used to supply the electromyogram signal to the bionic hand. Using the signal from electrode the bionic wrist is tested to determine the angle of repeatability of the joint angle. The experiment started when the electromyogram signal is supplied from electrode to the bionic hand. After the position of the wrist is identified, the frame is captured by using a digital camera. 30 different frames were acquired during this test, 10 frames are acquired from a backwards movement angle, 10 frames are acquired from a middle movement angle and the other 10 frames are acquired from a forward movement angle. The relative position of joint for flexion and extension is measured by using protector. From the data that is recorded, the graph of angle response angle of extension and flexion is constructed to evaluate the analysis of repeatability

Figure 3.14: Example of Result For Repeatability of Wrist for an Angle Movement

Based on Figure 3.14 above which indicate the three samples of result for a repeatability test conducted to observe the middle, forward and backward of angle movement for the wrist bionic hand. The long yellow line indicates the reference angle of bionic hand where the orange line indicates the movement of joint angle, whereas blue arrow indicate the forward movement of the joint angle and the orange arrow indicate the backwardness of the joint angle. Each angle is measured by using the protector. From the data that is recorded, one graph is constructed to evaluate the analysis of repeatability

3.4.2 Experiment of Accuracy Test.

In experiment to define the accuracy of bionic hand, the measuring results force of natural human hand and comparing the measurement of bionic hand force is constructed. Some equipment is used in this experiment. The hand dynamometer used to measure the force that is produced by bionic hand.

Figure 3.15: Hand Dynamometer Measurement [12]

Figure 3.15 showed the hand dynamometer that used during the experiment. In this project, hand dynamometer is used to measure the grasp force and pinch strength of bionic hand. But the hand dynamometer cannot directly give the value of measurement in term of force. However the measurement will be shown in term of voltage value. To get the value by using a hand dynamometer, the LapQuest2 is used to be the interface in this experiment. It is connected together and the measurement of bionic hand and human hand can measure directly. Figure 3.16 shows the LabQuest2 that is used to read the measurement in this experiment.

Figure 3.16: LapQuest2

. Two experiments is identified to analyze the performed of accuracy for bionic hand.

I. Pressing test between index and thumb finger
II. Pressing test for combination of all fingers.

During the experiment, the force characteristic of finger tips is measured by using the Hand Dynamometer, and each of data of Hand Dynamometer is monitored. The result of both experiments is compared with the natural human hand to find the result of accuracy. With this aim the accuracy of bionic hand can be evaluated.

3.4.2.1 Pressing Test Between Index, Middle and Thumb Finger.

The first test is the press the hand dynamometer by using the index and thumb finger. In this experiment the natural human finger is used to pressing the hand dynamometer. The result is recorded during 10 second pressing tests to take the constant force value of the natural human finger. Three different subjects are involved in this experiment where each of the subjects has different force strength. Each of subject need to hold the hand dynamometer for 10 seconds, and the data for each second is recorded to find the constant force for each of the tests. The experiment repeated 10 times to get the constant value of the test pressing. The same process of pressing test is constructed at Bionic hand. During the testing the bionic hand is placed horizontally to avoid falling hand dynamometer. Figure 3.17 showed the testing that is done before the experiment.

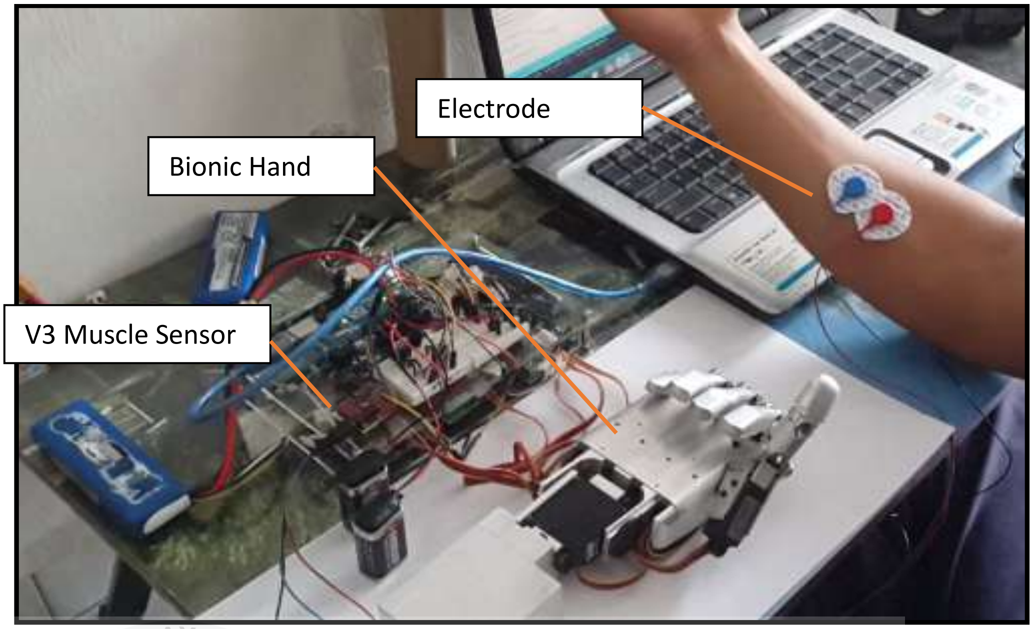


Figure 3.17: Testing the bionic hand Movement

The force result that has been produced by bionic hand is recorded. The process repeated until 10 times to get the constant force value of bionic hand. The electrode is used to control the bionic hand by using electomyogram signal during the test. During the experiment the value of electomyogram is monitored using question below to avoid the high voltage supply to Arduino controller.

$$ADC = \frac{Vref\ X\ 1023}{5V} \quad (1.1)$$

If the high voltage is given to the controller, the possibility of bionic hand to damage will high.

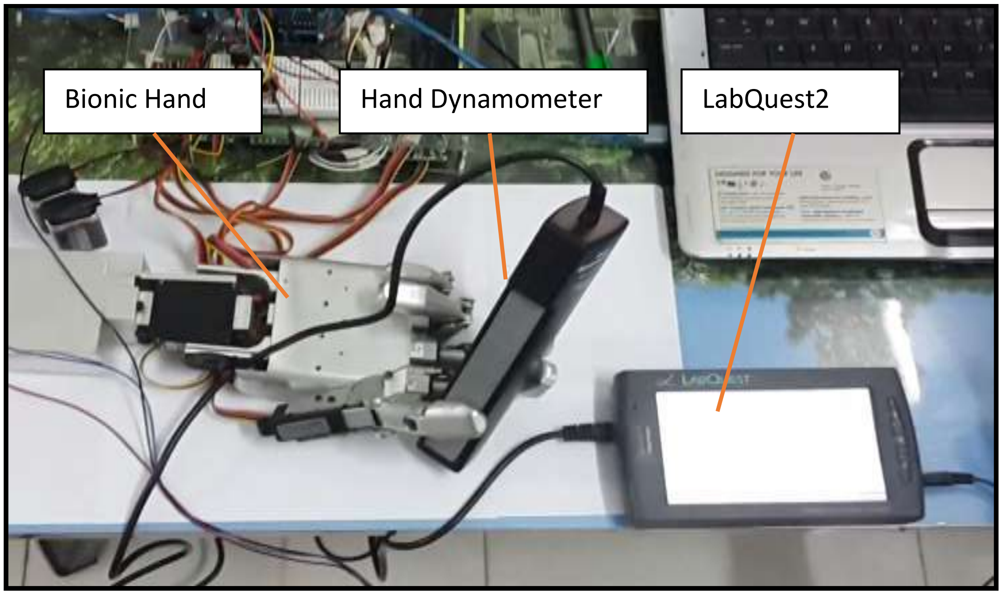


Figure 3.18: Experiment of Press Hand Force

From the experiment in figure 3.18, the result that is recorded by using LabQuest2 is transferred into the Excell. From the data, one table is constructed to define the average force of natural human hand and bionic hand. Each the data of natural human hand and the bionic hand in this experiment is compared with analysis of accuracy.

3.4.2.2 Grasp Hand Test

The second experiment is the grasp hand test by using the combination all fingers. In this experiment, the same procedure is conducted to determine the force of finger press is used to determine the human grasp force. The natural human finger is used to grasp the hand dynamometer in this experiment to determine the average of the natural human force and bionic human force. The result is taken during 10 second pressing tests to take the constant force value of the natural human finger. The experiment is repeated 10 times to get the constant value of the test pressing. The force result that has been produced by bionic hand and natural human hand is recorded by using LabQuest2.

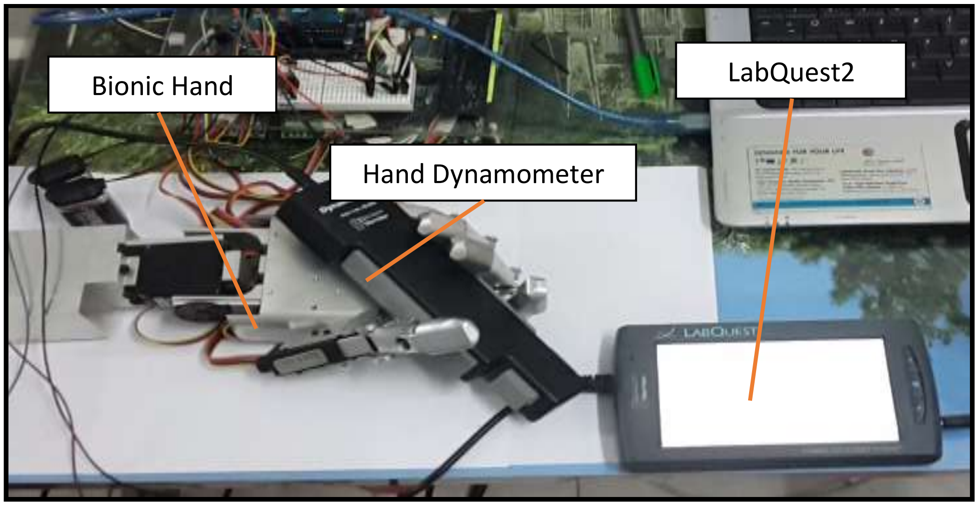


Figure 3.19: Experiment of Grasp Hand Force

Referring to the Figure 3.19, 10 grasp experiments were conducted to get the constant force value of bionic hand. The electrode is used to control the bionic hand by using electomyogram signal during the test. During the experiment the value of electomyogram is monitored using question (1.1) to avoid the high voltage supply to the controller. If the high voltage is given to the controller, the possibility of bionic hand to damage will high. From the data that is recorded by using LabQuest2, all, the result is converted to the Microsoft Excel before it can directly can be used. One average graph is constructed from the average table to evaluate the analysis of accuracy.

3.4.3 Canonical Hand Posture

In the section six postures of bionic hand were made to emulate the human hand posture during this experiment. The posture that is made by bionic hand is cylindrical, lateral, angular surface, spherical, grasp and platform. Using the electromyogram signal from forearm muscle, the bionic hand is actuated with the range that already put in the coding. Each goods were put in the palm of bionic hand and the signal from hand is given to actuate the bionic hand. Figure 3.20 showed some of the object that used in this experiment. All this object has different shape of surface therefore the bionic hand can be tested with different canonical hand posture.

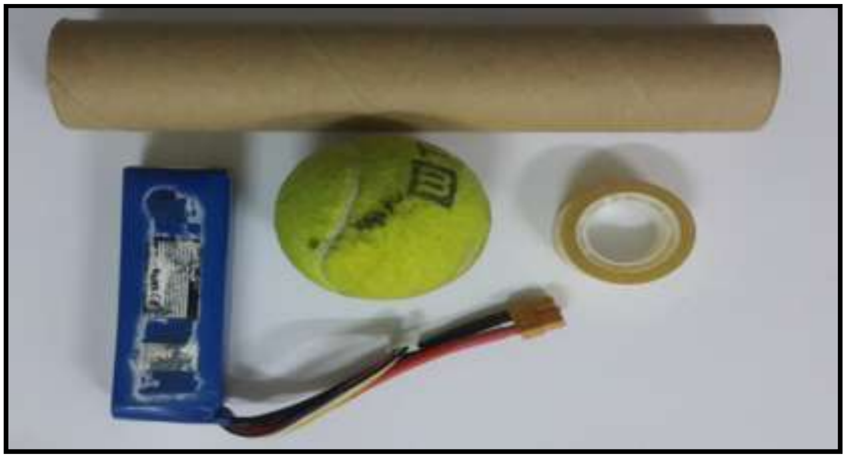


Figure 3.20: Object That Have Different Shape of Surface

During the test, all the object that used by bionic hand to grip before it can compare with natural human hand, whether it can emulate the posture of the human hand or not. Figure 3.21 below shows the experiment of canonical hand posture.

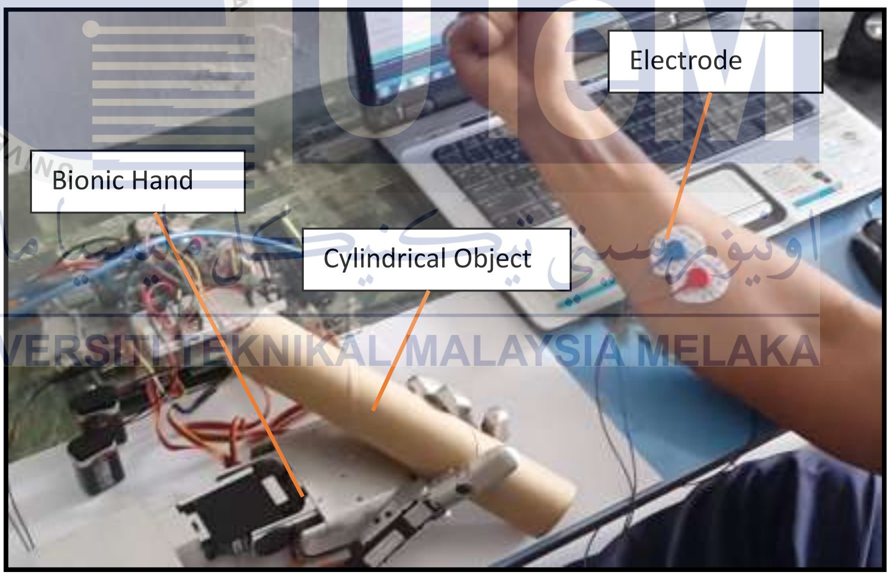


Figure 3.21: Cononical Hand Posture Test

Form the posture of bionic hand, the result after that compared with the natural human hand. The condition for all fingers of bionic hand during its grip the object is compared with postures of the human hand to see whether it can emulate the natural human hand or not.

3.5 Gantt chart

In this project, to achieve all the objective the Gantt chart is provided refers to the Figure 3.22. It used as guidelines during to finish this project successfully. It helps more to manage the time regarding the timeline that is suggested. The figure 3.22 below is the Gantt chart that should be followed to achieve three objectives in this project.

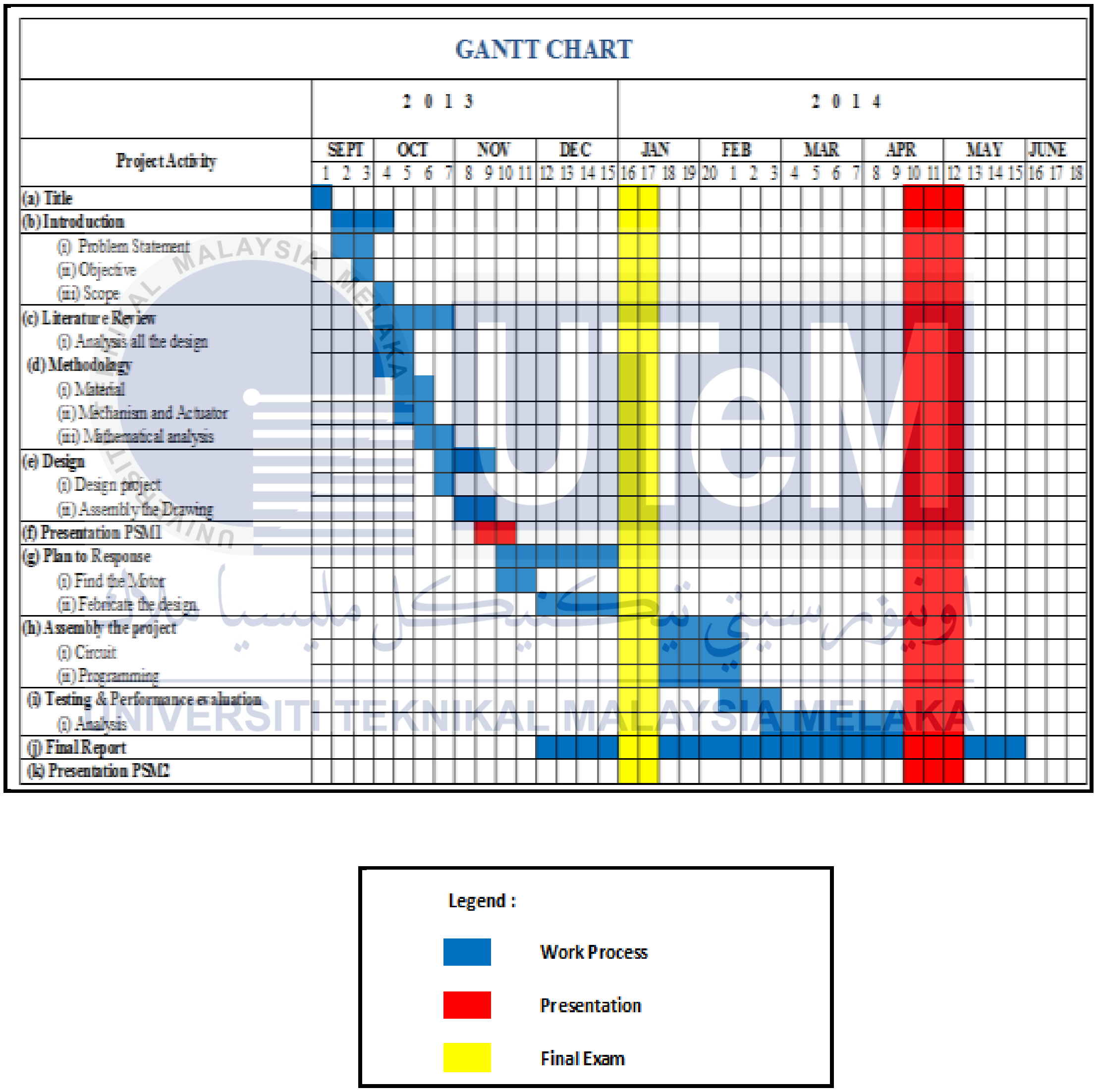


Figure 3.22: Gantt chart

3.6 Bill of Material

Table 3.4: Bill of material

Material	Price	Number of usages	Total
Fabrication	RM2300.00	-	RM1600.00
Linear DC Motor	RM 500.00	5	RM 2500.00
V3 muscle sensor	RM 250.00	5	RM 250.00
Arduino Uno	RM 80.00	1	RM 80.00
		Total Cost	**RM 3830.00**

3.7 Summary of Methodology

Project methodology in this project is showing the method that used to achieve all three objectives. In this chapter, the entire step consists of designing, integration of bionic hand and overview of experiment in this project is discussed in detail. To reach all, the objective of this project, the Gantt chart is developed to make sure all the planning following the guidelines. At the last in this chapter the bill of material is provided to show that the cost that need to construct the bionic hand.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter describes about the result and analysis referring to the objective of the project. The first section discussed about the design of bionic hand that already done by using SolidWorks 2014 and the second section is discussed about the construction of bionic hand and electrical integration. The analysis of results is made based on the third objective to analyze the performance of bionic hand in term of repeatability and accuracy, some of testing need to make to collect the measurement of movement and force that is generated. The results are analyzed after all the data are collected for the testing that has been done at the bionic hand. From the data that is collected, the graph is constructed based on the data that is tabulated to analyze the performance in term of the repeatability and accuracy. At the end of this section, the bionic hand analyzed in term of canonical hand posture. All the analysis will be discussed here in detail.

4.2 Design of Bionic Hand

The mechanical design for this bionic hand is done by using the SolidWorks 2014 software. Using this software, this bionic hand can be designed by following the dimension. This bionics hand is separated into 11 parts to design without including the actuator and mechanical linkages. The designs start with designing the Proximal Phalanx (PP) each of the fingers. Each of Proximal Phalanx (PP) has a different of dimension except the index finger and ring finger that have the same dimension of the Proximal Phalanx (PP).

