DEVELOPMENT OF PROSTHETIC TERMINAL DEVICE WITH SENSORY FEEDBACK

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ABSTRACT

There are numbers of prosthetic terminal devices which offer functional restoration to individual with upper limb deficiencies. Nowadays, there are great advancement in the electrical prosthesis. The most physically neutral electrical upper limb amputee prosthesis is myoelectric prosthesis system that use muscle activity from the remaining limb for the control of terminal device or joint movement. Myoelectric prosthesis present in one-way communication which is from the user to the prosthesis. One of the challenges facing prosthetic designers and engineers is to restore the missing sensory function inherit to hand amputation. The user are able to send the signal from the remaining muscle to the prosthesis but the prosthesis are not able to send the signal back to the user. Therefore, without noticing, the user may exert extra force and can accidently squeeze the object they hold. The objective of this research is to establish two-way communication prosthetic system by developing a prosthetic terminal device with sensory feedback. The terminal device will monitor amount of force exerted on an object and amount of force is translated into vibration that are identifiable by the skin of the user. This prosthesis allows user to control and supply adequate amount of force while grasping object. For the first part, a myoelectric controlled prosthesis, named ‘smartGrip’ that comes with a skin electrode, FSR sensor, vibration motor, microcontroller, battery and electrical terminal device was fabricated. The terminal device reprogrammed with a new setup and control unit. On the second part, analysis on two mechanical and one electrical terminal device was executed as a part of the study to investigate standard characteristic of terminal device. The performances of the device were tested on one transradial amputee and two normal subject. QUEST survey was also executed to evaluate user’s satisfaction toward the hand. The average force exerted by the mechanical terminal device is slightly lower than the electrical terminal device. Force distributed uniformly at different opening angle by electrical terminal device but changing with increase in opening angle by mechanical

terminal device. Besides that, with greater opening angle, electrical terminal device are capable to grasp bigger size object easily. Subjects can adapt well with the control protocol and the vibration mode as sensory substitution for the gripping activity. From the QUEST survey conducted, majority of the subject were satisfied with the durability, effectiveness and user friendliness of the device. More than 50% of the subjects were quite satisfied with the weight, comfort, safety and dimension of the developed prototype but 30% of the subject were not very satisfied with the ease in adjusting which is due to the placement of the electrode. With 'smartGrip', user are able to control delicate and fragile object securely as they can feel amount of grasping via the intensity of vibration mode. A complete mechanical design of a prosthetic hand with sensory feedback have proven to increased functionality over currently available products.

ABSTRAK

Terdapat beberapa peranti terminal palsu yang menawarkan pemulihan berfungsi untuk individu yang kekurangan anggota bahagian badan atas. Pada masa kini, terdapat kemajuan yang besar dalam prostesis elektrik. Prostesis elektrik anggota bahagian atas yang paling neutral ialah sistem prosthesis myoelektrik yang menggunakan aktiviti otot daripada anggota badan yang tinggal untuk mengawal peranti terminal atau pergerakan sendi. Myoelektrik hanya hadir dalam hanya satu haluan komunikasi iaitu dari pengguna dan prostesis mereka. Satu cabaran yang dihadapi pereka prostetik dan jurutera adalah untuk megembalikan fungsi deria yang hilang akibat pengkudungan tangan. Ini menjadikan pengguna dapat menghantar isyarat untuk prostesis tetapi prostesis tidak menghantar isyarat kembali kepada pengguna. Oleh itu, tanpa menyedarinya, pengguna boleh menggunakan daya tekanan berlebihan dan secara tidak sengaja boleh merosakkan objek yang mereka pegang. Tujuan kajian ini adalah untuk mencipta dua hala komunikasi peranti terminal prostetik dengan maklum balas deria. Peranti terminal dapat memantau jumlah daya yang dikenakan pada objek dan jumlah genggaman ditukarkan kepada getaran yang boleh dikenalpasti oleh kulit pengguna. Kenaikan jumlah tekanan pada objek akan meningkatkan intensiti getaran yang diletakkan pada lengan penguna. Prostesis ini membolehkan pengguna mengawal dan mengaplikasikan jumlah tekanan yang cukup semasa menggengam tanpa merosakkan mereka. Untuk bahagian pertama, myoelektrik prosthesis yang dinamakan ‘smartGrip’ yang diperbuat daripada elektrod kulit, sensor FSR, motor getaran, mikrokontroller, bateri dan peranti terminal elektrik telah direka. Peranti terminal di programkan semula dengan susunan dan unit control yang baharu. Dalam bahagian kedua, analisis pada dua mekanikal dan satu peranti terminal elektrik telah dilaksanakan sebagai sebahagian daripada kajian untuk menyiasat ciri umum peranti terminal. Peranti telah diuji pada satu amputee transradial dan pada dua subjek yang normal. Kaji selidik QUEST juga dijalankan untuk mengetahui kepuasan

penguna terhadap tangan ini. Daya purata dikenakan oleh peranti terminal mekanikal adalah sedikit lebih rendah daripada peranti terminal elektrik. Tekanan diagih sama pada sudut pembukaan yang berbeza mengikut peranti terminal elektrik tetapi berubah dengan tahap pembukaan oleh peranti terminal mekanikal. Selain itu, dengan pembukaan sudut yang lebih besar, peranti terminal elektrik mampu untuk mencapai objek yang bersaiz lebih besar dengan mudah. Subjek boleh menyesuaikan diri dengan protocol kawalan dan mod getaran sebagai pegganti deria untuk aktiviti genggaman. Dari tinjauan QUEST yang dijalankan, majoriti subjek berpuas hati dengan ketahanan, keberkesanan dan keramahan pengguna peranti. Lebih daripada 50% daripada subjek cukup berpuas hati dengan berat, keselesaan, keselamatan dan dimensi prototaip yang dibangunkan tetapi 30% daripada subjek tidak terlalu berpuas hati dengan kemudahan penyesuaian yang disebabkan oleh cara penempatan elektrod itu sendiri. Dengan 'smartGrip', pengguna dapat mengawal objek halus dan rapuh dengan selamat melalui kemampatan genggaman melalui getaran. Satu reka bentuk mekanikal lengkap tangan prostetik dengan maklum balas deria telah terbukti meningkatkan fungsi prostesis berbanding produk yang terdapat pada masa ini.

LIST OF PUBLICATIONS AND PAPERS PRESENTED

The research described in this thesis has led to the presentations, publications, publications, awards and patent of the following:

Journals

1. **N.A. Hashim**, N.A. Abd Razak, H. Gholizadeh and N.A. Abu Osman. Analysis of Voluntary Opening Ottobock Hook and Hosmer Hook for Upper Limb Prosthetics: a Preliminary Study. Biomedical Engineering/Biomedizinische Technik (BMT). (Accepted)
2. **N.A. Hashim**, N.A. Abd Razak, N.A. Abu Osman and H. Gholizadeh. Improvement on upper-limb body-powered prosthesis (1988-2015): systematic review. Proceedings of the institution of mechanical engineers part h-journal of engineering in medicine (Accepted with Revisions)

Proceedings

1. **N.A. Hashim** (M.Sc.Eng.), N.A. Abd Razak (PhD), N.A. Abu Osman (PhD). Development of a Lifelike Prosthesis Terminal Device with Sensory Feedback. MoHe Conference, Melaka
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LIST OF SYMBOLS AND ABBREVIATIONS

°	:	Degree
%	:	Percentage
m	:	Meter
mm	:	Millimeter
ROM	:	Range of Motion
EMG	:	Electromyography
FSR	:	Force Sensitive Resistor
MW	:	Myoware
FL	:	Lateral Force
FT	:	Tip Force
TD	:	Terminal Device
BP	:	Body Powered
MES	:	Myoelectric Signal
VO	:	Voluntary Opening
VC	:	Voluntary Closing
POP	:	Plaster of Paris
TVSS	:	Tactile-vision sensory substitution
LiPo	:	Lithium-ion polymer battery

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Chapter 2, literature review explores and evaluate previous works that have been done on upper limb prosthetics which covers from classics to high technology prosthetic system. This chapter will review and evaluate previous relevant studies and concluded with some new approach on the design and development of the prosthetic system.

The important goal of the rehabilitation for upper-limb amputee is the selection of convenient prosthetic device that grants the best prehension and functional movement (Godfrey, 1990). A significant number of adult and children wear body-powered (BP) prosthesis, although there is great advancement in electrical prosthesis (Biddiss & Chau, 2007; Shaperman, Landsberger, & Setoguchi, 2003). The benefit of body-powered prosthesis include silent action, light weight, moderate cost, durability and reliability, rough sensory feedback about the positioning of the terminal device and simple operational mechanism with intrinsic skeletal movement (which voluntary open/close a terminal device)(Beasley & Bese, 2007; Esquenazi et al., 1989; Jones & Davidson, 1996; Leonard Jr. et al., 1989; Pezzin, Dillingham, MacKenzie, Ephraim, & Rossbach, 2004).

In 2004, interviews with members of the Amputee Coalition of America found about 33.33% of upper-limb amputees were not satisfied with the comfort of the prosthesis and 18.4% of respondents being fit with a new prosthesis at least once a year (Pezzin et al., 2004). Some report claimed that as many as 50% of upper-limb amputee choose not to wear prosthesis, often citing the functional advantage or cosmetics did not outweigh the inconvenient of the prosthesis (Cupo & Sheredos, 1998; Doeringer & Hogan, 1995). Besides, according to source, primary indicators of prosthesis rejection include lack of perceived functional gains, prosthesis weight and socket discomfort

(Wright, Hagen, & Wood, 1995), and high rejection rates associated with higher amputation levels, congenital limb loss, females and student (Biddiss & Chau, 2007).

In functionality aspect, users expressed their interest for improved wrist movement and control, overall maneuverability, coordination, and sensory feedback. Besides, some other issues identified with BP prosthesis system include increased body movement and task-completion period compared to the sound limb (Doeringer & Hogan, 1995). Biddiss et al. (2007) reported that although it is not specifically reported in any literature, this additional gross body movement combined with the need to utilize the same activation force regardless of task can cause injury on user's body over time. Therefore, while BP prosthesis system currently prevail in the area of sensory feedback, users express their desire in further improvement here. In addition, increase grasp force is also one of special desire by BP prosthesis user (E. Biddiss, Beaton, & Chau, 2007). Standard upper-limb body-powered prosthesis have not changed significantly since development in the 1950s which were spurred by World War II. There is no great deal of change if one looks at the Manual of Upper Extremity Prosthetics first edition (1952) and the Orthopaedic Appliance Atlas-Artificial Limbs first edition (1960) compared with 1985 state of the art (LeBlanc, 1985). In addition, there is little or no research intended to improve body-powered arms being conducted. Therefore, more amputees are opting for externally powered prosthesis and the gap is getting larger between the two types (Trost, 1983).

The development of science and technology in recent years has led to the development of prosthesis with functional features and esthetic appearance in research domain especially for commercialization. The design of prosthetic hand is multidisciplinary, compelling knowledge of physiology, anatomy, electrical and electronics, mechanical design, software, and so on, depending on the nature of control. This contributed to the development of myoelectric control prosthesis which use muscle activity from the remaining limb for the control, actuated by electric motors and powered with an external power source. With myoelectric prosthesis, the use of unwieldy straps or body harness that causes muscle fatigue and restrict the motion in shoulders during prolonged operation is eliminated. No extra energy needed as the device use batteries to move the terminal device. The operation are faster compared to BP prosthesis as only one muscle need to be activated to operate the hand rather a full body movement. Besides that, light to moderate weights can be grasped with voluntary opening terminal devices, meanwhile very strong grip (maximum of 12 kg) can be supplied by myoelectric hand. Previous studies used different modes of sensory substitution technique in replacing the sensory while grasping object including tactile, auditory, visual substitution and nervous stimulation. The technique that usually used are electrotactile. Electrotactile techniques convert a non-tactile information to sense of touch via electrical stimulation by application of current to the skin which might be dangerous to the prosthetic hand user due to unexpected surge or spikes of the electric current.

This research will focus on developing a myoelectric hand that comes with sensory feedback, a self-regulating mechanisms, aims to provide the stability to the device which is achievable via sensory substitution in restoring user ability to perceive certain defective sensory information (touch) from a functioning sensory modality. Analysis on developed prototype was analysed and compared to BP terminal devices (voluntary closing Ottobock model 10A18 and Hosmer model 99P) were carried out in this study. The maximum opening and force supplied at different opening angle and different section of the split hook were measured. The research in this field will establish platform for the development of prosthetic terminal device that restore the sense of touch in upper limb amputee in Malaysia. The data from analysis of commercial products will provide references for prosthetist and manufacturer for the future development.

1.2 Problem Statement

The problem related to myoelectric prosthesis is the mass and cost of the device. Additional motors and batteries led to the increment of the weight of the artificial limb, unlike body powered and cosmesis hand. With advancement in technology, the size and weight of the components reduced and the burden decreased. Unfortunately, the price increased with decrease in size of components, and one problem of myoelectric hand remain unsolved. Although this hand are more expensive as compared to the other type of hand, myoelectric prosthesis offers the best quality in regard to both cosmetics and functionality. The major problem with myoelectric hand is that the hand operate in one-way communication system which is from the user to the device. With this one-way communication system, the user are able to send the signal to the prosthesis however the prosthesis hardly transmit the signal back. Therefore, the device will not able to detect grasping force applied to the object they hold and the user may exert extra force and accidently can squeeze and damage object.

Many prosthetic hand with additional features developed recently such as ‘i-limb’, ‘bebionic’ and more. This additional features comes with price due to additional components. Therefore, the users and manufacturer stuck in the viscous circle where the users are dissatisfied, the manufacturer starts to add function, the device become heavier and at the end of the day, the user becomes more dissatisfied. Based on the previous study, it was very clear that BP prosthesis were preferred by most of upper extremity prosthetic users and myoelectric system is on the cutting edge of innovative technology. Comparing a myoelectric hand to BP system, myoelectric hand seems a better system but only lack in proprioceptive feedback, mass and cost of the device. Literature work made on the sensory feedback and sensory substitution technique and related previous study reviewed in order to establish feedback system, reduce the mass and cost of the device.

1.3 Aims and Objectives

The aim of this research is to establish two-way communication prosthetic system by developing a prosthetic terminal device with sensory feedback. The terminal device are able to monitor amount of force exerted on an object and translate the grasping force to the vibration mode identifiable by the skin and therefore allowing the user to control object without damaging them. In order to achieve the aim, the following four objectives were established:

i. Research activities: To analyse prosthetic system available in the market and terminal device that were preferred by the upper limb amputee and to review sensory feedback and sensory substitution system.

ii. To develop prosthetic terminal device system with sensory feedback that enable the user to control amount of grasping force while grasping an object.

iii. To test and analyse the performance of the developed prototype and compare it to other available system.

1.4 Thesis Outline

The thesis entitled 'Development of Prosthetic Terminal Device with Sensory Feedback' is made up of five chapters includes Introduction, Literature Review, Methodology, Results and Discussion and Conclusion and Recommendation.

Chapter 1 – Introduction provides the full background information regarding the upper extremity prosthetics that covers the background of upper extremity amputee, upper extremity prosthetic, prosthetics system available in the market, problem faced by the end user, the latest products, innovation and technology on upper limb prosthetics field. This chapter concludes with the objectives and method involved in this study.