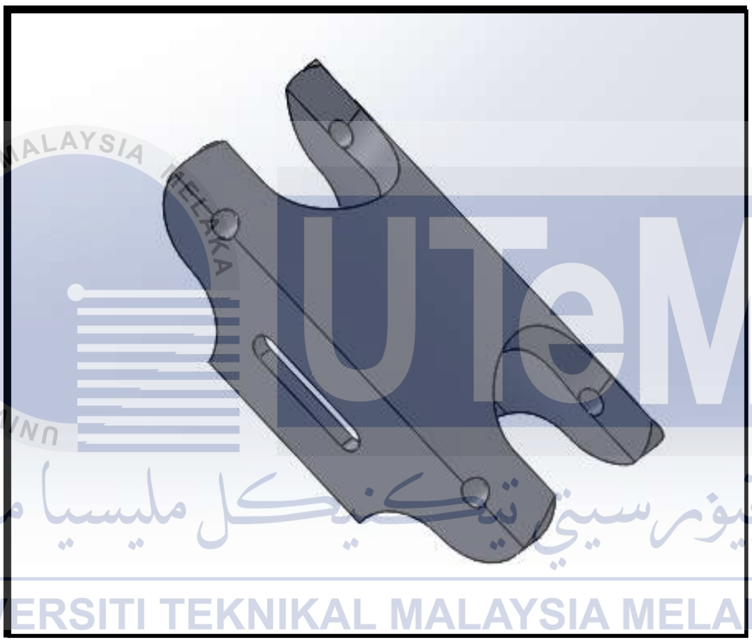


Figure 4.1: Proximal Phalanx (PP) for Thump

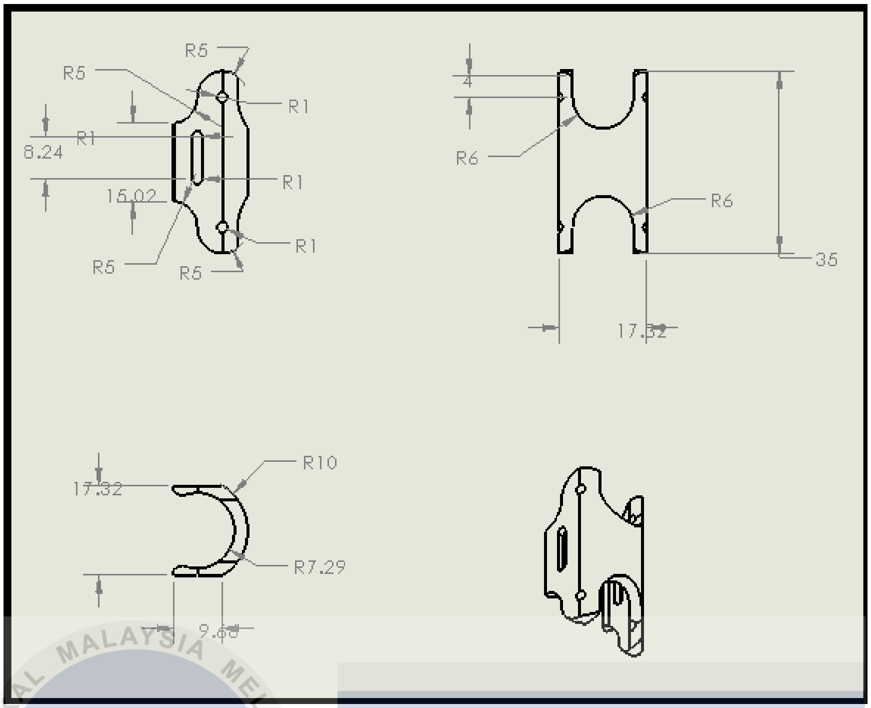


Figure 4.2: Dimension for Proximal Phalanx (PP) for thump

Figure 4.2 shows the dimension of the Proximal Phalanx (PP) for the thump. All the dimension is shown in three views which is a top view, front view and side view. The rest of dimension for a phalanx is attached in the Appendix C.

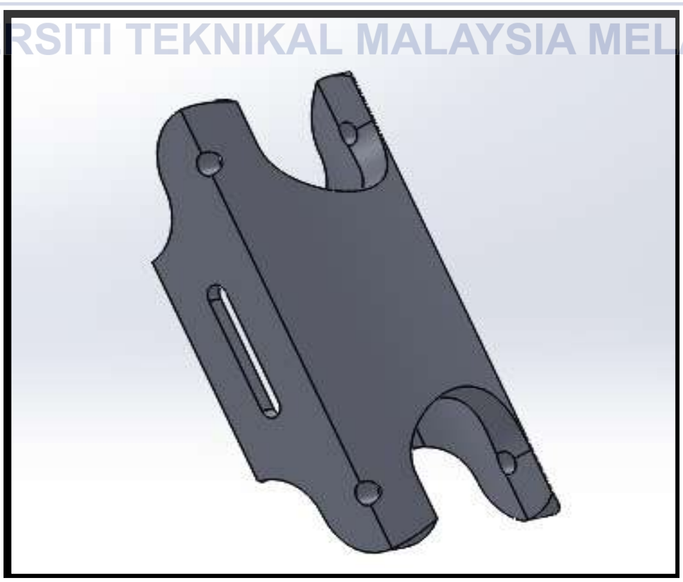


Figure 4.3: Proximal Phalanx (PP) pinkie finger

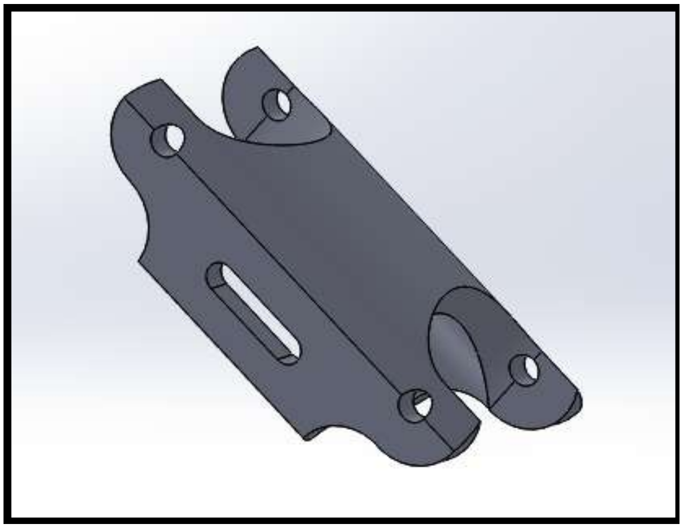


Figure 4.4: Proximal Phalanx (PP) for index, middle and ring finger.

The second step of mechanical design is to draw the part of Middle Phalanx (MP) and Distal Phalanx (DP) where the Middle Phalanx (MP) and Distal Phalanx (DP) is combining during the sketching to reduce the degree of freedom of bionic hand. All the Middle Phalanx (MP) and Distal Phalanx (DP) have a different dimension, except for the index and ring finger that have assumed to have the same dimension.

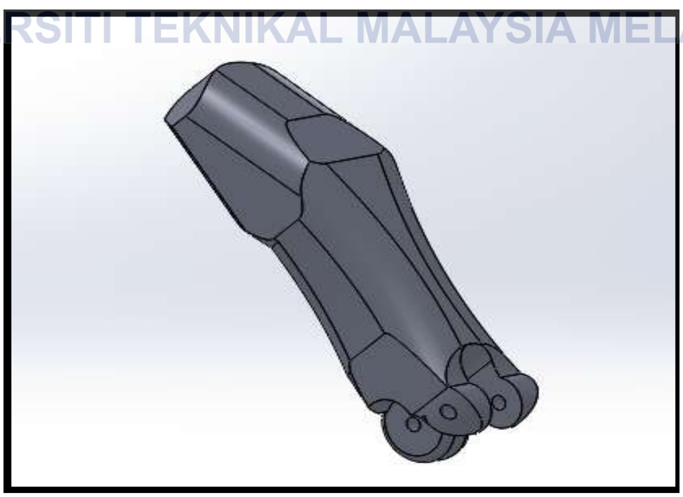


Figure 4.5: Combination of Middle Phalanx (MP) and Distal Phalanx (DP) for middle finger

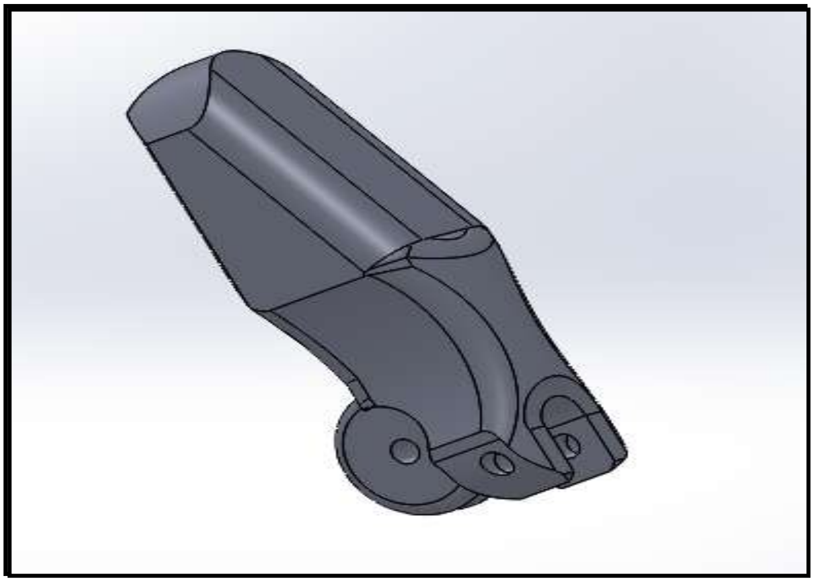


Figure 4.6: : Combination of Middle Phalanx (MP) and Distal Phalanx (DP) for pinkie finger

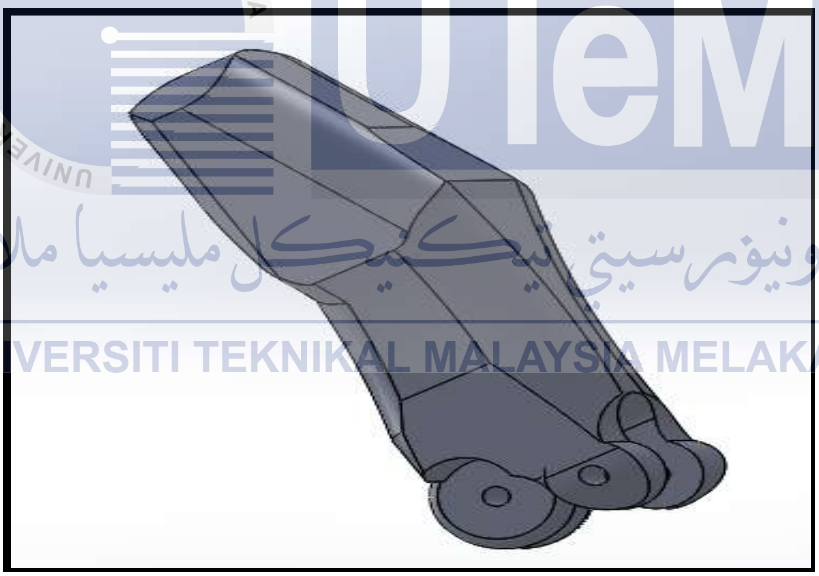


Figure 4.7: Combination of Middle Phalanx (MP) and Distal Phalanx (DP) for index and ring finger

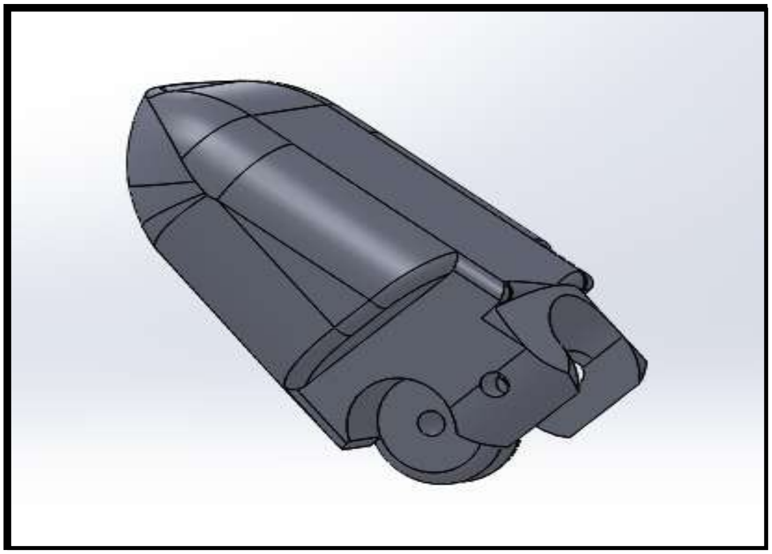


Figure 4.8: Distal Phalanx (DP) for thump

Figure 4.9 below shows the structure of mechanical linkages that is placed in the Proximal Phalanx (PP). The function of this mechanical linkage is used to pull and push the Middle Phalanx (MP) and Distal Phalanx (DP). By applying this method, the bionic hand can produce the movement to grip the same object.

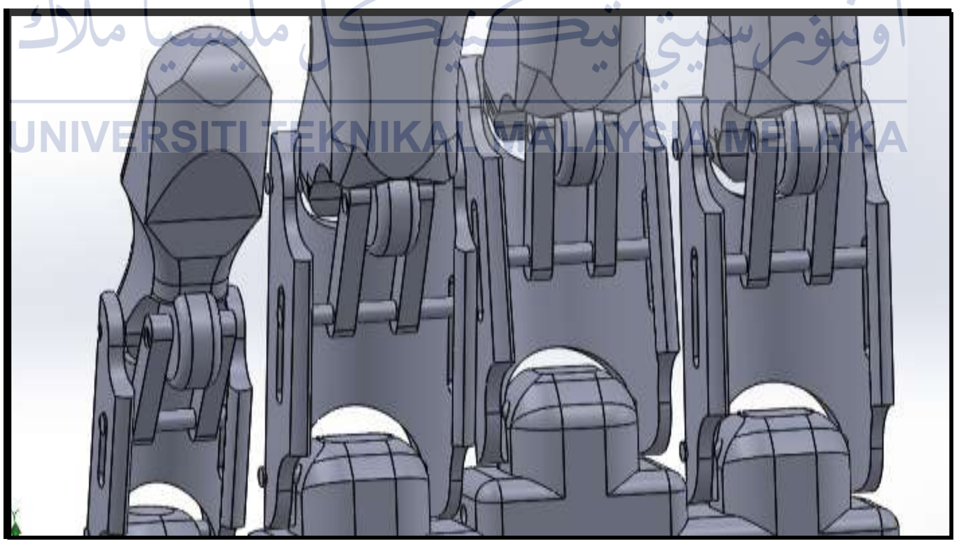


Figure 4.9: Mechanical Linkages Structure

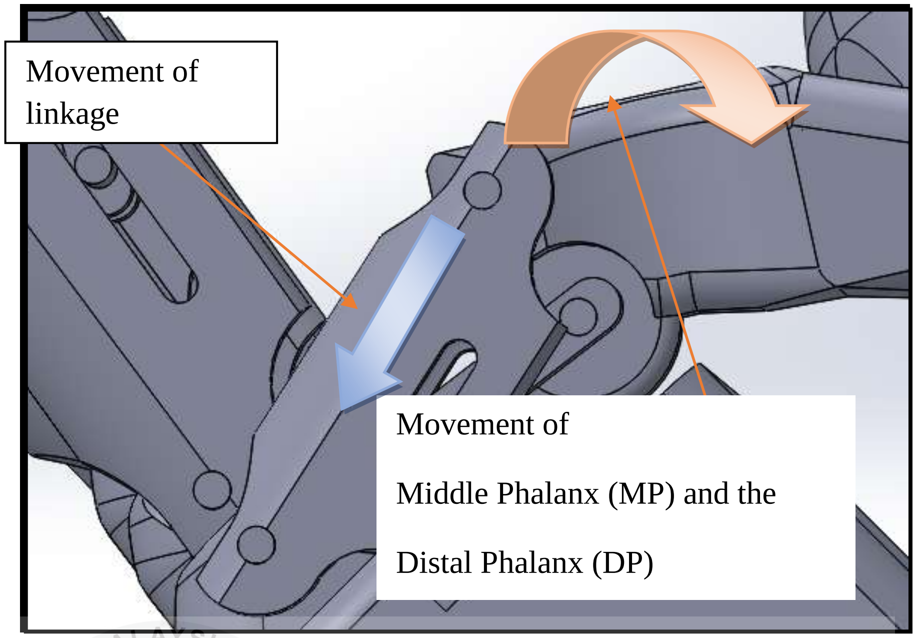


Figure 4.10: Movement of Mechanical Linkages

Figure 4.10 above, shows the function of mechanical linkages, the mechanical linkages will be slipping when it pull by a linear DC motor. When this happens, proximal phalanx (PP) will attract Middle phalanx (MP) and the distal phalanx (DP) will move down. Therefore the motion of each finger can be produced such as grasping.

The last part that's difficult to draw is palm part of bionic hand. That is because in this part all the components like actuator and mechanical linkages need to assemble together in this part. During sketching this part, the problem that needs to consider is, how to assembly all the part of the finger,linear DC motor and mechanical linkages.

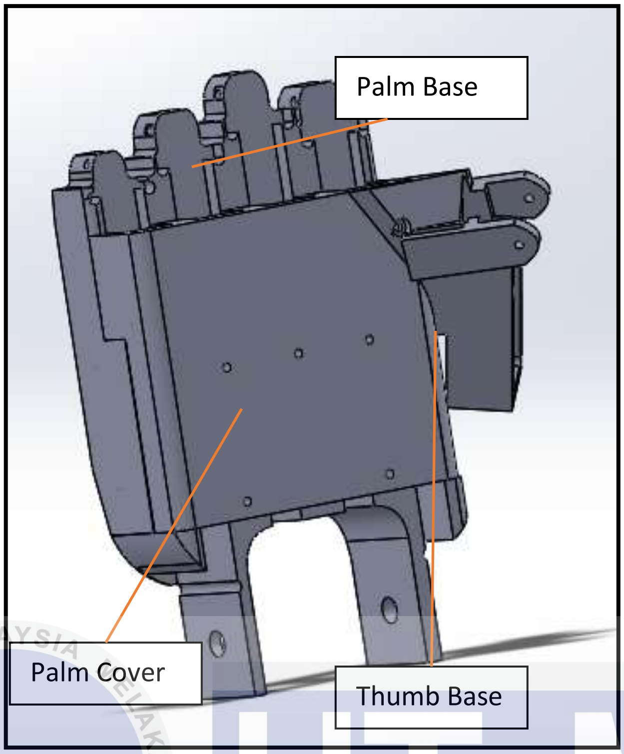


Figure 4.11: Design of palm

Referring to the to the Figure 4.11, Bionic hand consists of 3 based on the structure. The first structure calls palm base that functions as the main site. Whereas the second structure is called palm cover to protect the linear DC motor meanwhile the third structure called thumb base that function to hold that thumb finger

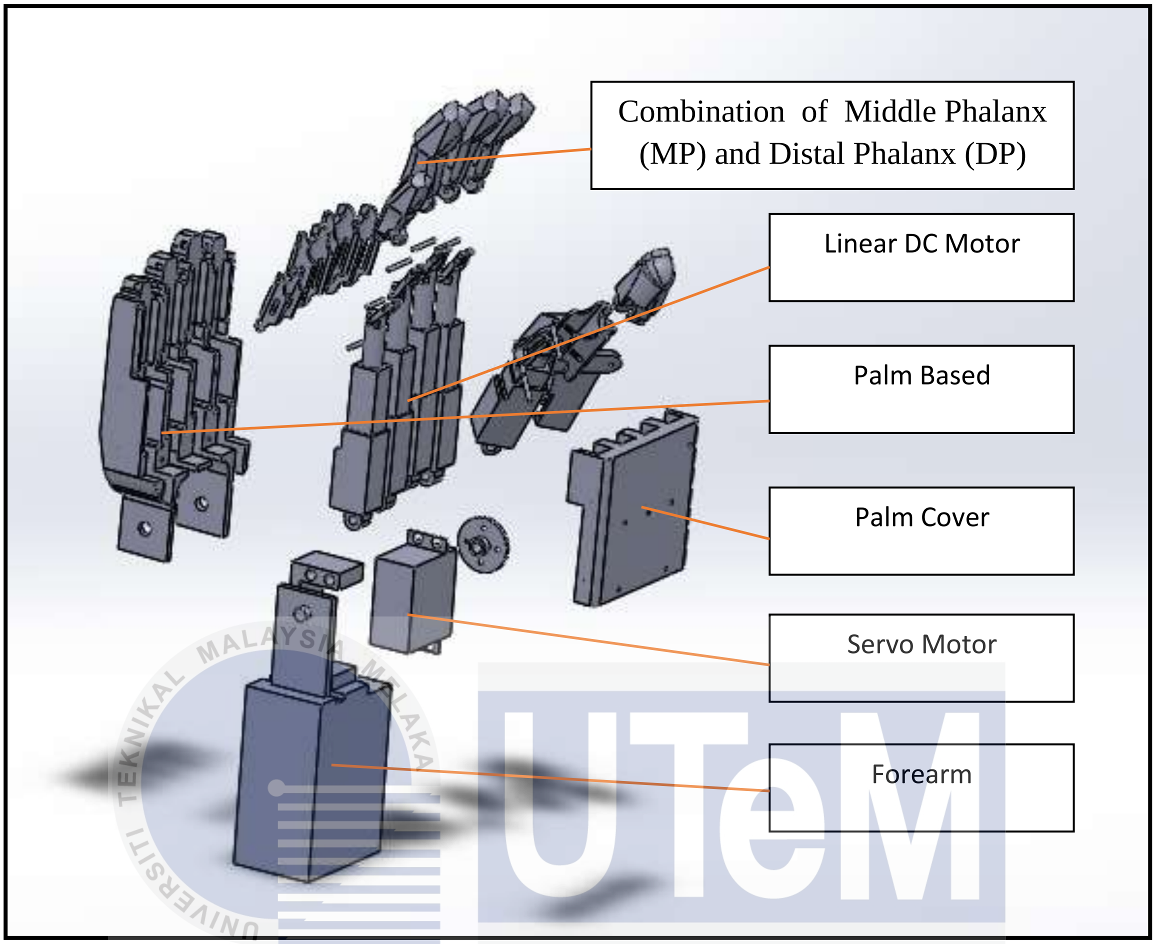


Figure 4.12: Explode View of Design

Overall, to the design of the bionic hand is subject to change in order to get the suitable shape movement. The size also will be depending on the actuator available in the market. After the assembly of bionic hand is completed, it is simulated to make sure the bionic hand can function smoothly. Figure 4.13 and Figure 4.14 showed the simulation that make to get the early result.

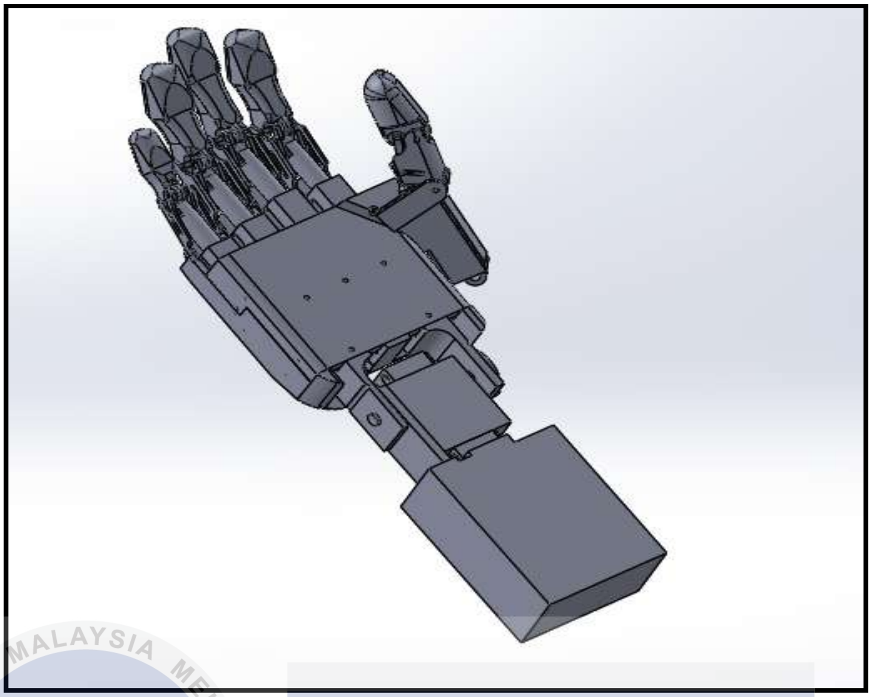


Figure 4.13: Simulation Test of Platform Hand Structure

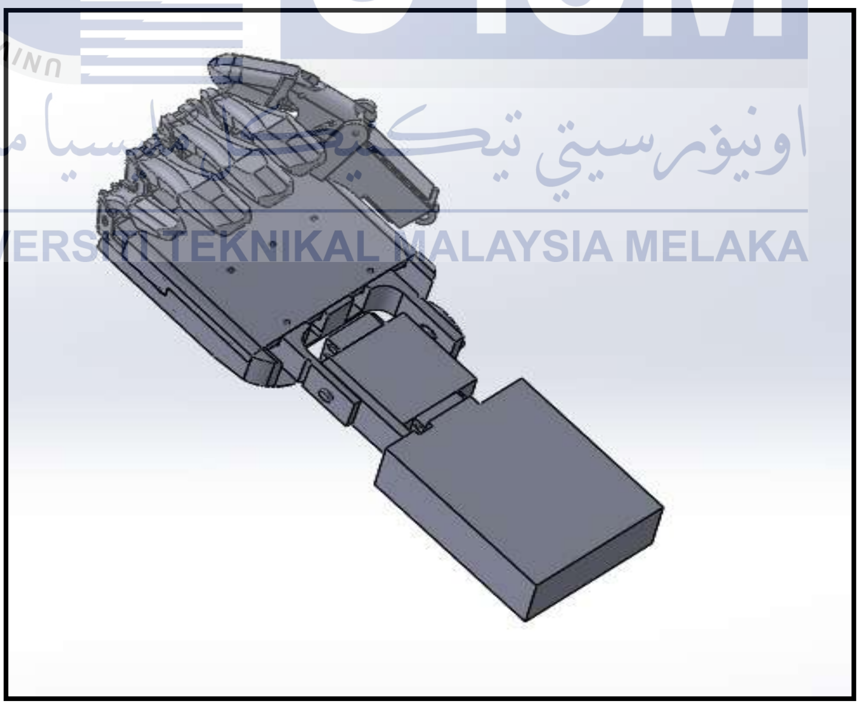


Figure 4.14: Simulation Test of Grasp Hand Structure

4.3 Fabrication of Bionic Hand

The second objective need to achieve is to construct the bionic hand, emulate the human hand shape. This project is consisted into three phases, the first phase is about the integration of mechanical part, the second phase is about the electrical intergration and the third phase is about the software design. The bionic hand is constructed by using CNC and Milling Machine while the structure of bionic hand is built with Aluminum Alloy 6061. After the structure is finished, constructed, the prototype will install together with linear DC motor and controller. The electrode is used to capture the signal of muscle activities and the signal will amplify by using V3 Muscle Sensor. After that the signal is used to control the linear DC motor of the bionic hand using Arduino microcontroller Uno R3.

4.3.1 Mechanical Integration

The figure shows the mechanical part of the exoskeleton model after fabrication. Aluminum Alloy 6061 has been used as a material to fabricate this design. The advantage of using this type of aluminum, it’s had a high quality material and it offers light weight and the strength is stronger compared to the other type of aluminum. Referring to the design, the mechanical linkages have been used to transfer the motion from linear DC motor to the finger. Each of the fingers is designed to emulate the human hand shape and 5 linear DC motors is attached inside the palm.

Figure 4.15: Proximal Phalanx for Bionic Hand

The Figure 4.15 above shows the part of proximal phalanx for all fingers. This part is the most significant part that role is to support the movement of combination distal and middle phalanx.

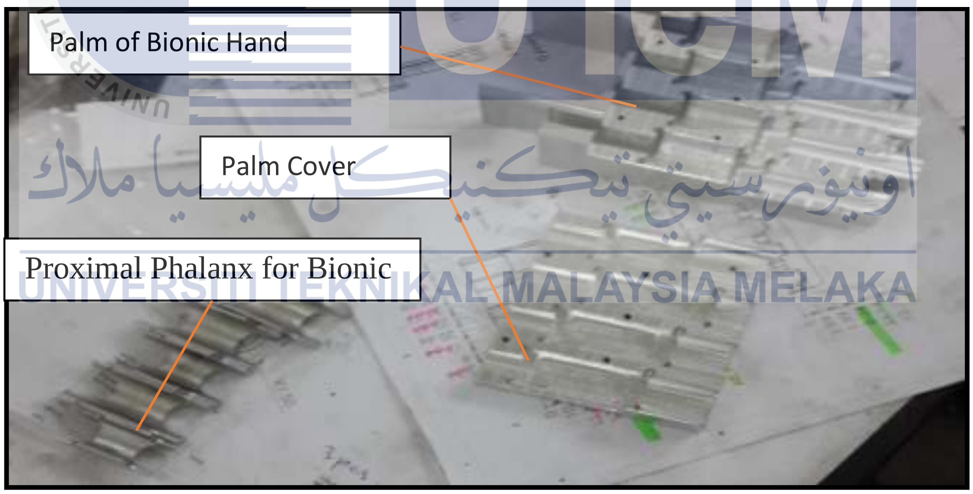


Figure 4.16: Palm Base and Palm Cover

The Figure 4.16 shows the completed palms. This palm is divided into two parts, the first part is the base of the palm and the second part is the cover of the palms. The inside of base palm is machined so the linear DC motor can placed inside the palm. Meanwhile, palm cover is used to cover and protect the linear DC motor from the outside. All this part has been produced using milling machines during the fabrication.

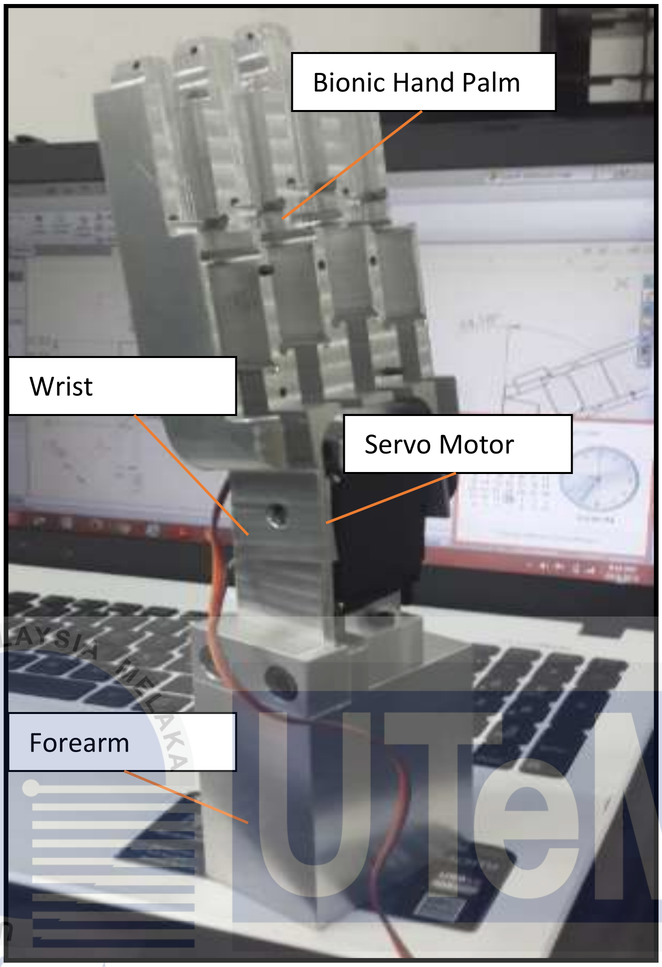


Figure 4.17: Combination of Palm and Forearm

In the Figure 4.17 above, shows the assembly part of the base for bionic hand. Servo motor is used to actuate the wrist most part follow the desired degree where it is attached between the palm and forearm of bionic hand.

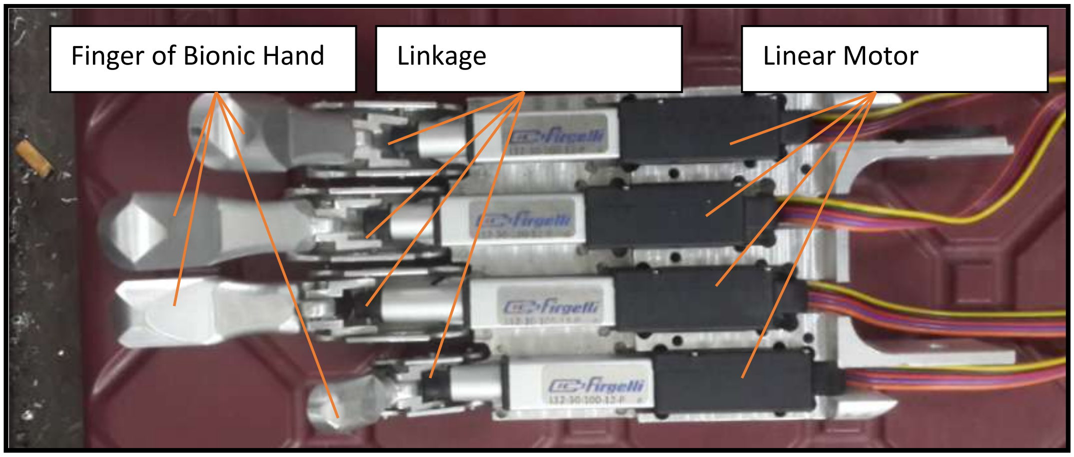


Figure 4.18: Motor Position

The figure 4.18 above shows the linear DC motor position. There are four linear motors is placed inside the base of the palm. Combination of linear movement of the linear motor and the mechanical linkages in Figure 4.16 is used during the fabrication to actuate every joint for each finger. Mechanical linkages are used as a mechanism to transfer the power that will generate from the linear DC motor for each of the Proximal Phalanx (PP), Middle Phalanx (MP) and Distal Phalanx (DP) finger. The mechanical linkages are connected to the palm, Proximal Phalanx (PP), Middle Phalanx (MP) and Distal Phalanx (DP) part and linear DC motor will generate the movement to retract or extend the entire phalanx.

Figure 4.19: Full Integration of Bionic Hand

From the Figure 4.19 above, all combinations of each of Bionic hands can be seen. There are five linear DC motors on the palms and one servo motor in the wrist Bionic hand. Every part of the finger will be open when the linear DC motor extends the shaft and each finger will be closed if retract the linear DC motor shaft.

4.3.2 Electrical Integration

The electrical design is the wiring between Arduino Uno R3, DC servomotor, electrode, V3 muscle sensor and other component. Figure 4.20 below, shows the integration of electrical component that used for the exoskeleton bionic hand. The function of electrode in the design is to capture the signal from muscle sensor. Servo motor And V3 muscle sensor is attached with external power supply.

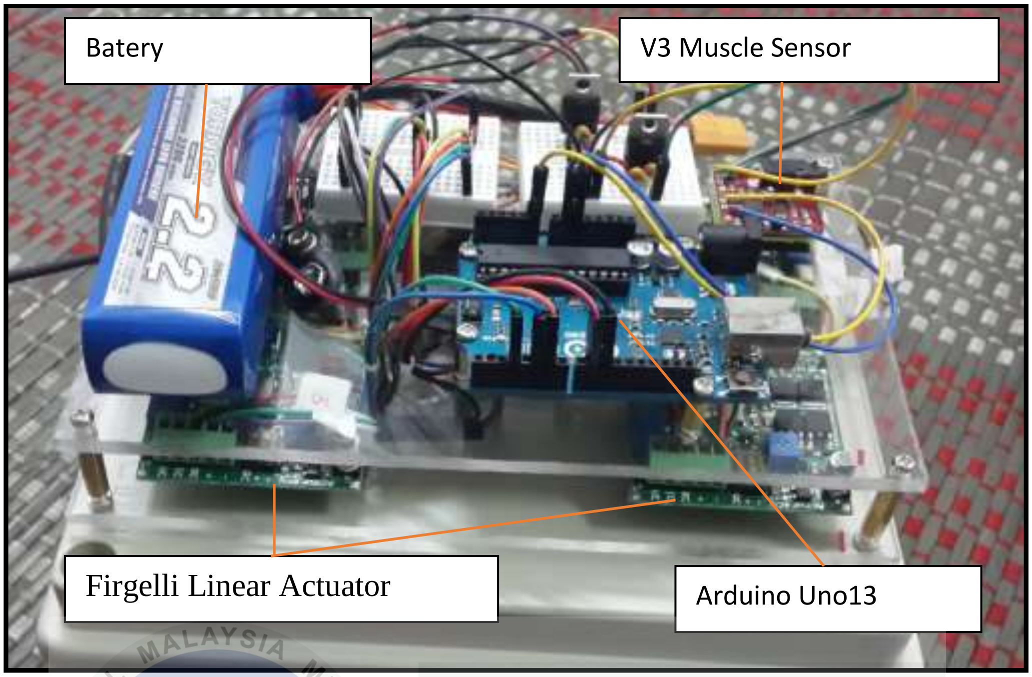


Figure 4.20: Final Electrical Integration

4.3.3 Software Design

In software design, the programming code is written using Arduino 1.0.3 software. The programming code has been written for controlling the bionic hand using V3 muscle sensor.

```
sensorValue = analogRead(potpin); // reads the value of the potentiometer (value between 0 and 1023)

if(sensorValue>=500)
{
myservo1.write(180);
myservo2.write(180);
myservo3.write(180);
myservo4.write(180);
myservo5.write(180);
Serial.print(" sensor ="); // Print the result of sensor valeu and output value
Serial.print(sensorValue);Serial.print('\n');
Serial.print(" Output =");
```

Figure 4.21: Programming Code Controlling Linear DC Motor Using V3 Muscle Sensor

Figure 4.21 shows the programming code that used to control the linear DC motor using V3 muscle sensor. “analogRead’ represent the reading from V3 muscle sensor. The control structure “if” used to control the reading from V3 muscle sensor. “myservo.write(180)’ represent the distance of linear DC when it extend the stroke. “Serial.print()” is represented the value of V3 muscle sensor and the length of linear DC motor stroke.

4.4 Integration of Hardware and Software Design

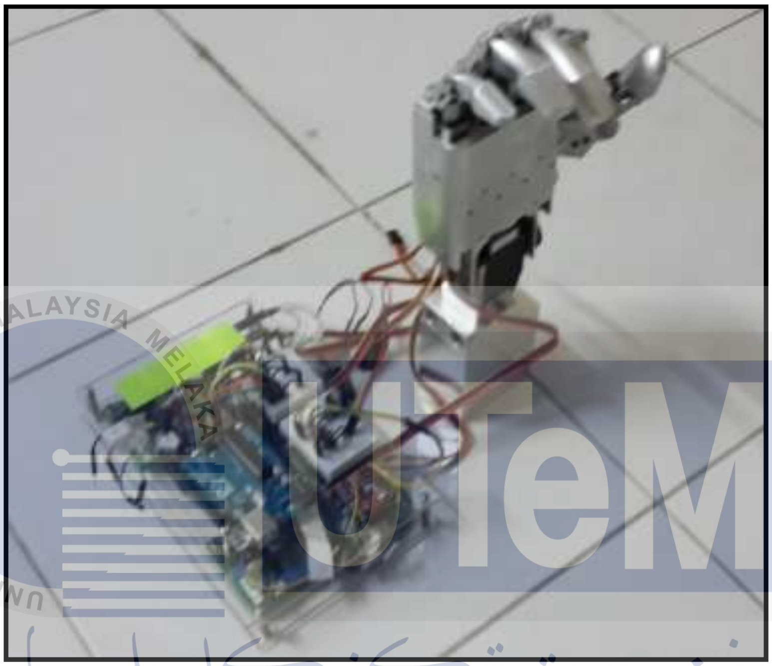


Figure 4.22: The Exoskeleton Bionic Hand

Figure 4.22 above shows the integration of hardware and software design for the exoskeleton bionic hand. The second objective to fabricate the bionic hand is successfully achieved and to make sure the bionic hand can emulate the natural human hand, this bionic hand need to analyze the performance in term of repeatability and accuracy

4.5 Performance Analysis of Bionic Hand

In this section, performance analysis of bionic hand is discussed through a set of experiments. The first part of the analysis involved repetability test for fingers and wrist movement of bionic hand respectively. While the second part of analysis discussed about accuracy tests in finger press and hand grasp strength. Finally, the bionic hand is analyzed based on the canonical hand posture. Results for each test are discussed in section accordingly.

4.5.1 Repeatability Analysis Test for Index Finger Movement

The repeatability test started by finding the range of electromyogram signal extracted from the forearm muscle of a subject for different fingers and wrist movement. The electrodes are attached to the forearm muscle with V3 muscle sensor used to measure and amplify the electromyogram signal. The electromygram signal is then converted in terms of analog digital converter value and used as analog input for the microcontroller. The conversion is done computationally through a set of programming in Arduino. Table 4.1 shows the range of analog digital converter value of hand movement used to actuate the bionic hand.

Table 4.1: Range of ADC Value For Various Muscle Activities

Natural Hand Movement	Range of Muscle Activities (ADC)	Bionic Hand
Hand Open	0-50	Hand Open
Hand Grasp	50-120	Hand Grasp
Wrist Move 45˚	121-200	Wrist Move Forward
Wrist Move 90˚	201-1023	Wrist Move Backward

4.5.1.1 Analysis of Repeatability Test for Fingers Movement of Bionic Hand

The results for repeatability test of extension and flexion of the fingers of bionic hand based on the natural human hand are illustrated in Table 4.2.

Table 4.2: Extension and Flexion (in degree) for Finger Repeatability Test

Number of Test	Degree of Finger Joint Angle (˚)									
	Thump		Index		Middle		Ring		Pinkie	
	Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion
1	31	28	65	75	84	76	88	68	90	60
2	30	27	66	75	84	75	84	70	90	59
3	30	27	66	76	83	75	80	72	89	60
4	31	28	65	77	85	77	84	70	89	60
5	31	27	66	77	84	76	82	72	90	60
6	31	27	65	75	84	75	80	73	89	59
7	30	27	65	74	85	74	83	70	90	59
8	31	28	67	77	84	75	84	74	90	58
9	30	27	66	77	85	74	80	69	90	60
10	30	28	66	77	84	75	80	68	90	60

Based on Table 4.2, the results of joint angle for 5 fingers of bionic hand are collected with two movements of angle for each finger are measured and recorded during the experiment. The first angle that is considered is Metacarpophalangeal (MP) that indicates extension angle and the second angle that is considered is Proximal Interphalangeal (PIP) that indicates the flexion angle.

50 frames are acquired from the experiment.10 frames from thumb, index finger, middle finger, ring finger and pinkie finger respectively. The relative position of joint for flexion and extension is measured by using protector. From the data recorded, the graphs of response angle for extension and flexion are constructed to evaluate the analysis of repeatability.