Chapter 2 – Literature review explores and evaluate previous works that have been conducted on upper limb prosthetics which covers from classics to high technology prosthetic system. This chapter will review and evaluate previous relevant studies and concluded with some new approach on the design and development of the prosthetic system.

Chapter 3 – Methodology part is divided into two; the development of prototype and the analysis of developed prototype. All components and procedure used for the development were presented in details. In the analysis, the developed prototype was tested on the real user and their performance was compared to the other available prosthetic terminal device available in the market.

Chapter 4 – Results & Discussion, major part in this chapter elaborates the outcome of the analysis on different prosthetic terminal device which include standard Pinch Force Test, Opening Angle, Pull Test and feedback from Test and Trial on the real patient.

Chapter 5 – Conclusion & Recommendation describe the impact of the result that proven the aim and objectives is achieved at the end of this study. The limitations of the study were also presented with some recommendation for future work.

1.5 Methodology Outline

The outline of the methodology as shown below.

Identify Problem

Different type of upper limb prosthetics system and factors of prosthetics rejection were evaluated.

↓

Literature Review

Information related to the topic were gathered from journal articles, conference proceedings, patents, books, and internet resources.

↓

Aim & Objective

Aim: to establish two-way communication prosthetic system.

Objective:

i. To analyse prosthetic system available / preferred by the amputee.
ii. To review sensory feedback and sensory substitution system.
iii. To develop terminal device system with sensory feedback.
iv. To test and analyse the performance of the prototype.

↓

Part I: Development

Prosthetic terminal device with sensory feedback was fabricated.

↓

Part II: Analysis

Analyse the developed prototype by using several test protocol:

i. Pinch Force Test
ii. Opening Angle
iii. Pull Test
iv. Test & Trial
v. QUEST Survey

↓

Result

All the data were analysed using SPSS and Excel spreadsheet

↓

Discussion & Conclusion

The result of the performance of the developed prototype, test and trial were further analysed and discussed.

CHAPTER 2: LITERATURE REVIEW

Chapter 2, literature review explores and evaluate previous works that have been done on upper limb prosthetics which covers from classics to high technology prosthetic system. This chapter will review and evaluate previous relevant studies and concluded with some new approach on the design and development of the prosthetic system.

2.1 Upper Limb

The human hand is an amazing instrument that can perform a multitude of functions, such as the power grasp and precision grasp of a vast array of objects. The excellent behaviors of the human hand are enabled by a highly complex structure, with 19 articulations, 31 muscles and more than 25 degrees of freedom (DOF) (van Duinen & Gandevia, 2011). In daily use, grasping is the most common function of the human hand (Schieber & Santello, 2004). Many studies have focused on grasping to mimic the ability for artificial hands (C.-H. Xiong, Li, Ding, & Xiong, 1999; C. Xiong, Ding, & Xiong, 2007).

Human use their hands for large variety of activities of daily living (ADLs) (Lawton & Brody, 1969). ADLs refers to the basic tasks of everyday life, such as eating, bathing, dressing, toileting, and transferring (Wiener, Hanley, Clark, & Van Nostrand, 1990). Based on survey of patients with upper extremity amputations conducted by Jang et. al, the most common difficulties experienced by amputees includes lacing shoes, removing bottle-tops with a bottle opener, and using scissors. As for performance, the anatomical hand is capable of speeds in excess of 40 rad/s (2290 degrees/s), and grasps involving all fingers of the hand can exert up to about 400 N (90 lbf) of force. Average physiological speeds for every day pick-and-place tasks have been found to be in the range of 3 to 4 rad/s (172 to 200 degrees/s), while most activities of daily living (ADL) require prehension forces in the range 0 to 67 N (0 to 15 lbf) [these forces are dependent on the coefficient of friction between the gripping surface and the object held (C. W. Heckathorne & Childress, 1981).

2.1.1 The Hand Grasping Pattern

As the hand reaches out to grasp an object, its shape gradually evolves into a posture that is appropriate (Santello, Flanders, & Soechting, 2002). Some factors that influence the posture of the hand during function include the shape and size of an object, miscellaneous factors (physical factors such as weight, texture, temperature or wetness and dryness and other factors including fear, distaste and hunger) and the influence of intended activity (Napier, 1956). Napier explained on the different grasping pattern used by the hand and emphasize on power and precision gripping option. Other most used gripping pattern to perform activities of daily living (ADLs): chuck grip, fine pinch, key grip, power grip, hook grip, tool grip as shown in Figure 2.1.

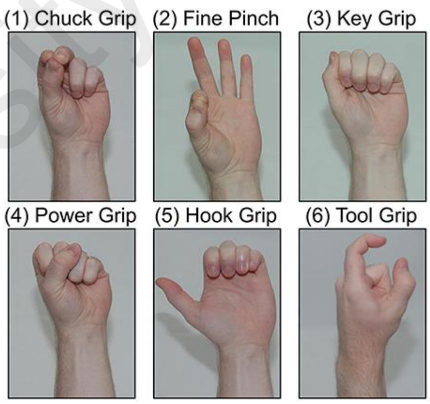


Figure 2.1: Gripping pattern to perform activities of daily living (ADLs): chuck grip, fine pinch, key grip, power grip, hook grip, tool grip. Adapted from "Dual Window Pattern Recognition Classifier for Improved Partial-Hand Prosthesis Control," by E. J. Early, L. J. Hargrove & T. A. Kuiken, 2016, Frontiers in Neuroscience, pp. 10.

2.1.2 Hand Grasping Force

The anatomical hand (all fingers of the hand) is capable to exert grasping force up to about 400 N of force and most of the daily living activities require prehension forces in the range 0 to 67 N (C. Heckathorne, 1992). The average adult male can produce an average of 89 to 107 N of finger prehension and 36N to 44 N by voluntary opening bowden cable controlled prosthesis (Billock, 1986).

Luntern et al., (1989) suggested that 10 N of pinch force is considered to be sufficient for most activities of children (Van Lunteren & van Lunteren-Gerritsen, 1989). Besides that, Smit et al. assumed that the desired pinch force for adult was about two times higher (20 N) and occasionally more than children (Smit, Bongers, Van der Sluis, & Plettenburg, 2012). Recently, in 2010 Van Der Niet et al. showed that an i-Limb, which had a maximum pinch force of 15 to 20 N, did not exert enough force to complete all tasks (Van Der Niet Otr, Reinders-Messelink, Bongers, Bouwsema, & Van Der Sluis, 2010).

There are great impact on upper limb amputee to execute all the activities of daily living as a very simple activity will become a great challenge in their life after amputation. The special characteristic of the hand especially the grasping pattern and force should be regarded as reference to mimic the hand characteristic to the function of the prosthetic hand.

2.2 Upper Extremity Amputation

Upper limb amputations tend to be less common than lower limb amputations, but can affect people of all ages. Amputation is a surgical procedure for removal of part or the whole of a limb. It involves removal of all or part of the fingers, hand, forearm, upper arm or shoulder. Different types of amputation in the upper limb are forequarter (2%), shoulder disarticulation (5%), trans-humeral (28%), elbow disarticulation (0.3%), trans-radial (19%), wrist disarticulation (2%), partial hand (19%) and digit (22%) (The National

Amputee Statistical Database Annual Reports, 2004). Upper extremity amputations are most frequently indicated by severe traumatic injuries. Many of upper limb amputees had difficulties in complex tasks and either change job or become unemployed (Jang et al., 2011).