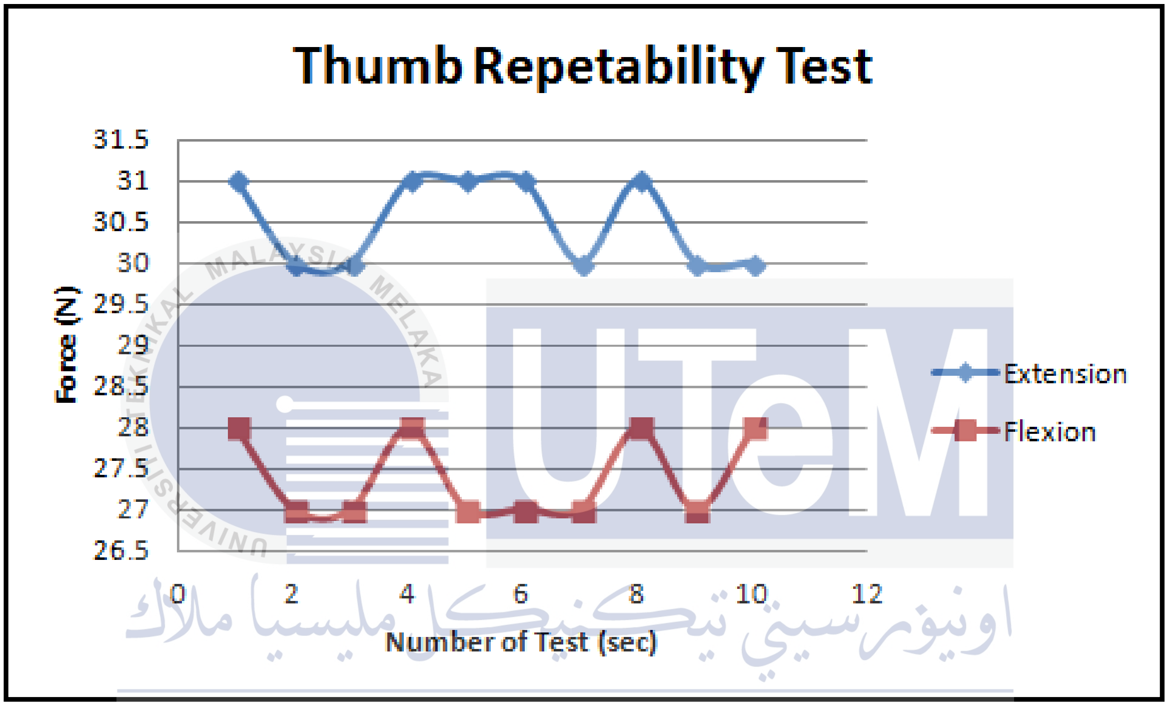


Figure 4.23: Graph Joint Angle against Number of Test for Thump

Referring to the result of repeatability for thumb, finger as presented in Figure 4.23, four test data yielded similar result for extension and flexion. The data are from test number 2, 3, 7 and 9 which, given the reading of 30 degrees for the angle of extension and 27 degrees for the angle of flexion. However, there has one of data that given the uneven result of the reading of the test number 5, 6, 7, and 10. This uneven results are due to the movement of mechanical linkages that is not too smooth caused by the distance between mechanical linkages and Proximal Phalanx of the finger is too close. From this situation, the finger of bionic hand is stuck and gave the different reading during the experiment.

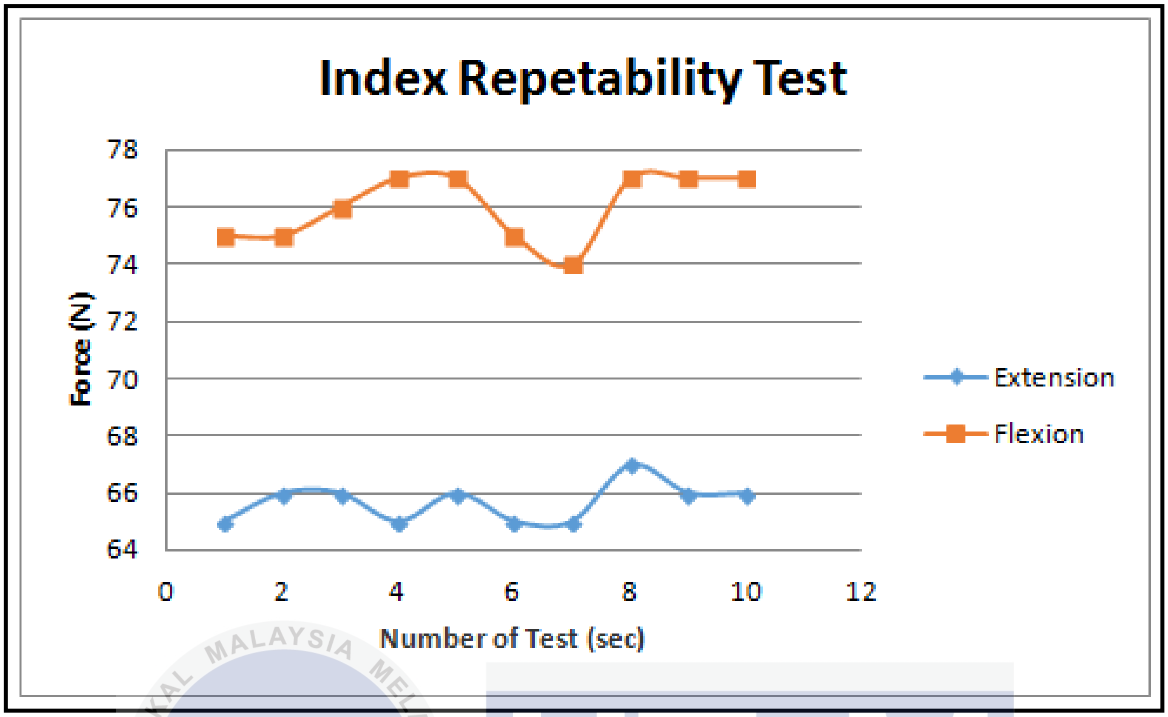


Figure 4.24: Graph Joint Angle against Number of Test for Index

The result of the repeatability test for index finger movement is shown in Figure 4.24. In this experiment, three tests yielded same value which is test number 5, 9 and 10. From this the three numbers of tests, the data are recorded for extension is 66 degrees while the result in flexion is 77 degrees. Meanwhile, another 2 number of tests gave the same reading for extension and flexion in this experiment. The first test and test number 6 gave the results 65 degrees for extension and 75 degrees of flexion joint angle.

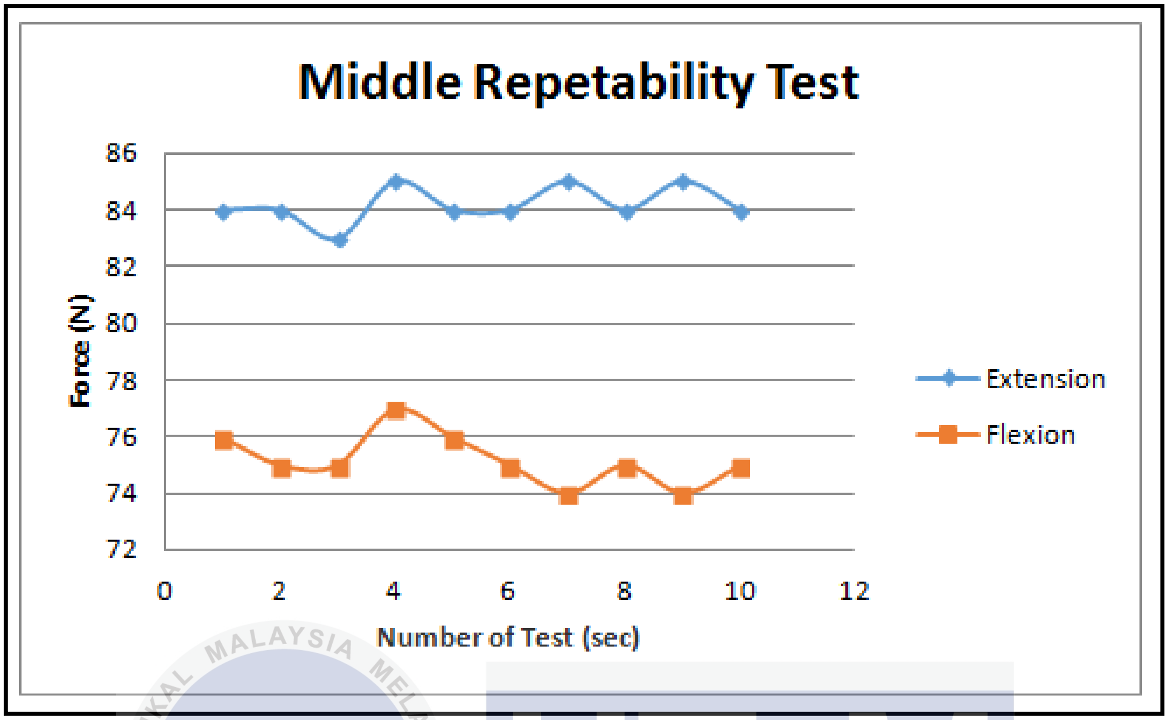


Figure 4.25: Graph Joint Angle against Number of Test Middle

During the experiment of repeatability of the middle finger, the small sticker is placed at the end of finger tips to make sure the tips of the middle finger are not obstructing the view of from another finger. Referring to the result of repeatability for middle finger as presented in Figure 4.25, four test data yielded similar result for extension and flexion. Data are from test number 2, 6, 8 and 10 gave the same result for extension and flexion. All this number of tests gave the reading of 84 degrees for extension and 75 degrees of flexion.

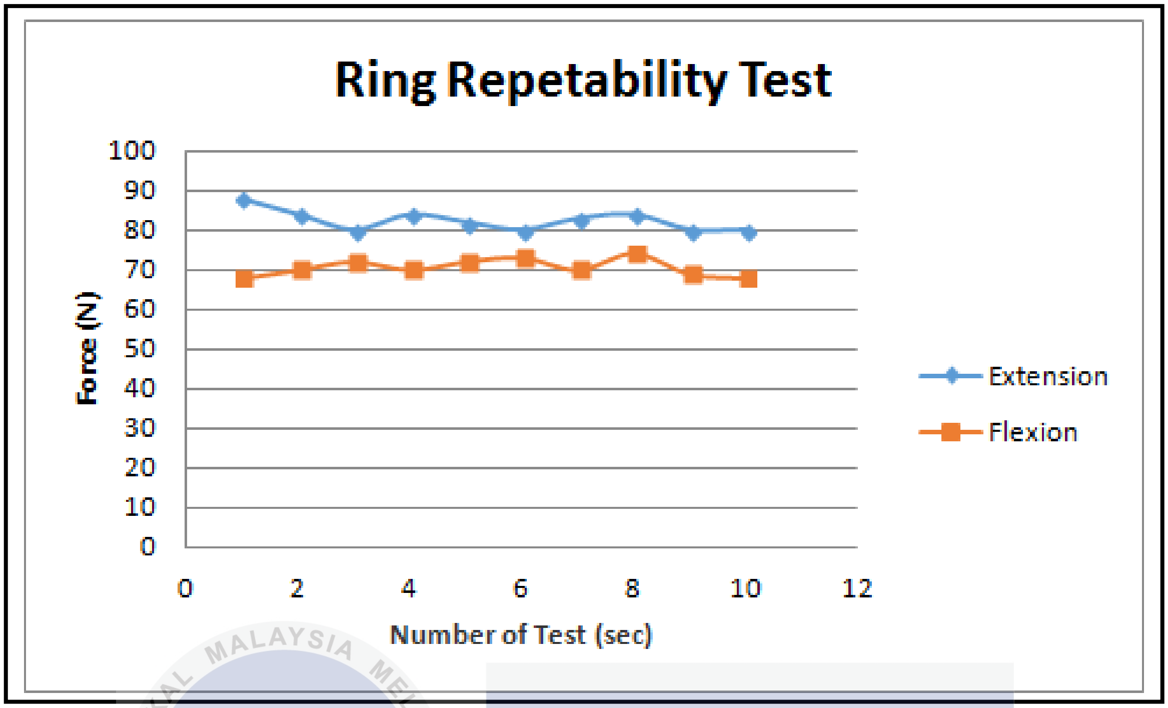


Figure 4.26: Graph Joint Angle against Number of Test for Ring

Actually the dimension of the ring and index finger is a same. In terms of theoretical understanding, the measurement for both fingers will give the same result. But referring to the result of repeatability for ring and index test at Figure 4.26 and Figure 4.25, the result of index finger more consistent compare to the result of the ring finger. In this experiment all the results from measurement give the different value, but the result for each joint angle still close. The test number 3, 6, 9 and 10 show the data that recorded almost the same where the result of this measurement of joint angle for extension is 80 degrees while the result of joint angle flexion is 72, 73, 69 and 68 degree. This situation happens due to a linear DC motor which cannot stop in the distance that is decided.

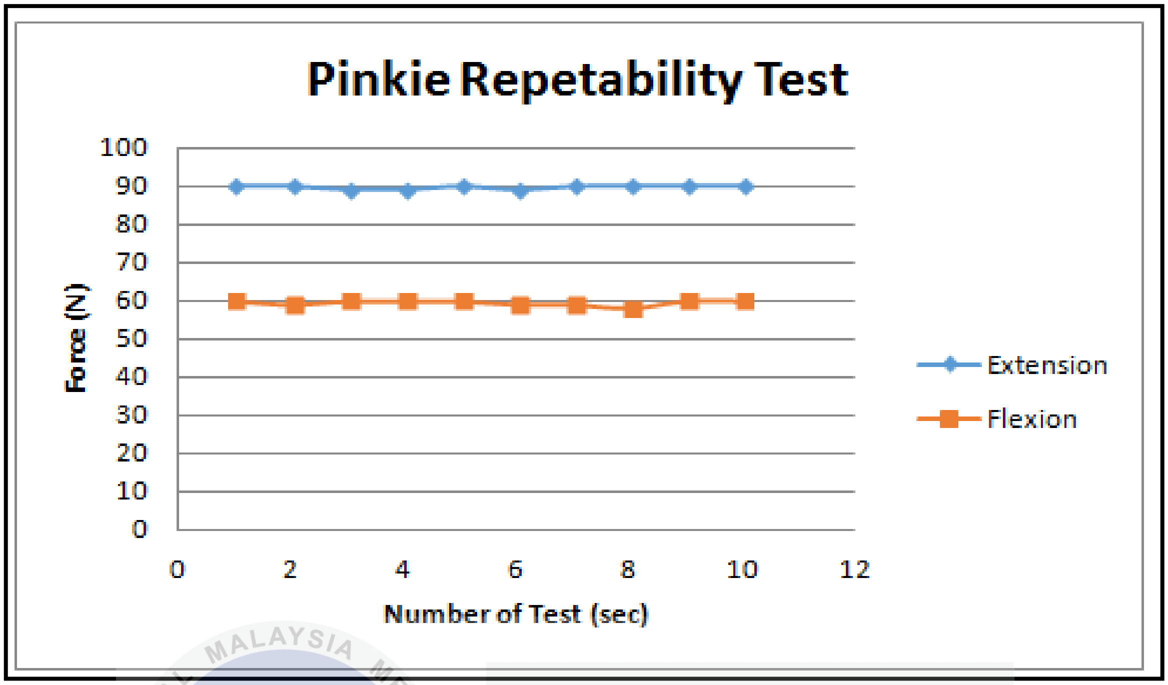


Figure 4.27: Graph Joint Angle against Number of Test for Pinkie

The result of repeatability for pinkie finger at Table 4.27 showed the almost the data give consistent measurement. There have four measurements yielded same value which are test number 1, 5, 9 and 10 and other measurement that is recorded have the nearly identical value. All this four test gave the result of 90 degrees for joint angle of extension and 60 degrees for the joint angle of flexion.

From the analysis in Figure 4.23, Figure 4.24, Figure 4.25, Figure 4.26, and Figure 4.27 shown the repeatability test shows all the bionic finger able to complete the repeatability test. There are at least three same data recorded for each finger during the test. Due to the smaller dimension of phalanx and mechanical linkages, pinkie finger yields the highest performance in term of repeatability while other fingers yields satisfactory performance. This can be seen in Figure 4.26 for the ring repeatability test where that graph shown the significant difference in the extension and flexion angle movement due to the movement of linear DC motor that not consistent is influenced each the movement of extension and flexion for the ring finger. Table 4.3 showed the average result of joint angle for all bionic fingers.

Table 4.3: Average Result of Joint Angle for Wrist Repeatability Test

Degree of Finger Joint Angle (˚)									
Thumb		**Index**		**Middle**		**Ring**		**Pinkie**	
Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion
30.5	27.4	65.7	76	84.2	75.2	82.5	70.6	89.7	59.5

Based on the data above, the average movement of extension and flexion for thumb is 30.5 degree and 27.4 degree, whereas the average of extension and flexion is 65.7 degree and 76 degree. The average for three other finger including middle, ring and pinkie for extension and flexion is 84.2 degrees, 75.2 degrees, 82.5 degrees, 70.6 degrees, 89.7 degrees and 59.5 degrees. For the analysis of repeatabily for each finger, the mean square error is calculated by using the equation as follows:

$$\text{MSE} = \frac{\sum_{i=1}^{n}(x - \check{x})^2}{n} \quad (4.1)$$

Where: x = Require value

$\check{x}$ = Measure value

n = Number of data item

The result of mean square error for finger repeateability test is tabulate in Table 4.3.

Table 4.4: Mean Square Error for Finger Repeatability Test

Fingger	Thump		Index		Middle		Ring		Pinkie	
	Extension	**Flexion**	**Extension**	**Flexion**	**Extension**	**Flexion**	**Extension**	**Flexion**	**Extension**	**Flexion**
Mean Square Error	0.5	0.5	0.8	2.2	0.4	0.8	10.9	4.3	0.3	0.7

From the mean square error, the error value between the estimator with what is estimate can be found. Referring to the result from Table 4.4, the mean square error for angle of extension and flexion of index, middle and ring fingers are 0.8, 2.2, 0.4, 0.8, 10.9 and 4.3 respectively, while means square error for angle of extension and flexion for thumb and pinkie fingers are 0.5, 0.5, 0.3 and 0.7 respectively. According to the result that are illustrated, pinkie had the lowest mean square error for angle of extension while thumb had the lowest compared to other finger. Thus, the data for pinkie and thumb are said to be more homogeneous. The result indicates that the bionic hand manages to yield various of finger angle movement repeatedly, which resemble the natural human hand.

4.5.1.2 Analysis of Repeatability Test for Wrist Movement of Bionic Hand

In this section the repeatability is conducted for wrist of bionic hand either it can repeat the same position or not. The result that listed in Table 4.5 is used to support the analysis of repeatability wrist movement of bionic hand.

The same experimental procedure conducted to analyze the performance of wrist movement. Based on the Table 4.5, the result shows the movements that are done by wrist of bionic hand where three movements of the wrist angle is recorded during the experiment. The process is repeated until 10 times by using the same range of analog digital converter .

30 frames are acquired from the experiment.10 frames from backward angle movement, middle angle movement and forward angle movement respectively. The relative position of joint for flexion and extension is measured by using protector. From the data recorded, the graphs of response angle for extension and flexion are constructed to evaluate the analysis of repeatability.

Table 4.5: Result of Joint Angle of Wrist Repeatability Test

Number of Test	**Degree (˚)**		
	Backwards	**Middle**	**Forward**
1	40.0	91.5	142.5
2	40.0	90.5	143.5
3	41.5	90.5	144.0
4	41.0	91.0	142.0
5	42.0	92.0	144.5
6	41.0	92.0	143.0
7	42.0	91.5	144.0
8	41.5	92.0	144.5
9	41.0	91.5	143.0
10	42.0	92.5	144.0

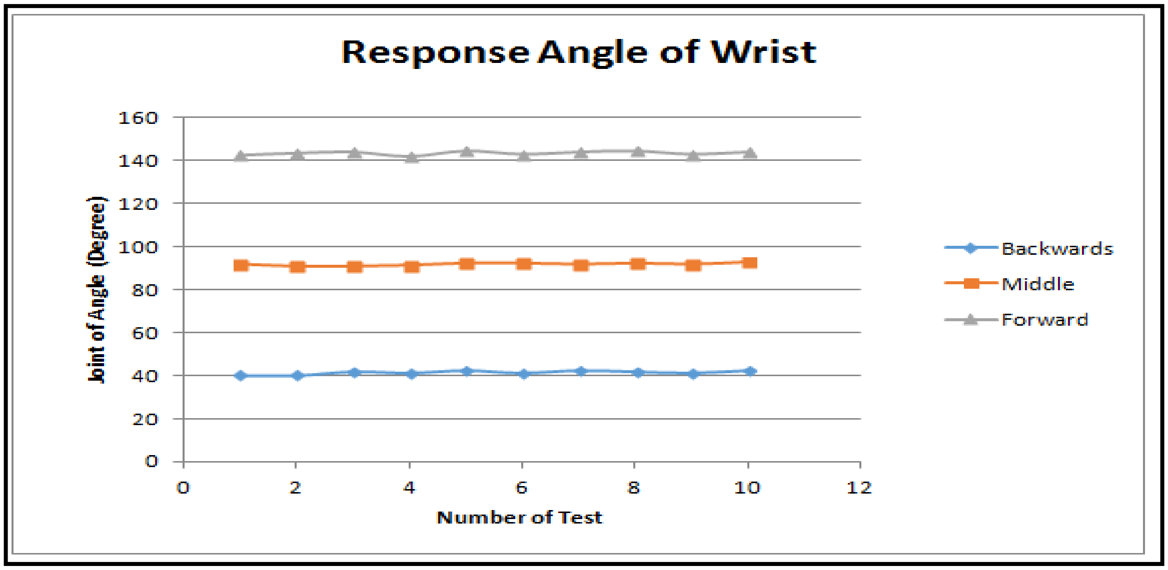


Figure 4.28: Graph Angle of Wrist against Number of Test

From the Figure 4.28 the repeatability test shows the bionic hand able to complete the test to close the wrist movement. The different color of the line indicates the different angle movement of the wrist. The gray color indicates forward angle movement where orange color indicates middle angle movement and blue color indicate backward angle movement. From the graph of response wrist angle above, tree test data yielded similar result of backward angle movement. The data are from test number 5, 7 and 10 with given the reading of 42 degrees. Meanwhile, for the middle movement angle, there are also yielded three similar data which given the reading 91.5 degrees. The data are from test number 1, 7 and 9. Referring to the gray line that indicate the forward angle movement, there are also given three similar data values it is 144 degrees from test number 3, 7 and 10. From the Figure 4.26 above, the range of backward angle movement is 41.2˚ where the range of middle angle movement is 91.5˚and the range of forward angle movement is 143.5˚. Using the mean square error calculation technique at equation (4.1), the result of repeatability of wrist tabulate at Table 4.4.

Table 4.6: Mean Square Error for Wrist Repeatability Test

Wrist Movement	**Backward**	**Middle**	**Forward**
Mean Square Error	1.55	2.43	1.5

From the result that presented in Table 4.6, the mean square error for backward angle movement, middle angle movement and forward angle movement are 1.55, 2.43 and 1.5 respectively. According to the result that are illustrated, the forward angle movement had the lowest compare the other movement. The result indicates that the bionic hand manages to yield various wrist movements repeatedly, which resemble the natural human hand.

4.5.1.3 Accuracy Analysis Test for Finger Press of Bionic Hand

In this section, three fingers, which are thumb, index, and middle finger used to analyze the performance of bionic hand in terms of accuracy. The fingers are used to press the hand dynamometer. In this experiment the data from the natural human finger is collected so that the data from bionic hand can be compared with data from natural human hand. Three different subjects were involved in this experiment, the subject that's involved in this experiment have different muscle strength. A result that is taken to support the analysis of accuracy as presented in Table 4.7, Table 4.8, and Table 4.9.

Referring to the table that already mention, the test is repeated five times by pressing the hand dynamometer using three fingers mentioned earlier for 10 seconds. During the 10 second pressing test, each of data for every second is collected. From the data that tabulated, three graphs were constructed from this experiment. The Figure 4.29, Figure 4.30 and Figure 4.31 showed the graph force against time, for each subject for press test analysis.

Table 4.7: Press Test Data for First Subject

Time (Sec)	Force (N)				
	Test 1	Test 2	Test 3	Test 4	Test 5
0	0	0	0	0	0
1	20.4	28.3	20.2	5.5	34.9
2	26.1	26.8	26.1	33.8	27
3	33.8	31.8	26.5	28.3	32.7
4	34	30.7	28.1	30.9	29.6
5	36	36.8	28.5	37.7	28.3
6	35.8	30.7	34.2	32.5	28.3
7	38.4	29.4	30.5	29	30.9
8	38.2	33.3	28.7	27.2	28.3
9	39.7	30.3	29.6	33.3	29.2
10	38.6	29	29.2	30.1	29.2

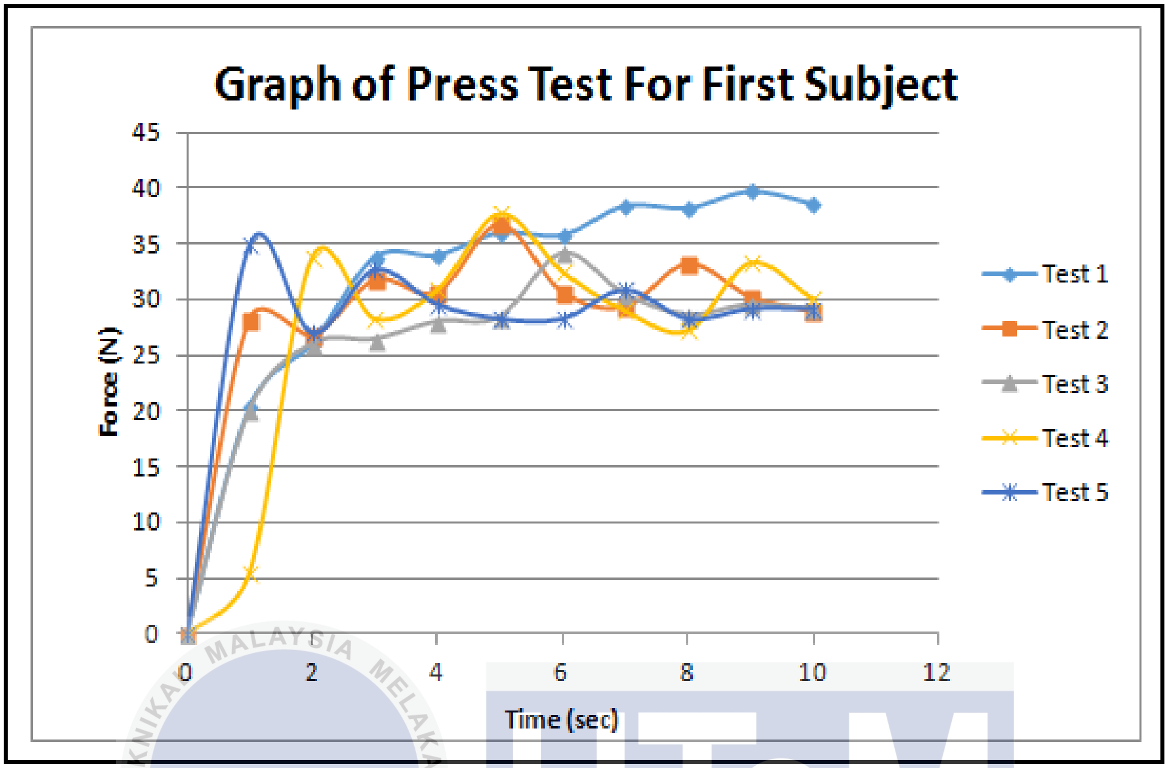


Figure 4.29: Graph Force against Time for First Subject

From the result that is shown in this Figure 4.29, five tests are conducted with different color of the line shown different number of test. The result yields high force before it reduce and become constant after 6 seconds. After 6 seconds of the test, the range of finger press force of all tests is around 25N to 40N. Comparing the result from second and third subject at Figure 4.30 and Figure 4.31, the first subject has a medium range force of finger press test.

Table 4.8: Press Test Data for Second Subject

Time (Sec)	Force (N)				
	Test 1	Test 2	Test 3	Test 4	Test 5
0	0	0	0	0	0
1	58.3	60.8	48.7	39.5	41.2
2	55.3	51.3	39.5	45.6	44.1
3	49.3	55.5	39.5	41.2	42.6
4	34	51.3	37.3	39	39.5
5	61.6	48.3	38.4	41.9	37.3
6	51.8	41.5	38.6	35.8	37.1
7	47.6	38.2	37.1	49.1	36
8	48	44.7	36.6	35.8	37.9
9	41.2	41.5	33.6	33.6	33.8
10	50	43	36.6	34.2	32.9

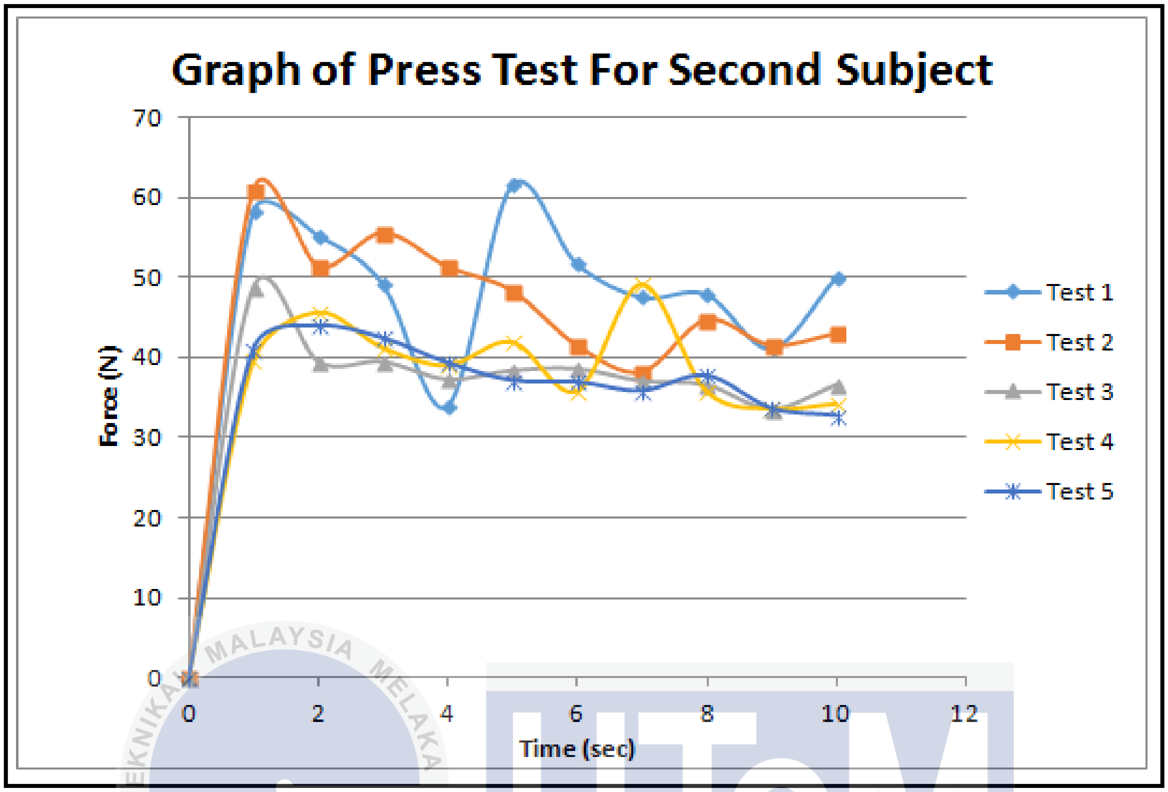


Figure 4.30: Graph Force against Time for Second Subject

Referring to the graph in Figure 4.30 above, the second subject recorded the highest measured during the experiment. Compare the result of a pressure test for the first and second subjects at Figure 4.29 and Figure 4.31. The result yields high force before it reduce and become constant after 6 seconds. Result from the graph showed the range of pressing test after 6 second for second subject is 30N to 65N.

Table 4.9: Press Test Data for Third Subject

Time (Sec)	Force (N)				
	Test 1	Test 2	Test 3	Test 4	Test 5
0	0	0	0	0	0
1	13.4	9.9	-0.4	1.3	15.4
2	15.8	12.1	12.3	13.2	16.9
3	27	21.1	12.5	14.3	19.3
4	19.3	18.6	13.8	18.9	20.2
5	22.8	20.4	15.6	20.8	20.4
6	23.9	20.2	15.1	20.4	21.1
7	22.8	20	18.9	21.9	22.4
8	22.6	19.5	19.3	21.3	22.6
9	22.6	19.7	19.5	21.1	21.9
10	22.4	19.3	20.4	21.1	22.4

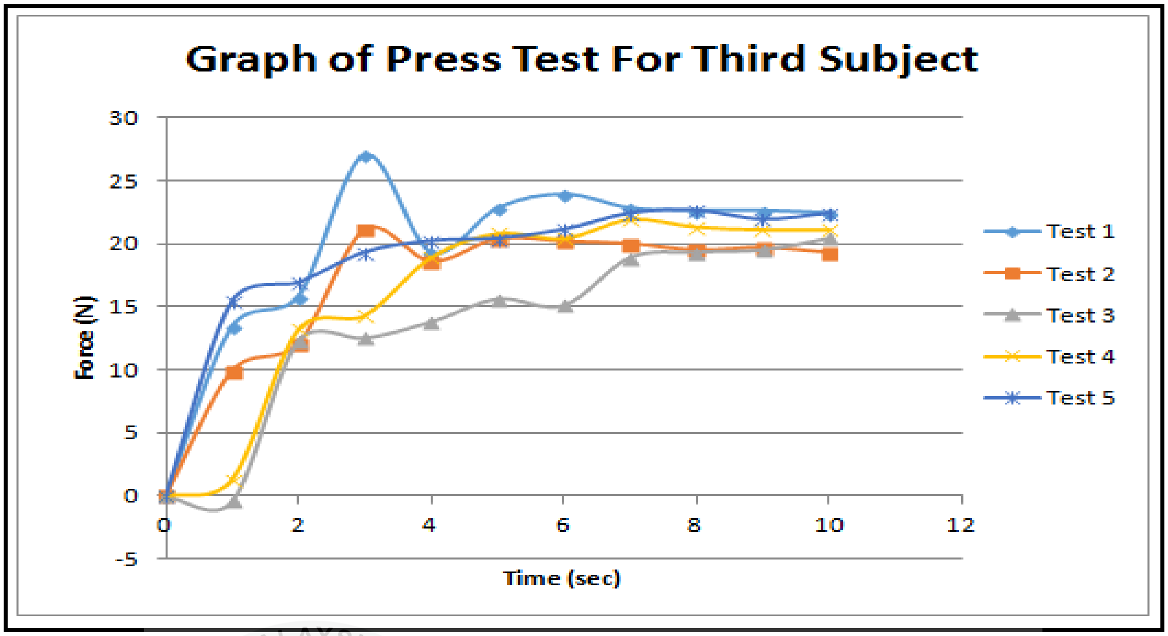


Figure 4.31: Graph Force against Time for Third Subject

The lowest finger grasp force is represented by the third subject that illustrated in Figure 4.31. The same result shown, these subject yield high forces before it reduce and become constant after 6 seconds. All five tests shown the range of finger press force for third subject is around 15N to 25N after 6 seconds during its press the hand dynamometer.

The same procedure of pressing test is constructed at Bionic hand. The force result that produced by bionic hand is recorded. The process repeated until 10 times to get the constant force value of bionic hand. The electromyogram signal is used to control the range movement of the wrist during the test by using V3 muscle sensor. During the experiment the value of the voltage is monitored to avoid the bionic hand press the hand dynamometer too long. Detail on data collected for press test for bionic hand is presented in Table 4.10, this table is used to support the analysis for accuracy test at the graph in Figure 4.32.

Table 4.10: Press Test Data for Bionic hand

Time (Sec)	Force (N)				
	Test 1	Test 2	Test 3	Test 4	Test 5
0	0	0	0	0	0
1	0.2	0	0.2	9.4	23
2	0.4	0.2	18.4	12.3	27.4
3	19.3	17.5	40.1	15.4	32
4	29	35.8	38.8	22.4	27.2
5	28.5	32	37.3	18.9	25.7
6	28.5	30.3	19.7	19.1	21.7
7	21.1	22	21.1	20.4	21.3
8	20.8	21.5	21.1	19.7	20.4
9	20.4	21.1	21.1	19.3	21.3
10	20.4	20.9	17.3	18.4	20.6

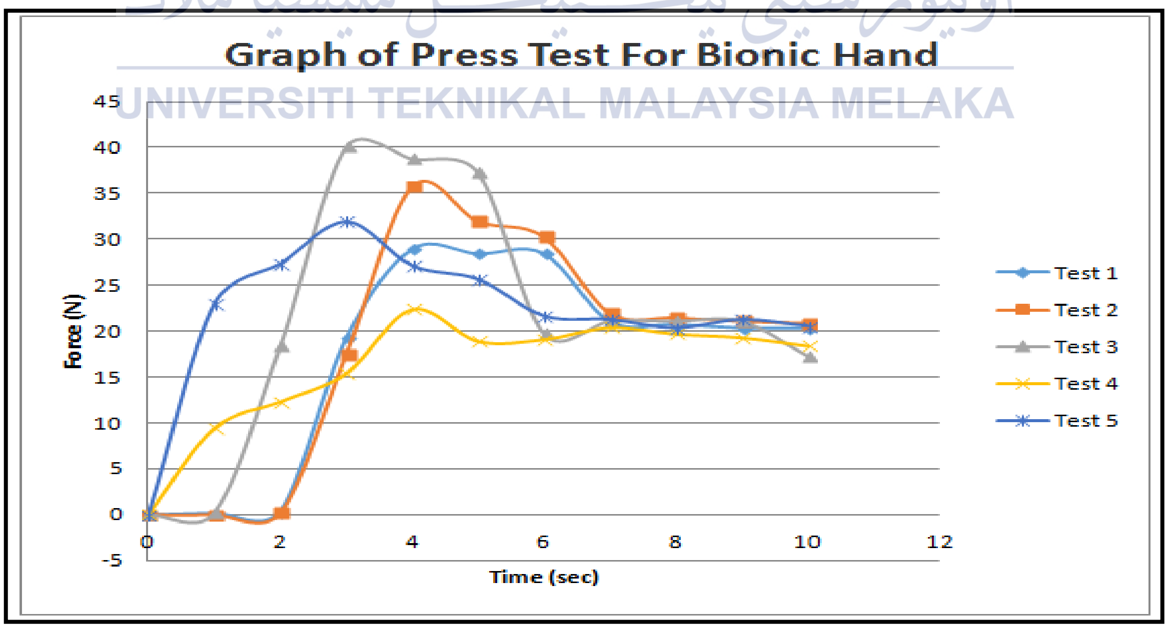


Figure 4.32: Graph Force against Time for Bionic Hand

Detail from Figure 4.32, the different color of the line shows the difference number of tests and each graph involved with five tests. The result of bionic hand shows in the early 6 seconds the bionic hand gives the high force before it starts to give the constant force value, after 6 seconds of the test. The highest graph line showed the highest press force that is recorded by bionic hand. This situation occurs because during the first 6 seconds, the bionic hand gives fully press force to the hand dynamometer and the linear DC motor to give the high force to each finger. After the bionic hand is fully pressed the hand dynamometer, the linear DC motor released some force to avoid the motor from damaged and give the constant force value to the bionic finger. These situations can be seen at all test result after 6 seconds of grasp hand test. During the experiment 10 seconds were given to complete each of the tests. From all graphs above, the forces start to be constant after 6 seconds. The constant value of each graph is used to make the comparison between natural human hand and bionic hand that mean all the force that above than 6 seconds is used to analyze. The average data of each graph were calculated and tabulated in the Table 4.9. From the data that is tabulated at Table 4.11, the graph of average force after 6 seconds is ploted in Figure 4.33.

Table 4.11: Average Data of Press Test

Time (Sec)	Force (N)			
	Person 1	**Person 2**	**Person 3**	**Bionic Hand**
6	32.3	40.96	20.14	23.94
7	31.64	41.6	21.2	22.12
8	31.14	40.6	21.06	21.6
9	32.42	36.74	20.96	21.44
10	31.22	39.34	21.12	21.4

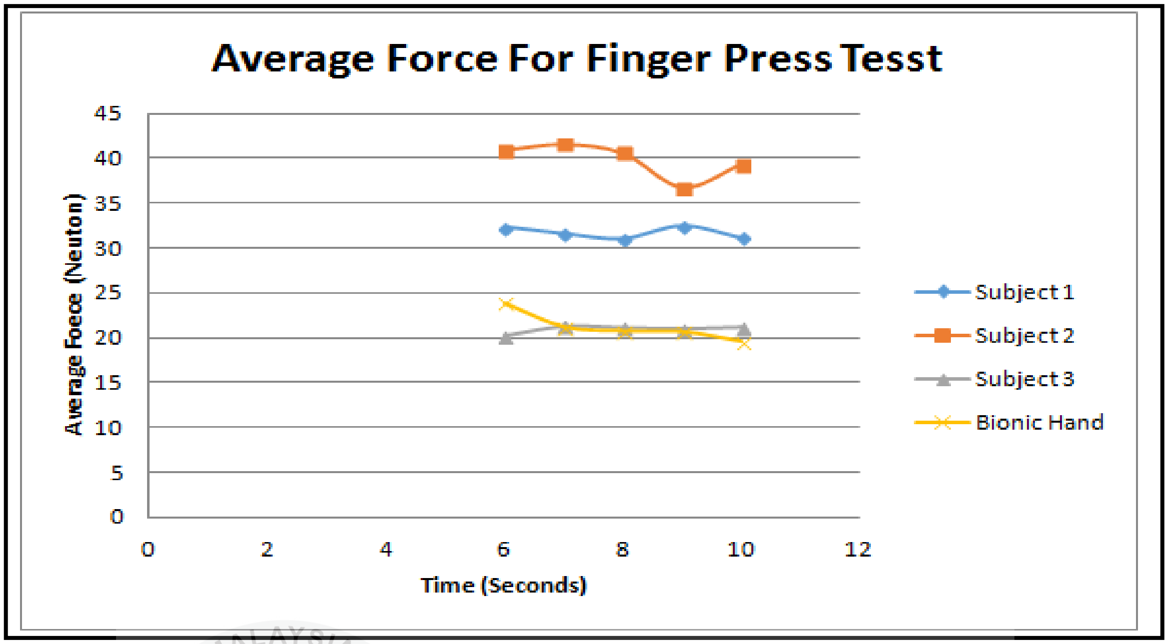


Figure 4.33: Graph Force against Time for Average Data of Press Test

From the Figure 4.33 above, there are four comparison data is plotted on the same graph. The blue line color indicated the average data for first person and orange color indicated average data for second person while gray and yellow line indicated the average data force for fourth person and bionic hand. The figure above shows the yellow line that indicates the average force of bionic hand relatively close to the gray line that indicates the average force of a third person. Meanwhile, the average force for press test between second subject and bionic hand showed a lot of significant strength force. whereas for the average press force between second subject and bionic hand hand showed the moderate comparison result. Using the equation percentage of error below, the result of the average press test of bionic hand is compared with the result of the second subject.

$$Percentage\ of\ Error = \frac{|\,Experiment\ Valeu - True\ Value|}{|True\ Value|} \times 100\% \qquad (4.2)$$

Table 4.12 : Percentage of Error Between True Value and Mesurement Value For Press Test

Time	Thrid Subject	Bionic Hand	Percentage of Error
6	20.14	23.86	18.47071
7	21.2	21.18	0.09434
8	21.06	20.7	1.70940
9	20.96	20.64	1.52672
10	21.12	19.52	7.57576

The percentage of error is calculated based on the difference value of time taken for each force. The percentage of error is tabulated in Table 4.12. Based on the tabulated data, the highest percentage of error is during 6 seconds where the percentage of error is 18.47071%. The error that occurred on every second of the bionic hand is because of the external factors that affect the experimental result, such as limitation of the structure of bionic hand. Besides that, the position of the hand dynamometer during a bionic hand press, it also be the cause of difference in experimental result.