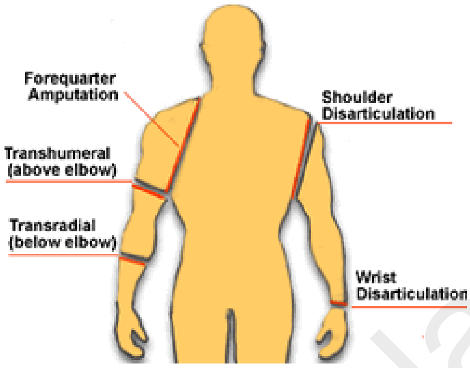


Figure 2.2: Level of amputation. Adapted from "Upper Extremity Amputations and Prosthetics," by S. A. Ovadia & M. Askari, 2015, Seminars in Plastic Surgery, 29(1), 55-61.

The location of the injury will determine the level of amputation. Preservation of extremity length is often a goal. The amputation site will have important implications on the functional status of the patient and options for prosthetic reconstruction (Ovadia & Askari, 2015). Generally, the longer the remaining limb and the more joints that are kept intact, the easier it is to be fit with and use a prosthesis. The major categories of upper-limb amputations are: wrist disarticulation, transradial (below elbow), transhumeral (above elbow), shoulder disarticulation and forequarter amputation (Figure 2.2). From the statistics values shown in many research, the transradial cases is the major population compared to other types of amputation cases (E. A. Biddiss & Chau, 2007; C. L. Taylor & Schwarz, 1955; Zollo, Roccella, Guglielmelli, Carrozza, & Dario, 2007).

As the type of prosthesis prescribed is based largely upon the length of amputees' residual limb, most of the amputee with higher level of amputation especially short transhumeral, shoulder disarticulation and forequarter amputation are having a critical problem. Most of the time, they cannot be prescribe with any type of prosthetic hand because of the difficulty in control and execution of the operation.

2.3 Prosthetic Hand

A prosthesis is an artificial device that replaces a part of the human body which is absent due to illness, injury or deformity. Prosthetic word comes from Greek word, “prostithenai” which means to add to, or put in addition (Miller et al., 2008). In 500 A.D., the prosthetic hands were designed like a hook that are still widely used until today (C. L. Taylor & Schwarz, 1955). Over the last thirty to forty years, many significant achievements discovered on the development of upper extremity prosthetics system. The design and construction of any prosthesis depends both on the complexity of the body part being replaced and the rehabilitative requirements of the prosthesis user (Head, 2014).

There are three types of upper limb prosthesis that are commonly available for potential prosthesis users which are myoelectric prostheses, body-powered prostheses and cosmetic (Figure 2.3) prostheses (Watve, Dodd, MacDonald, & Stoppard, 2011). Currently two types of active prostheses are available: The electric prosthesis and the body-powered (BP) prosthesis (Bowker, 1992). A prostheses can be either actuated by an operator, using his/her own body to power the device, or it can derive its power from an external source (Kyberd & Chappell, 1994).

Figure 2.3: Cosmetic hand. Reprinted from Prosthesis, In Wikipedia, n.d., Retrieved Disember 8, 2016, from https://en.wikipedia.org /wiki/ Prosthesis

The Bowden cable body-powered prosthesis with prosthetic hook terminal device was introduced in 1948 replacing bulky straps with a sleek, sturdy cable (Zuo & Olson, 2014). A significant number of adult and children wear body-powered prosthesis (Biddis & Chau, 2007; Julie Shaperman, Landsberger, & Yoshio, 2003), although there is great advancement in electrical prosthesis. The body-powered terminal devices function by utilizing forces generated by body movement (Craig L Taylor, 1955). The user uses their own muscular power to operate the prosthesis, usually via a cable link called a Bowden cable. A Bowden cable consists of two parts, an outer housing and an inner tension cable. The housing is fixed at both ends and serves as a flexible bridge between two points, maintaining a constant length regardless of any motion. The cable is free to slide within the housing (Childress, 1998).

Powered prosthesis have existed for decades, but it is only in recent years that they have become of clinical significance. Myoelectric prosthesis (Figure 2.4) requires no cables for control and for most below elbow amputees should not require any straps or harness for suspension (Scott & Parker, 1988). The prosthesis made up battery, control unit, motors and skin electrode to operate. The skin electrodes helps to pick up signal from the remaining muscle on the user residual limb and by contracting those muscle, signal sent to the prosthesis and the hand open. The only practical external power source is electric; this is due to the ease by which the power source can be recharged compared with the difficulties of recharging any other safe source (Millstein, Heger, & Hunter, 1986; Simpson & Kenworthy, 1973). Electronics also provide a compact controller. The resulting device can be more cosmetic in appearance, needing no straps to open it and much smaller bodily actions to operate it; in addition, it is less tiring to use (Kyberd & Chappell, 1994).

Figure 2.4: Myoelectric prosthesis. Reprinted from Prosthesis, In Wikipedia, n.d., Retrieved Disember 8, 2016, from https://en.wikipedia.org/wiki/Prosthesis# Myo.

2.3.1 Upper Limb Prosthetic Part

The prosthetic components or parts are different for every level of amputation and type of prosthesis used. The general parts of prosthesis include the terminal device, wrist unit, elbow unit (Figure 2.5) and body harness which function to move the prosthesis for a body powered system or holding the prosthesis in place for high amputation level myoelectric prosthesis system. There is variety of terminal device such as split hooks (either voluntary closing or opening), cosmetic and functional hands, and electric hands. Wrist unit connect the terminal device to the prosthesis and restore some of the function of the anatomical wrist and also it comes with variety design which are friction wrist (passive rotation), locking wrist (locked manually for lifting purposes), quick disconnect (allow swapping of terminal device) and flexion unit (provide flexion and bending of terminal device). Elbow unit classified into two categories which are for body-powered prosthesis which using cable locking system and for myoelectric prosthesis where the elbow operated electronically.

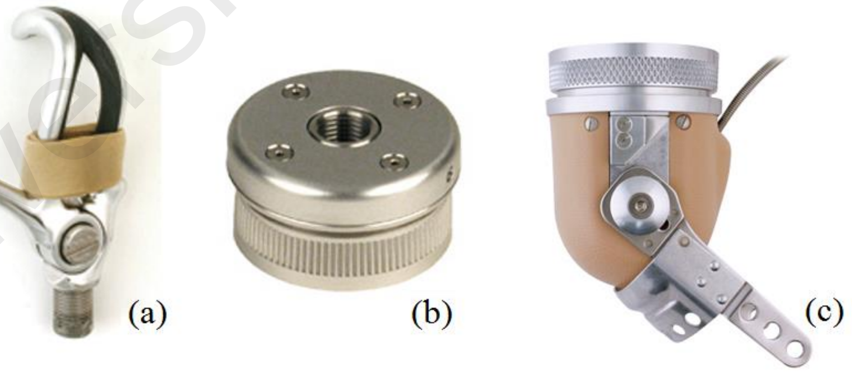


Figure 2.5: Upper limb prosthetics components (a) terminal device (b) wrist unit (c) elbow unit. Adapted from Arm prosthesis, by Otto Bock Orthopedic Industry Inc., Retrieved September 28, 2009, from http://www.ottobockus.com/ prosthetics/upper-limb-prosthetics/

2.3.2 Prosthetic Terminal Device

Today, there exist a significant number of prosthetic terminal devices. These terminal devices are designed as either mechanical or electromechanical systems and, as such, are either body-powered or electric powered (Billock, 1986). There are two general types of prosthetic hook terminal device which are Voluntary Opening (VO) and Voluntary Closing (VC) terminal device. For VO, users operate the terminal device by applying force through their cable system and the terminal device closes on its own with the aid of rubber bands, which limits the grip strength of the device to the strength of the rubber bands. With a VC terminal device, force must be applied to close it instead of to open it, making the grip strength dependent on the strength of the user instead of the strength of rubber bands or spring (Bowers, n.d.). Therefore, pulling the cable results in closing of the prosthesis in voluntary closing (VC) devices, or in opening in voluntary opening (VO) devices. (Craig L Taylor, 1954).

There are many papers reviewed on the efficiency of prosthetic hook. Corin et al. in the year of 1987 published his work on a broad range of adult and child size VO terminal device (Corin, Holley, Hasler, & Ashman, 1987). Carlson and Long (1988) measured one VO and one VC hook (Carlson & Long, 1988). In 1992, LeBlanc et al. assessed the mechanical efficiencies of five types of child size prehensor in order to determine required strength to operate body-powered prostheses for children. The prehensors tested include NYU Child Size Hand, Steeper, Adept F III Terminal Device, CAPP I Terminal Device and Hosmer 10X Hook and they discovered the work efficiency of hook is much higher than hand with Hosmer 10X (3 band) which has the highest work efficiency (M. LeBlanc, Setoguchi, Shaperman, & Carlson, 1992). Recently Smit et al. (2012) compared the mechanical performance of 4 hooks and 5 hands including Hosmer model 5XA hook, Hosmer Sierra 2 Load VO hook, RSL Steeper Carbon Gripper, Otto Bock model 10A60 hook, Becker Imperial hand, Hosmer Sierra VO hand, Hosmer Soft VO hand, RSL

Steeper VO hand and Otto Bock VO hand. Hosmer model 5XA hook with three bands reported as to be the best tested hook (Smit et al., 2012).

Though bionics clearly has a long way to go, there are already numerous terminal devices on the market to help upper-extremity amputees. Hosmer Dorrance Corporation and Otto Bock are major commercial hook providers for prosthetic terminal device. Other manufacturers and distributors of terminal devices for upper extremity amputees includes Motion Control Fillauer Company, Texas Assistive Devices (LLC), Liberating Technologies, Inc., and TRS, Inc.

Hosmer (Hosmer-Dorrance Corp., Campbell, Calif.) offers a variety of split-hook designs, which have somewhat different function including child size (12P, 10X and 10P), small adult size (99X and 99P), medium adult size (8, 8X and 88X) adult size (5, 5X, 5XTi, 5XA, 555, SS-555, 3-work, 7-work, 7 LO-work), APRL VC hook, Sierra 2 Load VO and UCLA CAPP model. Model by Hosmer (Hosmer; Campbell, California) made up of stainless steel and aluminum material. Most of child size terminal device made of aluminum, small and medium size for adult made of stainless steel and few adult size made of titanium material. For safety purpose, child size hook come with plastisol coating to eliminate sharp point on the canted finger hook and ideal for infants and kids. Models 5, 5X, 5XA, 5XTi, 8, 8X and 88X (Table 2.1) have canted tines for better visual feedback which allows the user to pick up paper, coins and other small fine objects from the side with ease. Model 555 and 555-SS have symmetrical tines for cylindrical grasp on objects, such as bottles, cans and other round objects. The APRL and Sierra 2-load hooks have lyre shaped fingers and a special mechanism which eliminates the use of rubber bands while permitting preselection of pinch force. The variable openings between the fingers help accommodate different shape diameter agricultural tools. All Centri work hooks have serrated fingers for a secure holding surface and tab as an additional holding surface. The tab used on models 6, 7 and 7LO have a nail slot for holding nails or wire and an extension designed for holding knives.

Otto Bock (Otto Bock Orthopedic Industry Inc., Duderstadt, Germany) supplies numbers of hook including VO Standard Hook 10A81, VO Adult Hook (10A18 and 10A60), VO Juvenile hook 10A37, VO child hook 10A11 and VO all-purpose hook 10A12 (Otto Bock, 2013). Otto Bock hook grippers are made of highly robust materials (e.g. stainless steel) which are easy to clean and lightweight (e.g. aluminum alloys). There are three model type which are hook for children and youths, standard hook for adults and work hooks for manual works (Table 2.2). The DMC plus System Electric Greifer (Figure 2.6) comes with sensitive response and a gripping speed and gripping force which automatically adjust to the corresponding muscle signal (gripping speed ranges from 8 to 180 millimeters per second). The hand has a safety mode which only releases a firm grip on an object after an above-average muscle signal is received to avoid loosening the grip unintentionally. Besides that, the Greifer has a large opening width, adjustable gripping tips, and a control wheel for manual operation, which can save energy.

Figure 2.6: System Electric Greifer DMC Plus. Adapted from Arm prosthesis, by Otto Bock Orthopedic Industry Inc., Retrieved September 28, 2009, from http://www.ottobock.com.tr/en/prosthetics/products-from-a-to-z/system-electric-greifer-dmc-plus/

Meanwhile DMC VariPlus Electric gripper is one of the Otto Bock terminal device that come with precision control. It is made by a new generation of microprocessors and optimized signal processing which support better adaptation to the individual needs of the user. The DMC VariPlus electric gripper is also suitable for manual work in particular. Another best product of Otto Bock electric terminal device is MyoHand VariPlus Speed and Michelangelo hand. MyoHand VariPlus Speed is a powerful and fast myo-prosthetic hand. Myohand VariPlus Speed® is an Otto Bock development that combines the properties of two proven terminal devices: the SensorHand Speed® and the DMC VariPlus System Electric Greifer. Objects can be grasped quickly and precisely due to the high gripping force and gripping speed. The special feature: with the 757T13 MyoSelect, a total of six different programmes can be selected and optimally adapted according to meet your individual needs. Summary of all terminal device products by Otto Bock as shown in Table 2.2 and Table 2.3.

RSL Steeper supplies pasive, mechanical and electrical prosthetic hook terminal device and all the device ranges between four sizes from child to adult. The cable and spring operated hand under the mechanical classification of RSL Steeper model (Figure 2.7) available with front and back pull or spring close options, range of handplates allows connection to RSLSteeper and other manufacturers' wrist systems, compatible with RSL range of full-length Elegance™ cosmetic gloves in either PVC or silicone and available in 19 skin shades. Meanwhile for the electric hand, Steeper offer a comprehensive range of electric products, from hands and wrists through to myoelectric shoulder units and powered elbows to accommodate all levels of amputation. RSL STEEPER Select Myo Electric Hands' (Figure 2.8) are electrically operated devices that combine optimum control function with cosmetic restoration. The finger assembly is driven by an electric DC motor via a set of gears. RSLSTEEPER Select Myo Electric Hands are controlled with Select Myo elxectrodes or switch inputs.

Figure 2.7: Cable and spring operated hand. Adapted from Steeper Prosthetics, by SteeperUSA, Retrieved November 24, 2016, from http://rslsteeper.com/products/prosthetics

Figure 2.8: RSLSTEEPER Select Myo Electric Hands. Adapted from Steeper Prosthetics, by SteeperUSA, Retrieved November 24, 2016, from http://rslsteeper.com/products/prosthetics

Motion Control, a Fillauer Company, is the leading US manufacturer of myoelectric and externally powered prosthetic arm systems. The Motion Control ETD (Electric Terminal Device) measures up to the most demanding wearers (Figure 2.9). The standard ETD can be used with the Utah Arm or ProControl system and is available with multi-flex Flexion Wrist or the ultra fast MC Wrist Rotator. The ETD ProHand comes with a controller inside the terminal device so that the user are able to interchange the system protocol with other manufacturers' systems.