4.5.1.4 Analysis of Accuracy Test for Hand Grasp of Bionic Hand

In these sections all fingers were used to analyze the performance of accuracy during the experiment. The combination all finger is used to grasp the hand dynamometer. In this experiment the data from the natural human finger is collected same with the previous experiment so that the data from bionic hand can be compared with data from natural human hand. These analyses have same experimental setup with the analysis of finger press test. Kindly refer to the Table 4.13, Table 4.14, 4.15 and Table 4.16 for data collected during hand grip force experiment that used to support the accuracy of grasp hand test.

Referring to the table that already mention, the result taken 10 second during pressing tests to take the constant force value of natural human finger and the. During the 10 second pressing test, each of data for every second is collected. From the data that has been tabulated, three graphs were constructed from this experiment. The Figure Figure 4.34, Figure 4.35 and Figure 4.36 show the graph force against time, for each subject for press test analysis.

Table 4.13: Grasp Test for First Subject

Time (Sec)	**Force (N)**				
	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
0	0	0	0	0	0
1	8.8	31.1	5.3	18.4	73.9
2	68.0	63.6	96.1	90.6	74.8
3	80.1	58.1	72.2	87.9	89.5
4	94.3	67.6	87.1	90.1	81.8
5	91.2	59.4	91.7	81.6	76.1
6	94.7	81.1	93.0	97.8	93.0
7	87.5	86.2	90.8	84.9	80.7
8	86.0	66.9	89.7	85.3	78.5
9	89.7	73.9	96.5	86.0	86.0
10	85.1	78.1	80.3	87.5	80.3

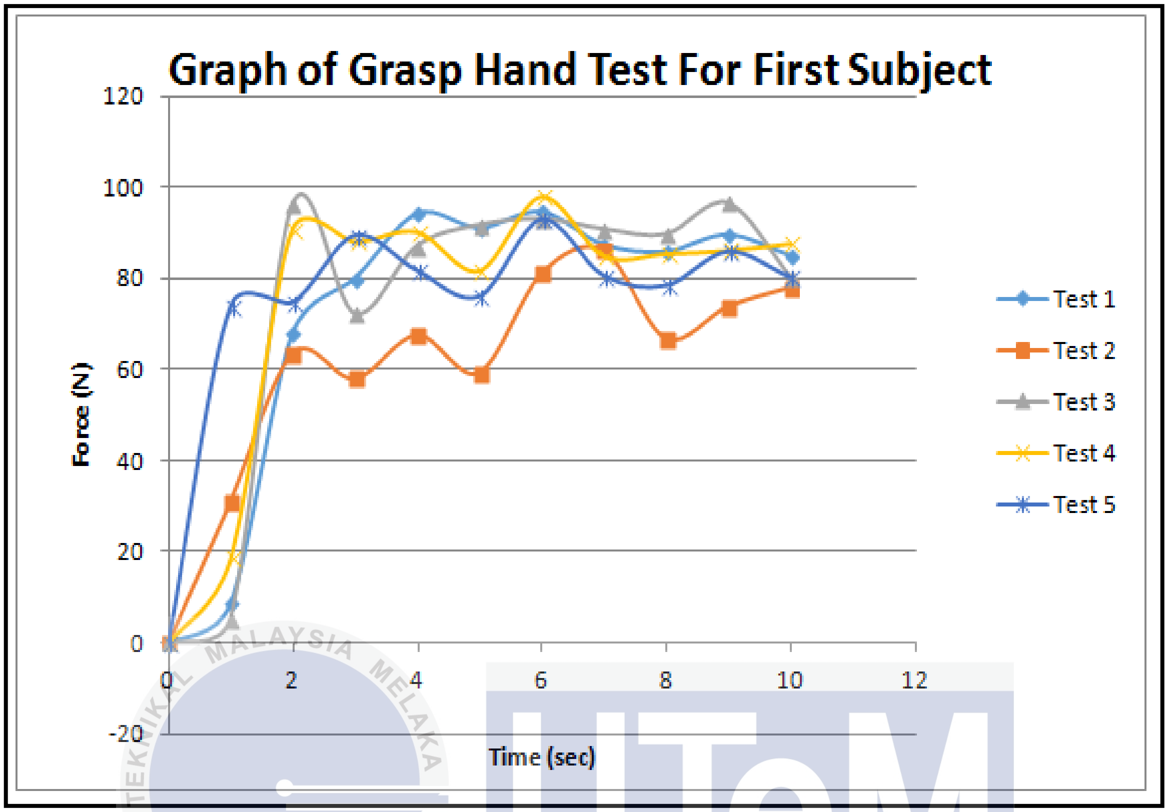


Figure 4.34: Graph Force against Time for First Subject

In this analysis, the three result of natural human hand and one of the results from bionic hand, the difference line color indicates the difference test during the experiment. Five difference test is conducted where each the graph consists with five result of grasp hand force. Base on the result of the grasp hand force for the first subject, the graph in Figure 4.34 shown After 6 seconds of the test, the range of finger press force of all tests is around 60N to 100N. Comparing to the result from the graph at Figure 4.35 and Figure 4.36 for the second and third subject, the first subject have a medium strength grasp force.

Table 4.14: Grasp Test for Second Subject

Time (Sec)	Force (N)				
	Test 1	Test 2	Test 3	Test 4	Test 5
0	0	0	0	0	0
1	18.6	62.5	135.8	110.1	105.9
2	92.3	121.1	123.7	84.7	124.6
3	90.6	107	108.8	105.3	131.2
4	84	107.5	134.4	104.2	104
5	123.9	101.5	112.3	102	126.8
6	98.5	89.7	108.3	89.7	49.8
7	84	98.5	104.6	129.8	150.7
8	109.4	80.9	85.3	98.9	116.2
9	95.8	93.2	89.3	85.3	114.5
10	74.1	107.5	128.5	110.1	94.5

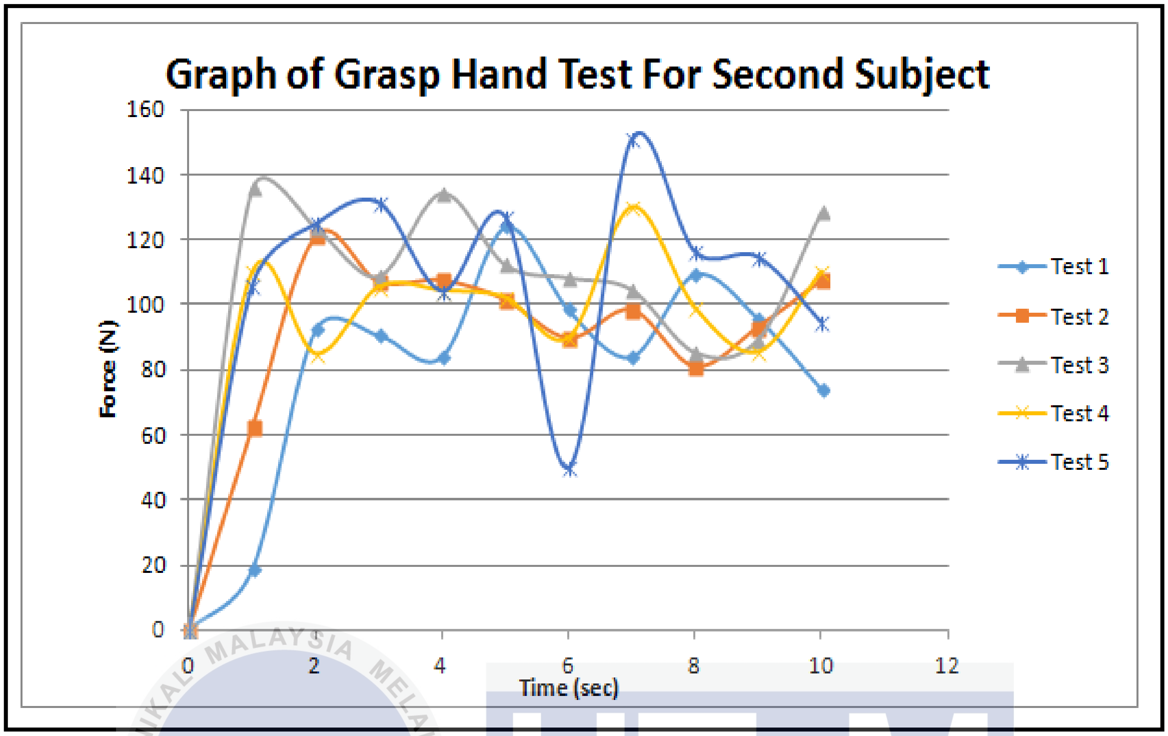


Figure 4.35: Graph Force against Time for Second Subject

From the result shown in this Figure 4.35, there have five tests is conducted to test the press force from the natural human hand. Different line color indicates the different test on this experiment. The graph shown, from all the test the force of natural human hand the force is more constant after 6 seconds during the experiment. After 6 seconds of the test, the range of finger press force of all tests is around 45N to 160N. Comparing the result from second and third subject at Figure 4.34 and Figure 4.36, the first subject has a higher range force of the hand grasp test.

Table 4.15: Grasp Test for Third Subject

Time (Sec)	Force (N)				
	Test 1	Test 2	Test 3	Test 4	Test 5
0	0	0	0	0	0
1	2.9	14.5	4.2	0.4	-0.4
2	10.8	8.8	14.7	16	18.2
3	11.4	8.8	14.3	20.4	22.6
4	13.6	10.3	14.9	15.8	23
5	16	20.4	21.9	25.4	22.8
6	19.1	20	21.3	19.7	22.8
7	20.4	19.5	21.3	20.6	22.4
8	21.9	22.6	21.3	21.3	22.4
9	24.8	21.1	21.1	21.5	22.2
10	23.9	21.3	20.6	21.1	21.9

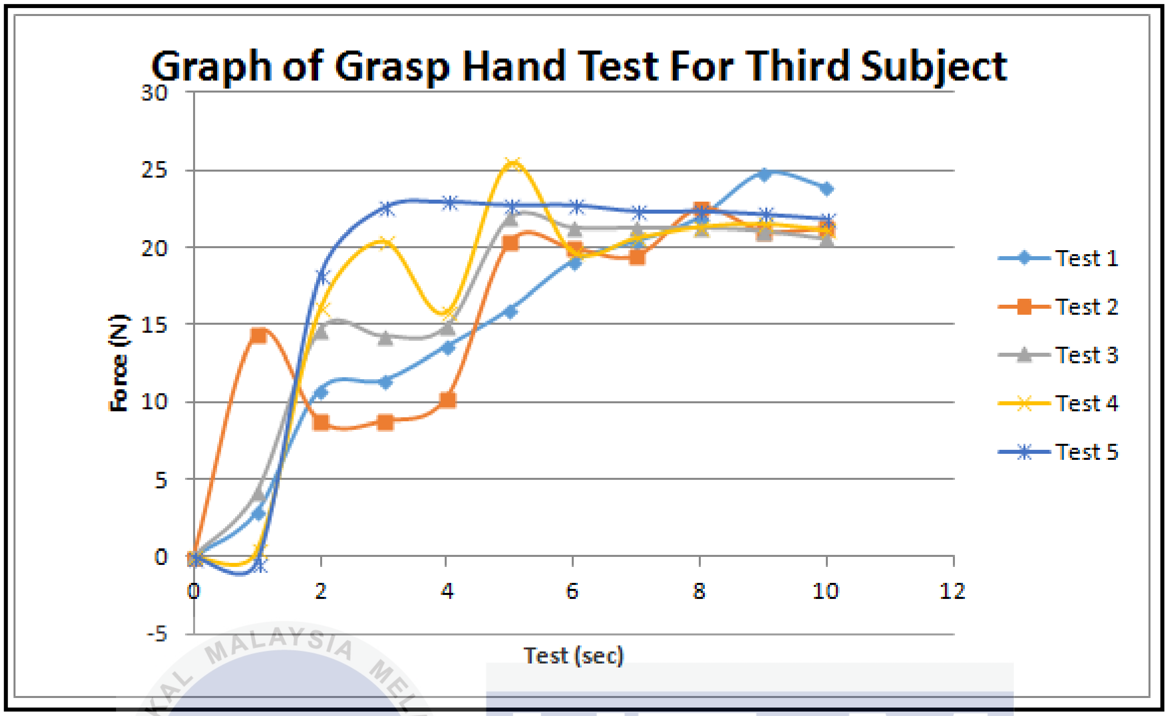


Figure 4.36: Graph Force against Time for Third Person

Referring to the graph presented in Figure 4.36, the range of hand grasp strength for the last subject shown the subject has the lowest strength of hand grasp force. The range for all the tests for last subject is around 15N until 25N after 6 seconds of each test.

The same procedure of grasp test is constructed at Bionic hand. The force result that has been produced by bionic hand is recorded in the table. The process is repeated until 10 times to get the constant force value of bionic hand where the electrode is used to capture the electromyogram signal from the muscle. From the signal that has been capturing the bionic hand can be actuated following the range that already provided in Table 4.1. During the experiment the value of the voltage is monitored to avoid the bionic hand press the hand dynamometer too long. Referring to the Table 4.16, the result from that table is used to plot the graph at Figure 4.37. The graph had shown the analysis of pressing tests for bionic hand.

Table 4.16: Grasp Test for Bionic Hand

Time (Sec)	Force (N)				
	Test 1	Test 2	Test 3	Test 4	Test 5
0	0	0	0	0	0
1	32	5.3	28.5	0.2	6.8
2	38.8	42.1	43.6	26.3	56.8
3	42.8	45.4	42.1	45.4	57
4	42.3	44.1	38.8	37.7	67.3
5	30.9	33.1	30.9	37.3	49.3
6	30.3	29.8	26.1	34	32.9
7	30.1	29.6	25.7	31.8	32.2
8	30.1	29.4	25.4	21.9	32.2
9	29.8	27.6	25.4	21.9	32.5
10	29.6	27.6	25.2	22.2	32.2

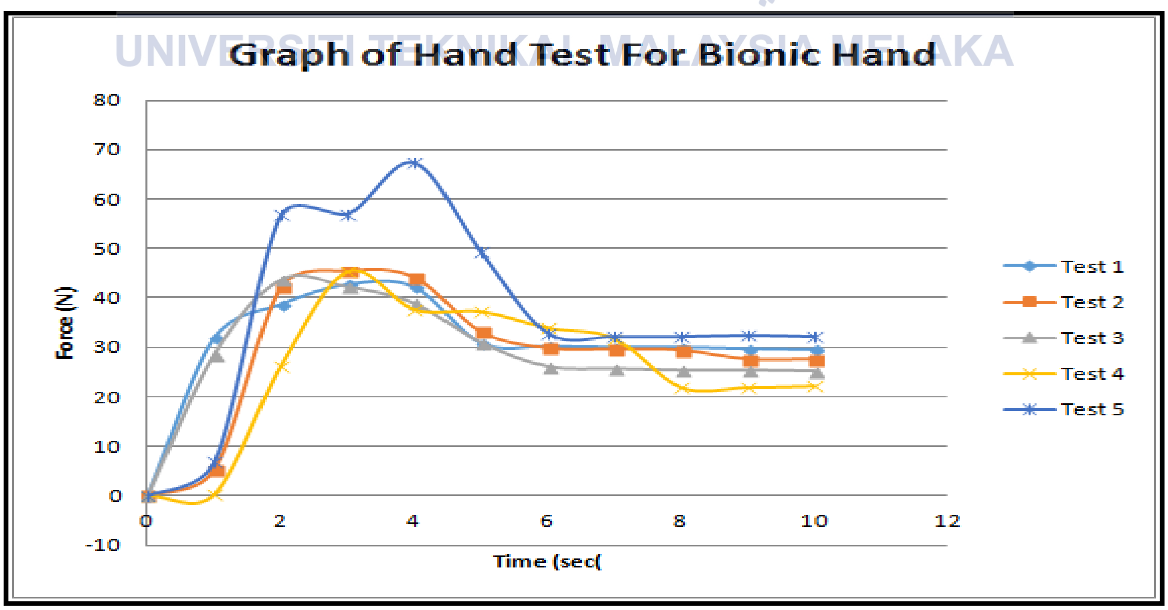


Figure 4.37: Graph Force against Time for Bionic Hand

Based on Figure 4.37, the different color of the line shows the difference number of tests and each graph is involved with five tests. The result of bionic hand shows in the early 6 seconds the bionic hand gives the high force before it starts to give the constant force value after 6 seconds of the test. The highest graph line showed the highest press force that is recorded by bionic hand. This situation occurs because during the first 6 seconds, the bionic hand is fully grasps the hand dynamometer and the linear DC motor to give the high force to each finger. After the bionic hand is fully grasped the hand dynamometer, the linear DC motor released some force to avoid the motor from damaged and give the constant force value to the bionic finger. These situations can be seen at all test results after 6 seconds of grasp hand test. During the experiment 10 seconds were given to complete each of the tests. From all graphs above, the forces start to be constant after 6 seconds. The constant value of each graph is used to make the comparison between natural human hand and bionic hand that mean all the force that above than 6 seconds is used to analyze. The average data of each graph were calculated and tabulated in the Table 4.17. From the data that is tabulated in Table 4.17, the graph of average force after 6 seconds is plotted in Figure 4.38.

Table 4.17: Average Data from Grasp Test

Time (Sec)	Force (N)			
	Person 1	**Person 2**	**Person 3**	**Bionic Hand**
6	91.92	87.2	20.58	21.18
7	86.02	113.52	20.84	20.98
8	81.28	98.14	21.9	20.8
9	86.42	95.62	22.14	20.66
10	82.26	102.94	21.76	20.52

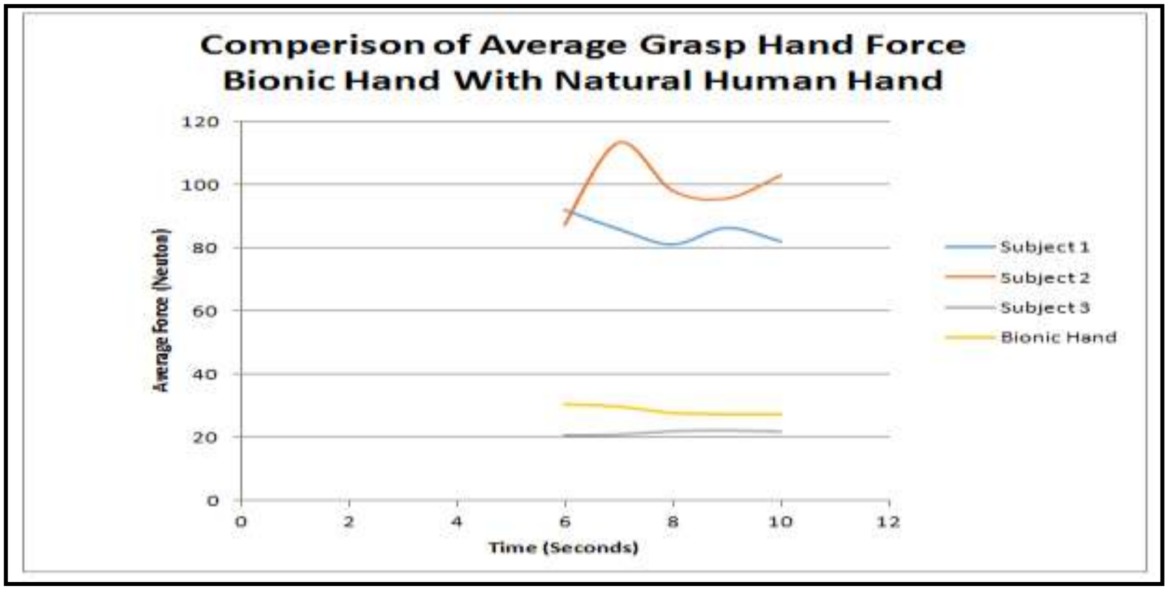


Figure 4.38: Graph Force against Time for Average Data from Grasp Test

Referring to the result in Figure 4.38, there are four comparison data is plotted on the same graph. The blue line color indicated the average data for first person and orange color indicated average data for second person while gray and yellow line indicated the average the data force for the third person and bionic hand. During the experiment 10 seconds were given to complete each of the tests.

From the result in Figure 4.34, Figure 4.35, Figure 4.36 and Figure 4.37 above, the forces start to be constant after 6 seconds. The constant value of each graph is used to make the comparison between natural human hand and bionic hand that mean all the force that above than 6 seconds is used to analyze. The average the data of each graph is calculated and tabulated in the Table 4.18. From the data that tabulated, one graph is plotted using the same data to compare force value. The Figure 4.38 shows the yellow line that indicates the average force of bionic hand slightly lower that the gray line that indicates the average force of a third person. Meanwhile, the average force for press test between second subject and the bionic hand showed a lot of significant strength force. Whereas for the average press force between second subject and bionic hand hand showed the moderate comparison result of average grasp force. From three ranges average force that collected from three different subjects, the range of the closest to the average force of bionic taken to be used to calculate the percentage of error. Using the equation (4.2) percentage of error, the result of the average pressure test of bionic hand is compared with the result of the second subject.

Table 4.18: Percentage of Error between True Value and Measurement Value for Grasp Test

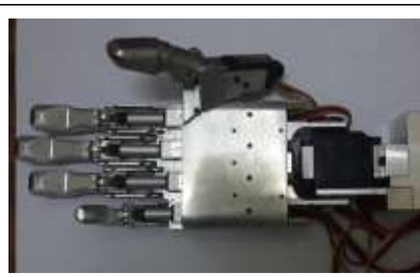
Number Of Test	Third Subject	Bionic Hand	Percentage of Error
6	20.58	30.62	48.78523
7	20.84	29.88	43.37812
8	21.9	27.8	26.94064
9	22.14	27.44	23.93857
10	21.76	27.36	25.73529

The percentage of error is calculated based on the difference value of time taken for each force. The percentage of error is tabulated in Table 4.18. Based on the tabulated data, the highest percentage of error is during 6 seconds where the percentage of error is 48.78523%. The error that occurred on every second of the bionic hand is due to the limitation of bionic hand that cannot grasp overall surface of hand dynamometer. Based on the structure of the natural human hand that has flexible characteristic, the palm of bionic hand is fabricated by using the aluminium. According to the strong characteristic of aluminum that have, the palm of bionic hand cannot change the structure during its grasp that hand dynamometer. However, from the data that has been plotted the bionic hand considered accurate because it can reach the value of 20N force.