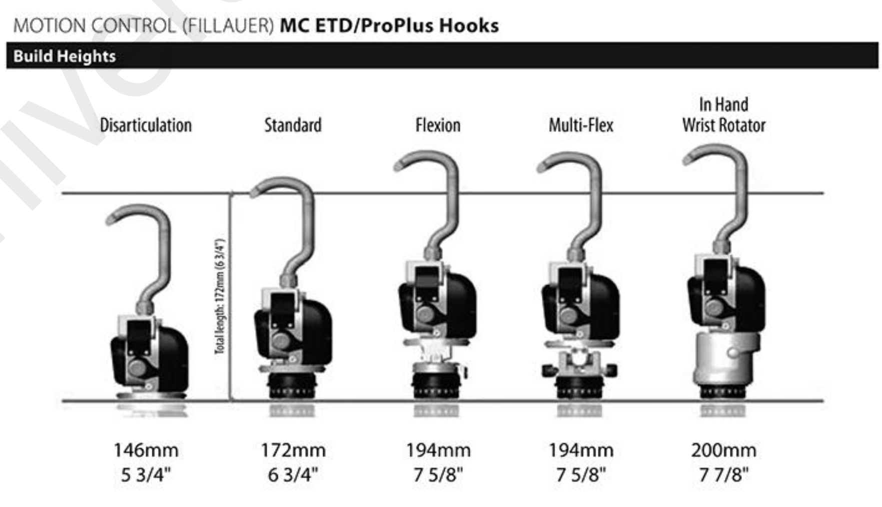


Figure 2.9: Motion Control Electric Terminal Device/ProPlus hooks. Adapted from Motion Control, by Fillauer Company, Retrieved November 24, 2016, from http://www.utaharm.com/etd-electric-terminal-device.php

TRS Inc. which started their operation in 1979 is one of prosthetic manufacturer that focused mainly on upper limb prosthetic. They manufactured variety of upper extremity prosthetic terminal devices including standard hand (for children and adult) and prehensors for sport and recreation. Their commercial products includes Grip Prehensors, Lite Touch hand and GRIP 5 Evolution Prehensor. TRS Grip prehensors for adults (Grip 2S, Grip 3(T), Grip 3 (BK)) are as shown in the Figure x below. Grip Prehensors are high performance hand replacements and sophisticated tools, capable of a wide range of prehension from delicate manipulations to maximum gripping power. Lite Touch Children's Biomechanical Hands has high efficiency voluntary closing mechanics, has compliant fingers and surfaces and comes with 4 sizes (micro, small, medium and large). Meanwhile the Lite Touch Adult Hand has smooth voluntary closing operation, compliant polymer, fingers and surfaces and molded anatomical details.

Figure 2.10: TRS Grip prehensors for adults (Grip 2S, Grip 3(T), Grip 3 (BK)). Adapted from Adult Grip Prehensor, by TRS Company, Retrieved November 25, 2016, from http://www.trsprosthetics.com/product/adult-grip-prehensors/

Table 2.1: Hosmer prosthetic hook terminal device.

Child size			Small Adult size		Medium Adult size		

Model 12P	Model 10X	Model 10P	Model 99X	Model 99P	Model 8	Model 8X	Model 88X

Adult size

Model 5	Model 5X	Model 5XTi	Model 5XA	Model 555	Model SS-555	APRL	Sierra 2 Load

Note: Adapted from Products/Hook, by Hosmer Company, Retrieved November 25, 2016, from http://hosmer.com/products/hooks/

Table 2.2: Prosthetic hook by Otto Bock.

		
Child size	Standard size	Work Hook

Note: Adapted from Hooks, by Otto Bock Orthopedic Industry Inc., Retrieved September 30, 2016, from http://www.ottobock.com.tr/en/prosthetics/products-from-a-to-z/hooks/

Table 2.3: Overview of prosthetic hands without cosmetic glove applied.

Child Hand | **Female hand**

Child NY Mechanical Hand	Child CAPP Hand	Child Dorrance 200 Mechanical Hand	Childs Myoelectric Hand by Centri®	Female Soft Voluntary Opening (SVO) Hands	Female Robin-Aids Soft Mechanical Hand	Female Dorrance 300 Mechanical Hand	Female Myoelectric Hand by Centri®

Male Hand

Male Soft Voluntary Opening (SVO) Hands	Male Soft Voluntary Closing (SVC) Hands	Male Robin-Aids Soft Mechanical Hand	Male Dorrance 400 Mechanical Hand	Male Myoelectric Hand by Centri®	Male Becker Lock Grip Hand	Male Becker Imperial Hand	Male APRL Voluntary Closing Hand	Sierra Voluntary Opening Hand

Note: Adapted from Arm prosthesis, by Otto Bock Orthopedic Industry Inc., Retrieved September 30, 2016, from http://www.ottobockus.com/prosthetics/upper-limb-prosthetics/

2.3.3 Latest Technology on Prosthetic Terminal Device

The Development of robotic started since 1984 with MIT/Utah dexterous hand (Jacobsen, Meek, & Fullmer, 1984), a mechanical hand that mimics the function of a hand. This hand was designed for use in research studying robot dexterity. This device could never be used in prosthetics because the actuators and computer system required to control this hand occupy the space of two small filing cabinets, and power is supplied externally from electrical mains.

In 2010, The Delft Institute of Prosthetics and Orthotics (DIPO) has started a research program focusing on the development of an improved voluntary closing body-powered prosthesis system. This program aims to design a system that require significantly lower physical control effort than commercially available voluntary close body-powered prostheses. At the first step to this development, analysis of mechanical performance on currently available voluntary close devices was conducted due to limited data available on body-powered prostheses (Smit & Plettenburg, 2010).

Compare to myoelectric prostheses, the technology in this area is rapidly changing, driven by advances in biomedical engineering especially by the U.S. Department of Defense Advanced Research Projects Agency (DARPA), which is funding a public and private collaborative effort on prosthetic research and development. Areas of development include the use of skin-like silicone elastomer glove, artificial muscles, and sensory feedback. Besides, recently smaller motor, microcontrollers, implantable myoelectric sensors, and re-innervation of remaining muscle fibers are being developed (Latest, Date, & Grade, 2015).

Some of recently developed technology of myoelectric prosthetic hands are SensorHand™ by Advanced Arm Dynamics with features of AutoGrasp that operate at the speed up to 300mm/s and advanced EMG signal processing. Next, the first myoelectric hand with individually powered articulating fingers i- LIMB™ hand by Touch Bionics. Besides, Touch Bionics just developed a ProDigits™ is a prosthetic digits for one or more fingers in patients with amputation at a trans-metacarpal level or higher. The products of Touch Bionics will usually covered by LivingSkin™, silicone glove that resemble the skin of the patients. Not only that, a hybrid system, a combination of body-powered and myoelectric components, may be used for high-level amputations (at or above the elbow) is one of current development in prosthetics field. Hybrid systems allow control of two joints at once (i.e., one body-powered, one myoelectric) and are generally lighter and less expensive than a prosthesis composed entirely of myoelectric components.

Based on the review made in this field, there are many shortcomings of the prosthetic hand system that have been improved since the last 10 years .The advancement of technology made it possible for the development of high technology prosthetic hand by commercial hand developer. A new system, which is the hybrid system was also introduced to add on to the existed system. Comparison between each of the advance prosthetics system produced has been executed in order to investigate whether there is still deficiencies to be corrected in the upper limb prosthetic system.

2.4 Myoelectric Signal

Progress in myoelectric control technology has over the years been incremental, due in part to the alternating focus of the Research and Development between control methodology and device hardware (Parker, Englehart, & Hudgins, 2006). The myoelectric control-based prosthetic hand aids to restore activities of daily living of amputees in order to improve the self-esteem of the user. All myoelectric control-based prosthetic hands may not have similar operations and exhibit variation in sensing input, deciphering the signals, and actuating prosthetic hand (Geethanjali, 2016).

The EMG signal has been used in prosthetic hand actuation since 1948 (Popov, 1965) producing commercial prosthetic hand using MES began in 1957 at the Central Prosthetic Research Institute, Moscow to drive stepper motor (McKenzie, 1965). This was later upgraded with permanent magnet DC motor and electromagnetic relays. Later, the myoelectric control strategy had been widely analysed and a simple on–off control scheme was developed.

MES are detected by placing three electrodes on the skin. The surface EMG signals for artificial hand control are sensed from the surface of the skin and are preferred due to their ease of access and the procedure being non-invasive. The dexterity of prosthetic hand is less in surface EMG due to limitation in identifying the locations to acquire signals. Using surface electrodes, it is possible to identify three to four possible locations from the residual limb to acquire signals for sequential control. However, collecting the intramuscular EMG signals is an invasive technique and requires surgical skill for using the implantable myoelectric sensor (Al-Ajam et al., 2013; Farrell & Weir, 2005; Weir et al., 2009).

Three electrodes were usually used and intact to the skin of the user. The reason is with two electrodes, there will be voltage difference with the presence of myoelectric signal when the user contracting and relaxing agonist and antagonist muscle. In order to reduce the noise from muscle activity that interfere with the output from the other electrode, third electrode positioned at neutral area such as bony area. All the signal collected and processed and amplified with a differential amplifier and finally, the amplified signal is used to control electromechanical or electronic devices (bin Tahir, 2016).

Myoelectric signals (MES) have been used in various applications, in particular, for identification of user intention to potentially control assistive devices for amputees, orthotic devices, and exoskeleton in order to augment capability of the user. The method of utilizing MES signal as a control source for prosthetic hand has received considerable attention as the approach is straightforward and the technique was able to provide strong and stable signal and has advantage of neutral psychological acceptance.

2.5 Rejection of Prosthetic Hand

Many patients abandon their upper-limb prosthesis after some time. Studies show rejection rates varying from 23–45% (E. A. Biddiss & Chau, 2007). Patients are often not satisfied with their prosthesis because it does not fulfil their basic demands. These basic demands can be summarized by the words: Cosmetics, comfort and control (Plettenburg, 1998; Smit, Plettenburg, & van der Helm, 2015) . Prosthesis users have a large range of needs and priorities. They often want their prosthesis to be aesthetically pleasing, comfortable to wear all day, easy to don and doff, and intuitive to control without a high mental or physical load. Current prostheses do not fulfil these demands simultaneously (Smit et al., 2012).

A major complaint about body powered prosthesis control is the physical load imposed on the user. Often large activation forces are required. This results in muscle fatigue, discomfort and irritation, particularly in the axilla when using a shoulder harness (Collier & LeBIanc, 1996; M. A. LeBlanc, 1985).Although prosthetic limbs have been developed and recently used (Jang et al., 2011), the prosthetic limbs themselves still fail to reproduce precision movement functions and have a slow movement speed showing that there are still continuing substantial problems in the prosthetics replacement of hands.

Gripping an object remains the main weakness of most modern prostheses even though they offer a greater degree of freedom than ever before (Hučko, Uherčík, & Horvát, 2014). The major factors limiting prostheses to tools are practical ones due to the severe weight, power, and size constraints of hand/arm systems as well as the difficulty in finding a sufficient number of appropriate control sources to control the requisite number of degrees of freedom. Researchers also found that quite a number of amputees have reported the low wearing period of prosthesis with the dissatisfaction in terms of low functional in community and annual daily life activities (ADLs), cosmetic appearance and the discomfort of harness (Carey, Highsmith, Maitland, & Dubey, 2008).

Prosthesis acceptance and rejection factors should be taken in consideration while developing a prosthetic hand. Most research found the rejection of upper limb prosthetics is dominated by the lack of control as a high technology hand is useless if the control mechanisms are not available. Besides, the performance of current mechanisms comes nowhere close to meeting the maximum speed and force of which the anatomic arm and hand are capable.

2.6 Sensory Feedback and Sensory Substitution System

One of the challenges facing prosthetic designers and engineers is to restore the missing sensory function inherit to hand amputation. Several different techniques can be employed to provide amputees with sensory feedback (Antfolk et al., 2013). The concept of closed-loop control system can be used to provide sensory feedback system to the prosthetic hand (Scott, 1990). Sensory substitution is a method to provide sensory information to the body, through a sensory channel different from that normally used or through the same channel but in a different modality (Kaczmarek, Webster, Bach-y-Rita, & Tompkins, 1991).

In the past, sensory substitution studies were purely academic; with rare exceptions, none of the devices ever reached the market. Dhillon et al. developed a direct neural sensory feedback and control of a prosthetic arm by implanted electrodes within individual fascicles of peripheral nerve stumps in amputees. The stimulation through these electrodes produce graded, discrete sensations of touch (Dhillon & Horch, 2005). In 2007, Murguialday et al. demonstrated practical Brain-Computer individuals (BCI) control of a prosthetic device (Murguialday et al., 2007). The overview of the principal works and devices employed to provide upper limb amputees with sensory feedback elaborated by Antfolk et al. that focus on sensory substitution and modality matched feedback; the principal features, advantages and disadvantages of the different methods are presented (Antfolk et al., 2013). Prevalent techniques that have been used are either vibrotactile or electrotactile sensory substitution Table 2.4.

2.6.1 Vibrotactile Sensory Substitution

The development of new technologies has now made it plausible to provide patients with prosthetic arms with tactile and kinesthetic sensibilities (Riso, 1999). Vibrotactile stimulation is evoked by a mechanical vibration of the skin, at frequencies ranging between 10 and 500 Hz (Kaczmarek et al., 1991). In the recent years vibrotactile systems have been used in research with the Otto Bock, Motion Control and iLimb myoelectric hand prosthesis (Chatterjee, Chaubey, Martin, & Thakor, 2008; Saunders & Vijayakumar, 2011; Sears, Iversen, Archer, Linder, & Hays, 2008). Cipriani et al. (2012) reported a group of healthy subjects were able to discriminate different force amplitudes exerted by the device (accuracies greater than 75%) simultaneously (Cipriani, D'Alonzo, & Carrozza, 2012). Study in 2013 by Christiansen et al. has demonstrated that vibrotactile feedback is a viable method to convey hand position information and proven to enhance the control of myoelectric prosthesis (Christiansen, Contreras-Vidal, Gillespie, Shewokis, & O'Malley, 2013). Generally, the use of vibrotactile feedback improves user performance through a better control of grip force and by lowering the number of errors in task execution.

2.6.2 Electrotactile Sensory Substitution

Electrotactile stimulation evokes sensations within the skin by stimulating afferent nerve endings through a local electrical current (Kaczmarek et al., 1991) with typical currents range within 1-20 mA, with pulse frequencies ranging from 1 Hz to 5 kHz. Subjects described electrotactile sensations qualitatively as a tingle, itch, vibration, touch, pressure, pinch, and sharp and burning pain depending on the stimulating voltage, current and waveform, as well as on the electrode size, material and contact force, and the skin location, hydration, and thickness (Kaczmarek, 2000).

The electrical substitution can be divided into biphasic current pulse, coaxial or concentric or annular electrode, electrotactile or electrocutaneous stimulation, and monophasic current path. Jorgovanovi et al. investigated the capability of human subjects to control grasping force in closed loop using electrotactile feedback with a realistic experimental setup for virtual grasping, and has proven its benefits of the feedback and practically relevant, of closed-loop control (Jorgovanovic, Dosen, Djozic, Krajoski, & Farina, 2014).