4.5.5 Analysis of Canonical Hand Postures of Bionic Hand

Six postures of bionic hand were made to emulate the human hand posture during this experiment. The posture that is made by bionic hand is cylindrical, lateral, angular surface, spherical, grasp and platform. Using the electromyogram signal from forearm muscle, the bionic hand is actuated with the range of from the Table 4.19. Each goods were put in the palm of bionic hand and the signal from hand is given to actuate the bionic hand.

Table 4.19: Canonical Hand Postures

Posture	Bionic Hand	Natural Human Hand
Cylindrical		
Angled Surface		
Lateral		
Spherical		
Grasp		
Platform		

Based on Table 4.15, bionic hand is tested with a set of canonical human posture to analyze the ability of the bionic hand to emulate the natural human hand. From the results, it can be clearly seen that for cylindrical posture, literal posture, grasp posture and platform posture of bionic hand perfectly can emulate the canonical natural human posture.

During the experiment, the index finger required 1.9 seconds to close from the fully open position. Assuming 90 degree range of motion for each joint, this time-to-close indicates joint velocity of 0.83 rad/Sec, assuming the constant velocity during the 1.9 seconds closing. Based on typical activities of daily living require finger joint speeds of approximately 4 rad/Sec [6], the bionic hand cannot reach the target because of the speed on the linear DC motor is too slow.

4.6 Summary of Analysis and Discussion

In this section three analyses are discussed, it is repeatability analysis, repeatability analysis and canonical hand posture. Two analysis of repeatability and two analysis of accuracy is conducted to achieve the third objective. During the analysis of canonical hand posture, bionic hand can emulate six postures of natural human hand.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The first objective is to design the bionic hand that resembles the real human hand is discussed in detail it previous chapter. This section all the method that used to design the bionic hand is shown, while the first phase will discuss about mechanical design and the second phase will discuss about the component selection.

The second objective is discussed about the construction of bionic hand, emulate the human hand shape. In this section this proposal is discussed about the material selection and electrical component that will used to contract this bionic hand. Aluminum 6061 series is selected to construct this bionic hand while electrode is used to capture the signal of muscle activities and the signal is amplified by using V3 muscle sensor. After that the signal will use to control the motor of the bionic hand using Arduino microcontroller Uno R3

The last objective need to achieve in this project is to performance of the exoskeleton bionic hand model in term of repeatability and accuracy. Three types of tests are conducted to achieve this objective. The two experiments of repeatability and the two experiments of accuracy are conducted. The hand canonical posture is constructed to determine whether the bionic hand can emulate the natural human finger of note. In the last of this proposal, the design of bionic hand shown as a final result. The designed still in the research to get a good result of movement.

5.2 Recommendation

There is some vulnerability in this project that identified during conducting the experiment. Form the vulnerability that is identified, some improvement can be added to make this project more efficient. The first improvement that can be made is by replacing the Arduino Uno to Arduino Mega, due Arduino Uno delayed response to the output when Musle Sensor gives the input. This situation happens because of the crystal clock inside the Arduino Uno that has limitation frequency. Beside that, to improve that vulnerability is by connecting that Arduino Uno direct to the computer or laptop

Second improvement that can be made in this project is to apply the sensor at the end of each finger. By applying the sensor at the end of the finger the movement of each finger can be controlled to stop if this bionic hand during it grasps some object. Beside that it will avoid the damage to the bionic hand when high force is applied to grip the object.

The second method to improve this project is by design the bionic hand following the standard size of a human hand by following the standard of human hand size, the bionic hand will perform better and can imitate the characteristic of the human hand.

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[12] http://artofcircuits.com/product/l298n-motor-driver-board/

[13] http://www.texasvernier.com.php?language=en&module=product&content=add product&action=view&pid=421

[14] http://www.youtube.com/watch?v=Al5RhaJgxxU

APPENDIX A

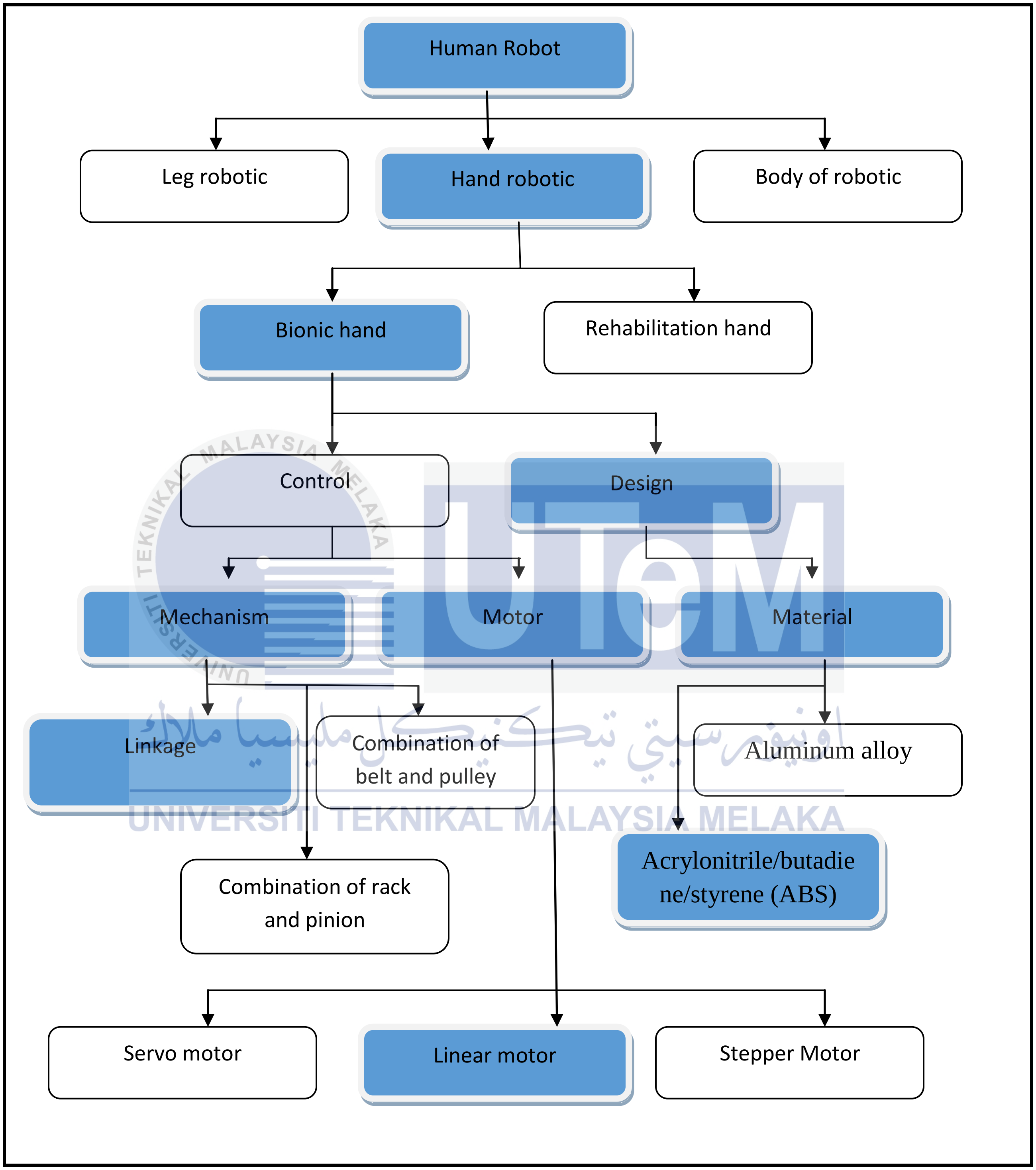

Figure B1 : K Chart

APPENDIX B

```
#include<Servo.h>

Servo myservo1; // create servo object to control a servo

Servo myservo2;

Servo myservo3;

Servo myservo4;

Servo myservo5;

Servo myservo6;

int potpin = A0; // analog pin used to connect the potentiometer

int val; // variable to read the value from the analog pin

int sensorValue;

int voltageValeu;

void setup()

{

Serial.begin(9600); //initial serial comunication

myservo1.attach(3); // attaches the servo on pin 9 to the servo object

myservo2.attach(5);

myservo3.attach(6);

myservo4.attach(9);

myservo5.attach(10);
```

```
myservo6.attach(11);

}

void loop()

{

sensorValue = analogRead(potpin); // reads the value of the potentiometer (value between 0
and 1023)

voltageValue = ( sensorValeu * 5 ) / 1023;

if(sensorValue<=50)

{

myservo5.write(150);

//delay(2000);

myservo1.write(150);

myservo2.write(150);

myservo3.write(150);

myservo4.write(150);

Serial.print(" sensor ="); // Print the result of sensor valeu and output value

Serial.print(sensorValue);

Serial.print(" voltage ="); // Print the result of voltage valeu and output value

Serial.print(voltageValue);

Serial.print('\n');

Serial.print(" Output =");

Serial.print(" extand")
```

```
;delay(1000);Serial.print('\n');}

if(sensorValue>50 && sensorValue<120)

{

myservo1.write(85);

myservo2.write(20);

myservo3.write(20);

myservo4.write(20);

delay(2000);

myservo5.write(20);

Serial.print(" sensor ="); // Print the result of sensor valeu and output value

Serial.print(sensorValue);

Serial.print(" voltage ="); // Print the result of voltage valeu and output value

Serial.print(voltageValue);

Serial.print('\n');

Serial.print(" Output =");

Serial.print(" extand")

;delay(1000);Serial.print('\n');

 // waits for the servo to get there }

if(sensorValue>121 && sensorValue<200)

{

myservo6.write(40);
```

```
Serial.print(" sensor ="); // Print the result of sensor valeu and output value

Serial.print(sensorValue);

Serial.print(" voltage ="); // Print the result of voltage valeu and output value

Serial.print(voltageValue);

Serial.print('\n');

Serial.print(" Output =");

Serial.print(" extand")

;delay(1000);Serial.print('\n');}

if(sensorValue>200)

{

myservo6.write(140);

Serial.print(" sensor ="); // Print the result of sensor valeu and output value

Serial.print(sensorValue);

Serial.print(" voltage ="); // Print the result of voltage valeu and output value

Serial.print(voltageValue);

Serial.print('\n');

Serial.print(" Output =");

Serial.print(" extand")

;delay(1000);Serial.print('\n');

}

}
```

APPENDIX C1

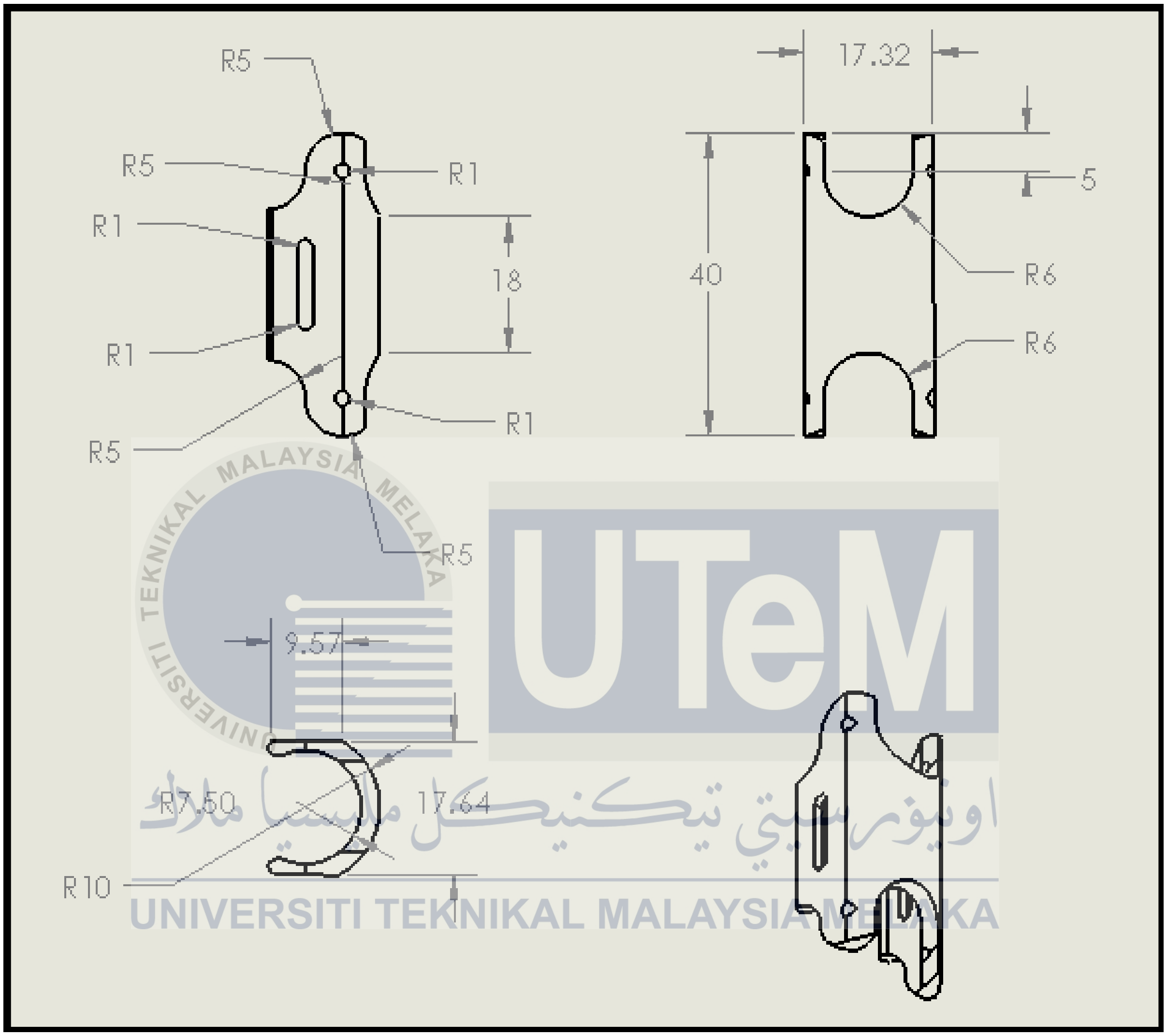

Figure C1 : Dimension of Proximal Phalanx (PP) for ring and index finger

APPENDIX C2

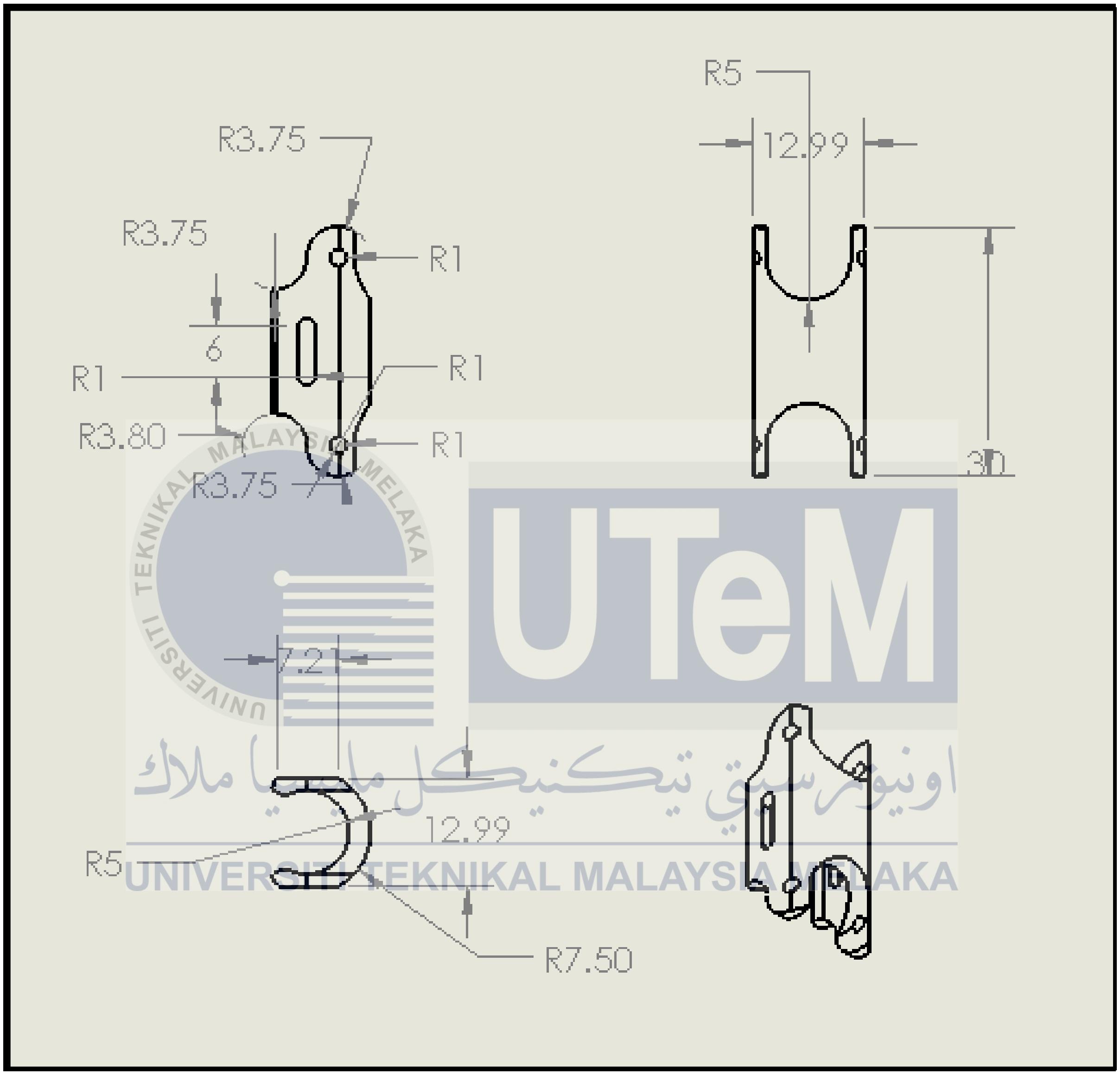

Figure C2: Dimension of Proximal Phalanx (PP) for pinkie finger

APPENDIX C3

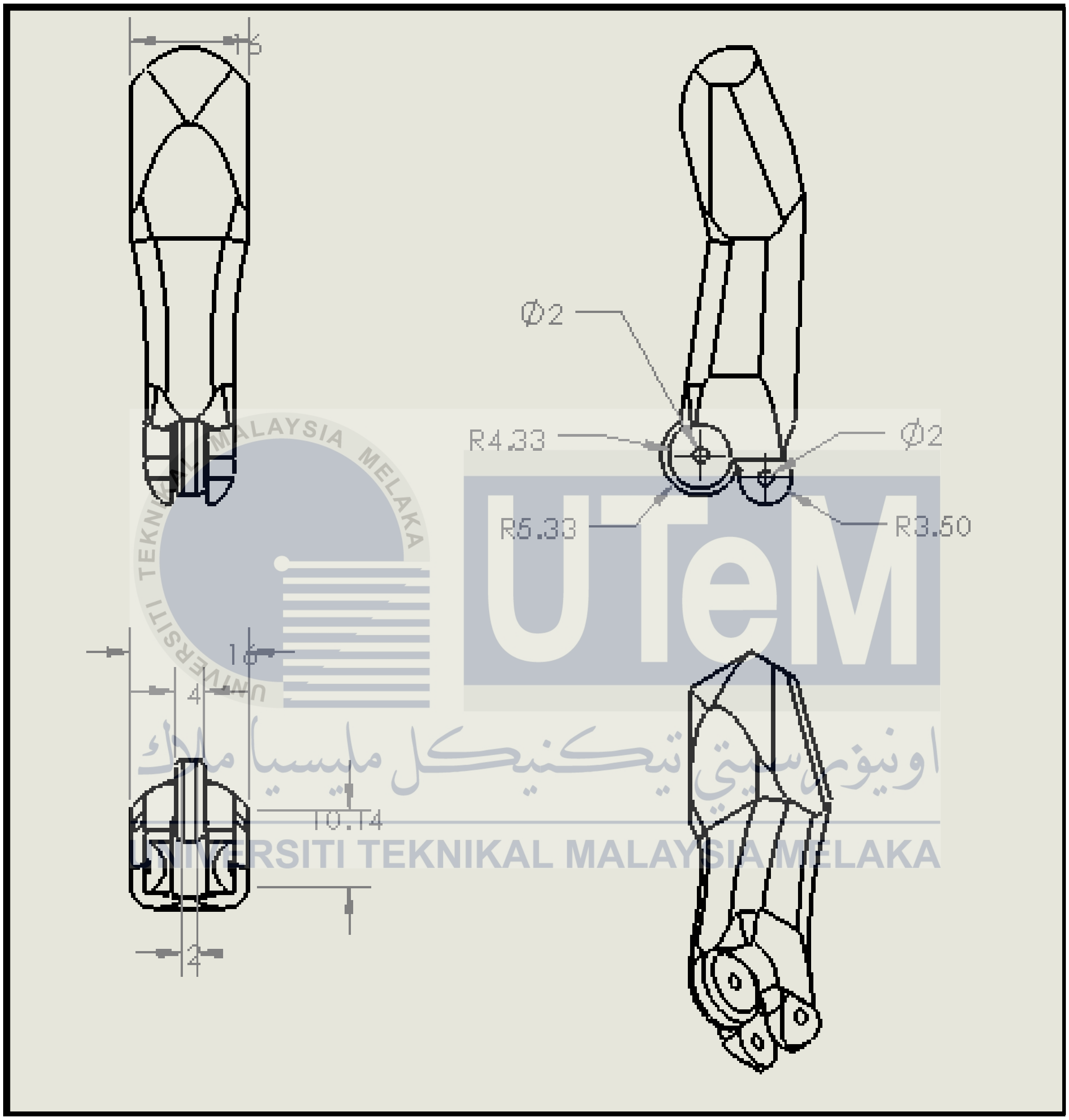

Figure C3: Dimension of Middle Phalanx (MP) and Distal Phalanx (DP) for middle finger

APPENDIX C4

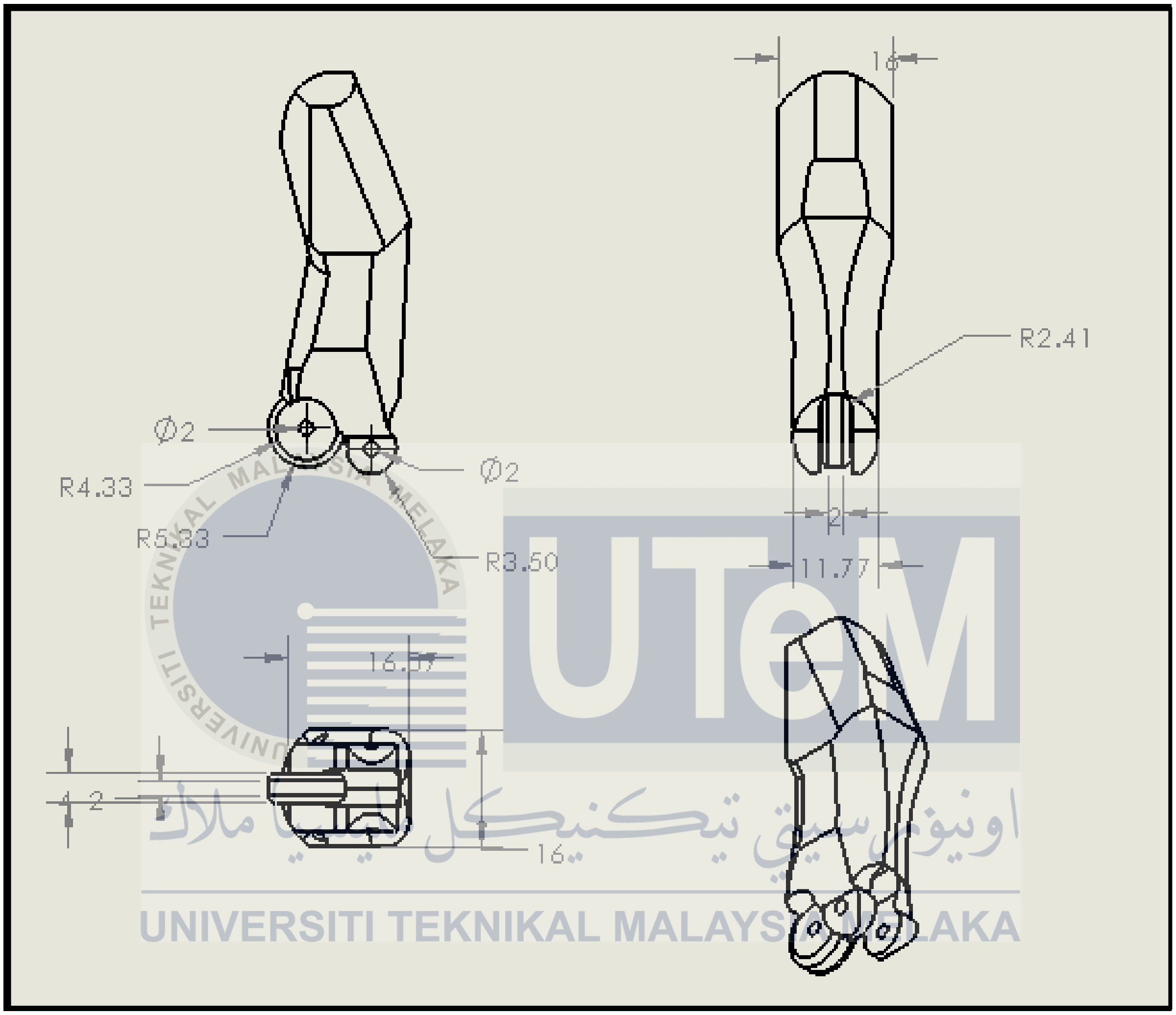

Figure C4: Dimension of Middle Phalanx (MP) and Distal Phalanx (DP) for middle and ring finger

APPENDIX C5

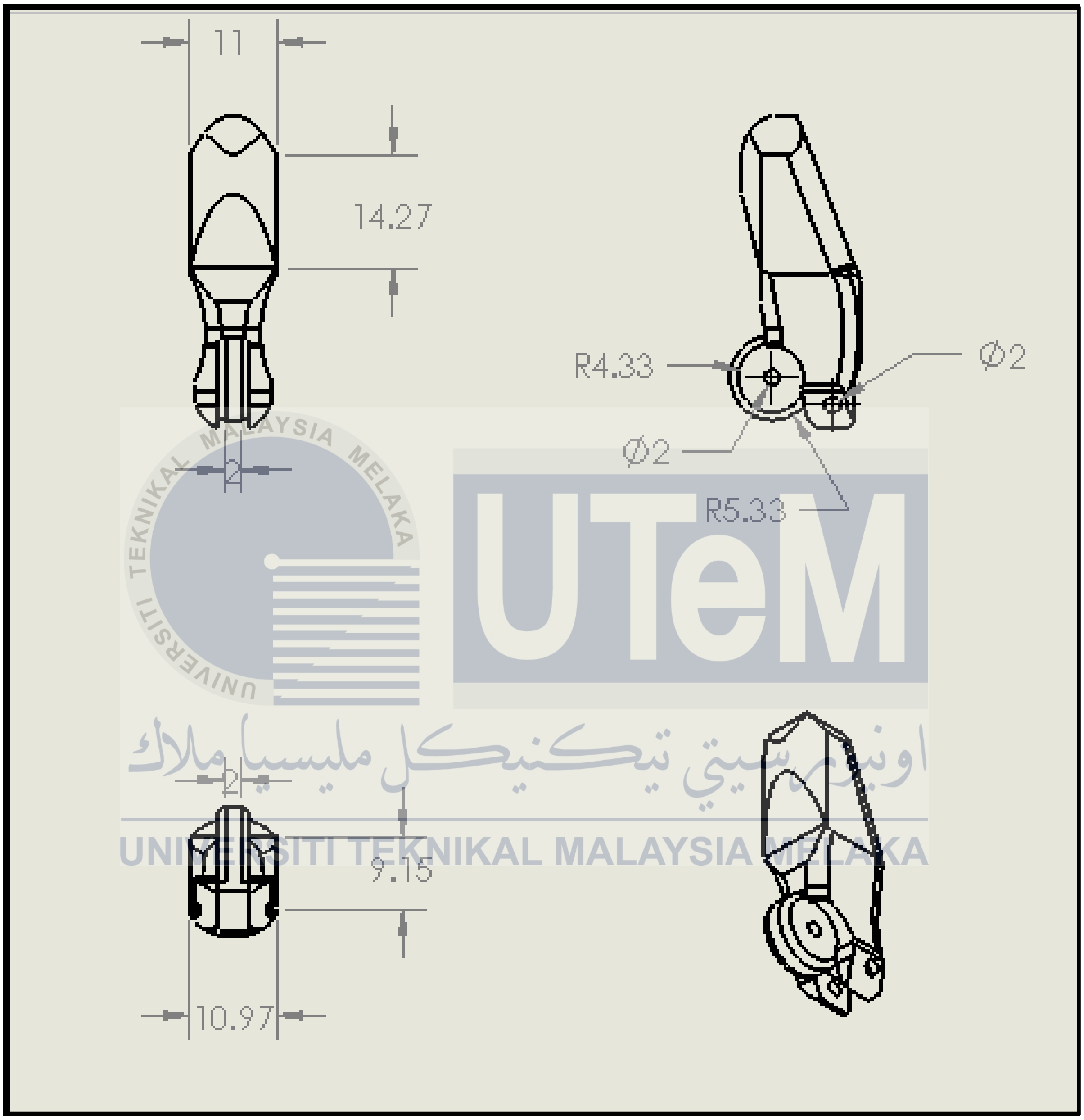

Figure C5: Dimension of Middle Phalanx (MP) and Distal Phalanx (DP) for pinkie finger

APPENDIX C6

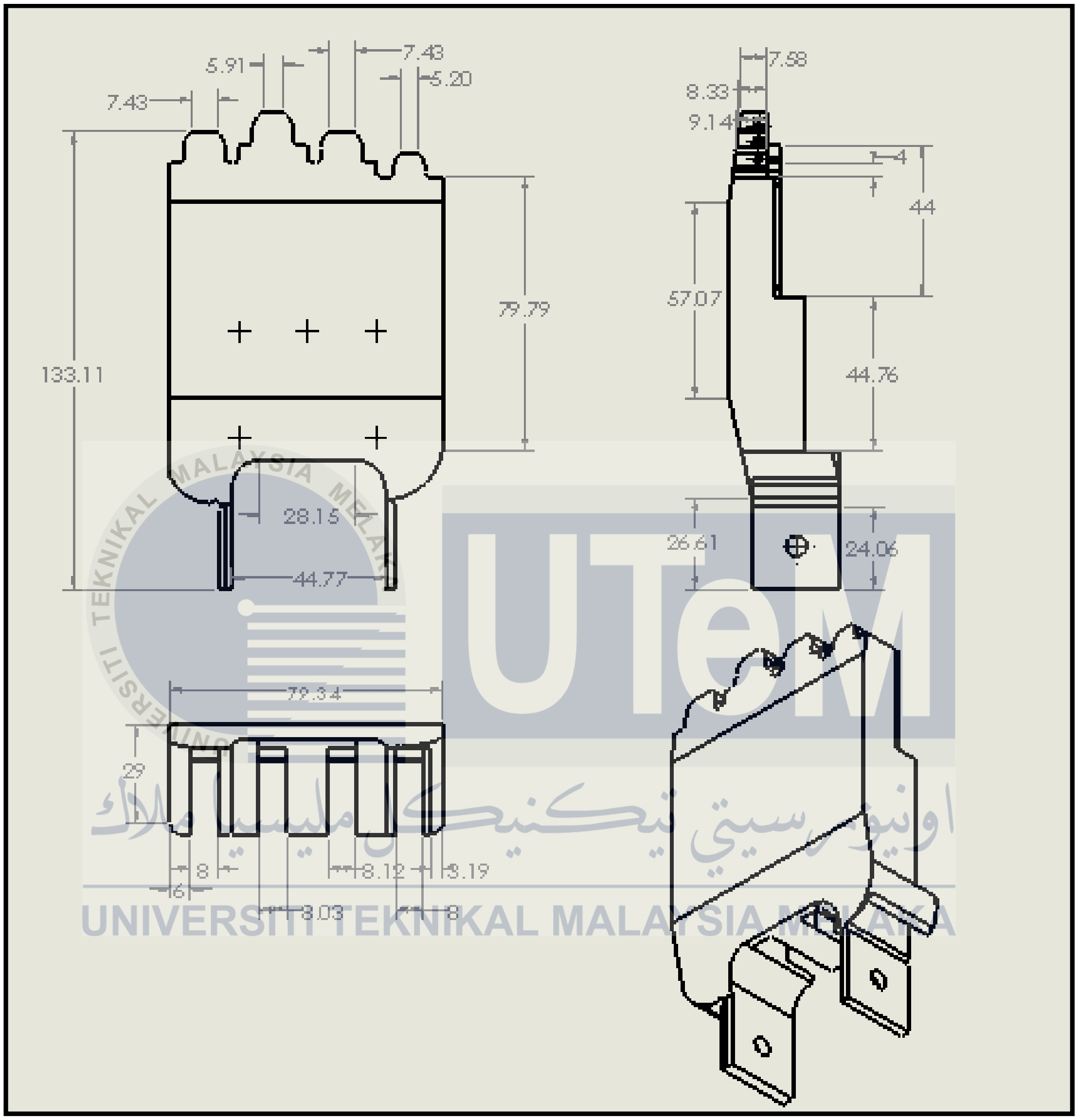

Figure C6: Dimension of palm

APPENDIX C7

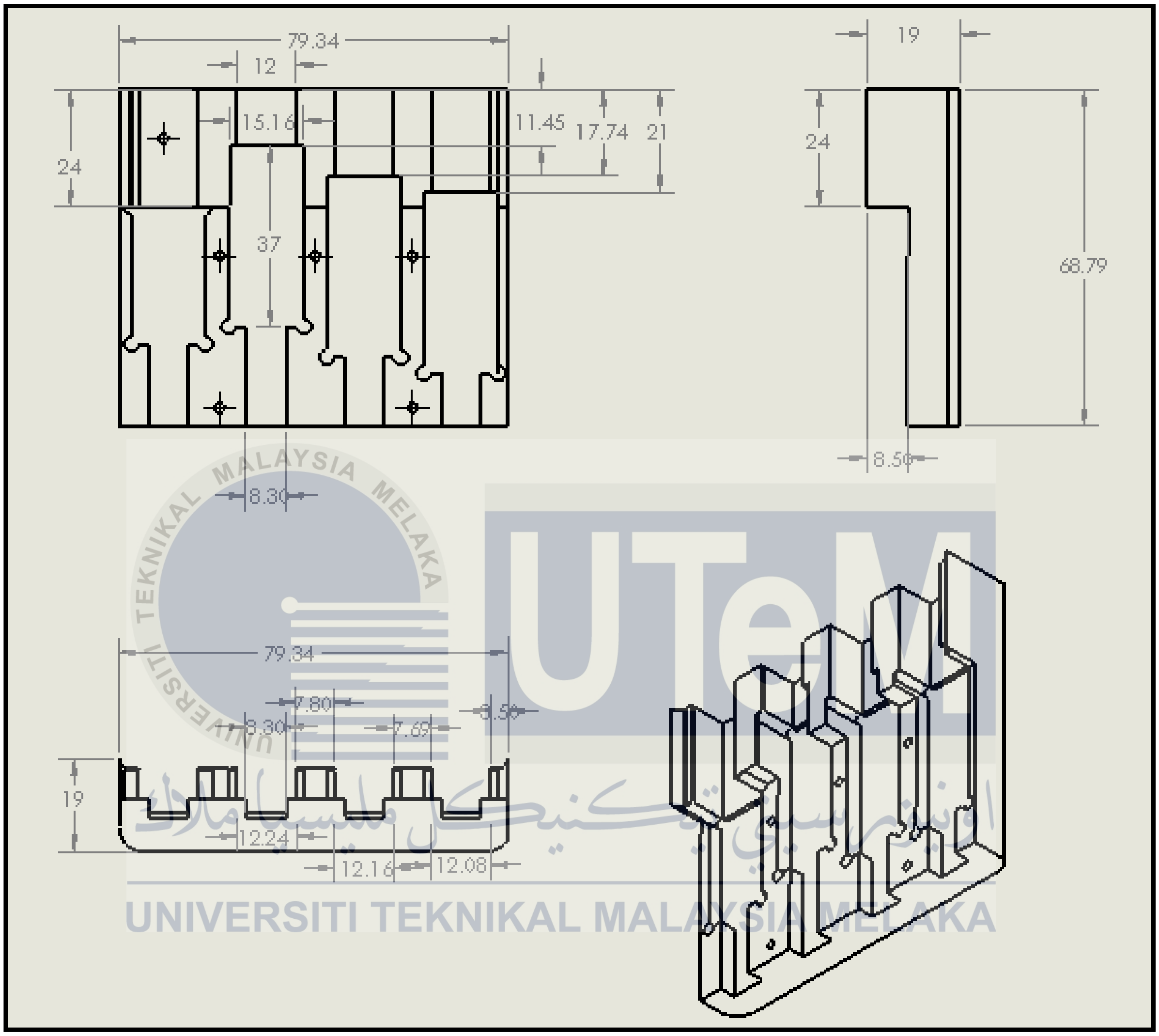

Figure C7: Dimension of palm cover

APPENDIX C8

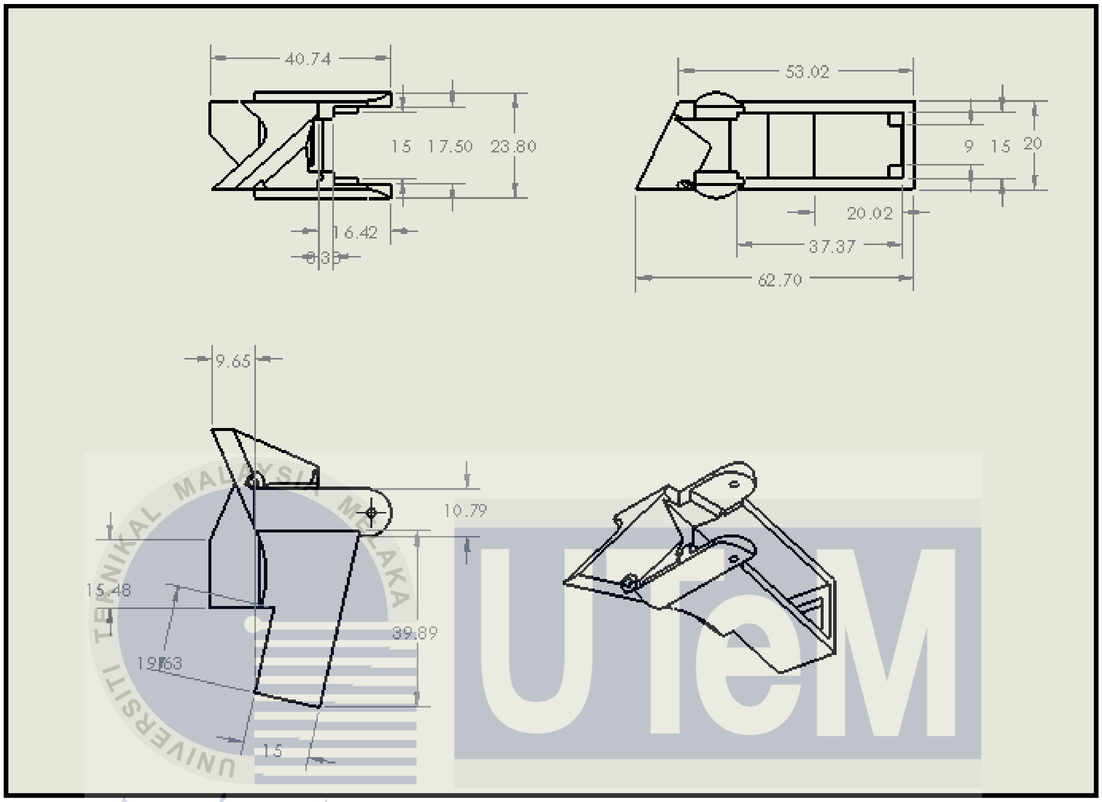

Figure C8: Dimension of thump base

APPENDIX C9

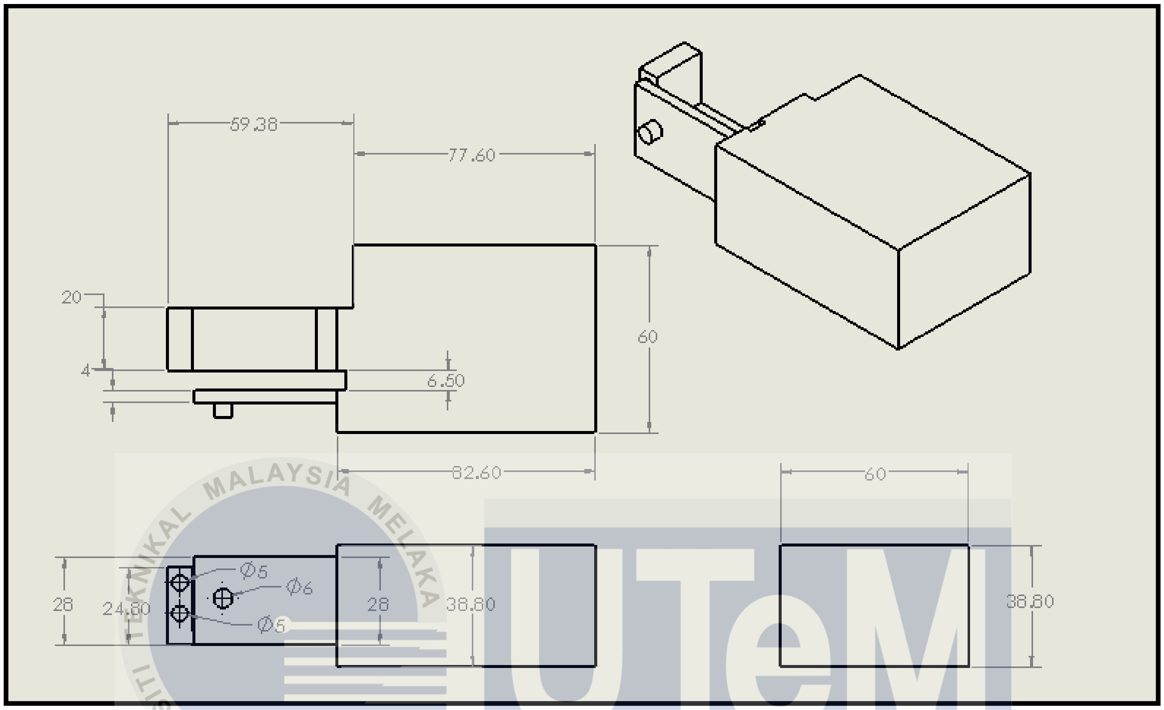

Figure C9: Dimension of wrist of bionic hand