The study in this area become very intense nowadays. Many other sensory substitution technique such as auditory, visual and nervous stimulation have been used to replace the sense of touch that is lost after amputation. Vibrotactile and electrotactile technique of sensory substitution is among the best method as it has advantage of psychological acceptance (Shannon, 1976). As electrotactile techniques convert a non-tactile information to sense of touch via electrical stimulation, the application of current to the skin might be dangerous to the prosthetic hand user especially due to unexpected surge or spikes of the electric current and therefore electrotactile will be more preferable to be used in this study.

Table 2.4: Summary of previous research on development of upper limb prosthetic system with sensory feedback. (E: electrotactile; V: vibrotactile; M: mechanotactile; N: nervous stimulation and O: other

Study (year)	Input	Output	Stimulation position	Main findings	Ref
Mann et al (1970)	Elbow joint position	V	Residual limb of upper limb amputee	Improvement of precision and accuracy in positioning tasks with sensory feedback	[23]
Pylatiuk et al (2006)	Grasp force	V	Residual limb of transradial amputee	A significant reduction of the applied grasping force with feedback	[30]
Cipriani et al (2008)	Grasp force	V	Upper arm of healthy subjects	Subjective reports stated the feedback system would be useful during grasping task, however, no statistical difference was found between using the system or not	[28]
Chatterjee et al (2008)	Grasp force	V	Upper arm of healthy subjects	Visual feedback improved performance at all force levels. Training is needed to fully utilize vibrotactile feedback	[27]
Saunders et al (2011)	Grasp force	V	Forearm of healthy subjects	With feedforward controller uncertainty, after training, either visual or vibrotactile feedback enabled successful task performance	[25]
Scott et al (1980)	Grasp force	E	Residual limb of transradial amputees	Subjects reported satisfaction with the electrotactile feedback	[35]
Wang et al (1995)	Grasp force	E	Forearm of healthy subjects	Users can differentiate the appropriate gripping force for a wide class of activities	[37]
Lundborg et al (1998)	Finger force	E	Upper arm of nerve injury patients and amputees	With feedback, users were able to discriminate location and regulate grip force to predefined levels	[36]
Meek et al (1989)	Grasp force	M	Forearm of healthy subjects	Successful manipulations of the test's object increased with the use of sensory feedback	[54]
Panarese et al (2009)	Grasp force	M	The first and second toe of healthy subjects	Participants incorporated sensory feedback received on the foot in their sensorimotor control of a robotic hand	[48]
Sensinger et al (2009)	Force	M	Reinnervated chest area of amputees	Feedback area had near-normal force sensitivity compared to contralateral normal skin	[46]
Antfolk et al (2012)	Passive hand touch	M	Residual limb of transradial amputees	Subjects are able to discriminate feedback sites and pressure levels using a completely passive system	[45]
Weir et al (2001)	Grasp force and finger position	O (EPP feedback)	Residual limb of amputees with cineplasty	Cineplasty and harness-based body powered control showed similar performance with lower variability using cineplasty suggesting a higher consistency	[50]
Wheeler et al (2010)	Elbow joint position	O (skin stretch)	Upper arm of healthy subjects	Targeting errors in blind movements with the feedback device were lower with feedback.	[42]
Gonzales et al (2012)	Hand configuration	O (auditory)	-	The usage of an auditory display to monitor and control a robot hand improves the temporal performance greatly, and reduces mental effort.	[41]
Clippinger et al. (1974)	Grasp force	N	Medial nerve of amputees	The patient correlated the grasp force to the sensation provided by direct nerve stimulation	[58]
Dhillon et al (2005)	Elbow joint position and finger force	N	Median nerve of amputees	Participants could discriminate force applied to the thumb sensor and static position of the elbow joint of the artificial arm	[9]
Rossini et al. (2010)	Finger movement	N	Medial and ulnar nerve of amputees	Phantom limb syndrome was alleviated after 4 weeks of use	[10]
Horch et al (2011)	Finger force and position	N	Ulnar and median nerve of amputees	Tactile and proprioceptive feedback is needed when discriminating object size and stiffness	[59]
Patterson et al (1992)	Grasp force	V,M	Upper arm of healthy subjects	Vision together mechanotactile feedback produced the lowest error rates	[55]
Marasco et al (2011)	Passive hand touch	V,M	Reinnervated area of the upper arm of amputees	Physiologically appropriate sensory feedback appears to elicit an incorporation of a prosthetic limb into the self-image.	[47]
Antfolk et al	Passive hand	V,M	Forearm of healthy	Placement of feedback devices on a complete	[57]

Note: Adapted from "Sensory feedback in upper limb prosthetics," by C. Antfolk, M. D'Alonzo, B. Rosén, G. Lundborg, F. Sebelius, and C. Cipriani, 2013, Expert review of medical devices, vol. 10, pp. 45-54.

2.7 Neuroplasticity

Human beings have an amazing capacity to learn new skills and adapt to new environments (Green & Bavelier, 2008). Neuroplasticity or brain plasticity is define as the adaptive capacities of the central nervous system or its ability to modify its own structural organization and functioning that response to the functional demand (Bach-y-Rita, 1990). Experience is a major stimulant of brain plasticity in animal species as diverse as insects and humans. It is now clear that experience produces multiple, dissociable changes in the brain including increases in dendritic length, increases (or decreases) in spine density, synapse formation, increased glial activity, and altered metabolic activity (Kolb & Whishaw, 1998). In both animals and humans, motor skill learning is usually measured by a reduction in reaction time and the number of errors and/or by a change in movement synergy and kinematics (Ungerleider, Doyon, & Karni, 2002).

Neuroplasticity is very important aspect during learning process of prosthesis initial fitting as at this time user train their brain to get to use to the device with cortical and subcortical rewiring of neuronal circuits in response to training as well as in response to the environment. Training is very important in order to stimulate brain plasticity. Specificity of learning is also a feature of cognitive training. For example, a wealth of studies now exists on the impact of cognitive training in older adults. By and large, these studies demonstrate improvements on attention, memory, and reasoning tasks following training (Basak, Boot, Voss, & Kramer, 2008; Plemons, Willis, & Baltes, 1978; Verhaeghen, Marcoen, & Goossens, 1992; Willis et al., 2006). Therefore, in order for the patient to familiarize with the sensory substitution, neuroplasticity is very important and by training, the user can master the targeted operation easily within short period of time.

2.8 Summary

In this research we reviewed the important topic related to upper limb amputation, available prosthetic system, rejection factors and features describing sensory feedback in upper limb prosthetics as well as summarize of significant work carried out in the field. Upper limb amputee has lost their grasping ability and the sense of touch after amputation. In order to help these people, we need to provide them with an artificial hand that can help them to perform activities of daily living. Technological improvements are making prosthetic hand more reliable, and several works conducted to identify ways of providing feedback to the user especially the state and grip strength of the terminal device. Various approaches to the designs of prosthetic sensory feedback systems have been presented over the years, but none has yet been convincingly proven usable and thus been made commercially available. Many other sensory substitution technique including auditory, visual and nervous stimulation have been used to replace the sense of touch while vibrotactile and electrotactile stimulation are having the greater potential to provide this feedback as presented by the previous study. Besides that, there is no evidence of direct comparison of benefits and drawbacks of these methods.

CHAPTER 3: METHODOLOGY

Chapter 3 – Methodology part is divided into two; the first part is on the development of the terminal device with sensory feedback and the second part; the analysis of the terminal device. In the first part, all components and procedure used for the development of prototype were describe in details meanwhile for the second part, the performance of developed prototype was tested on the real user and their performance was compared to the other available prosthetic terminal device available in the market.

3.1 Development of Prosthetic Terminal Device with Sensory Feedback

The major part of the prototype made of socket, terminal device and vibrating armband. The socket which is the foundation of the prosthesis is one of the important part in prosthetic device. Prosthetic socket is the part of the prosthesis that encases the residual limb and to which other components are attached. Terminal device connected at the end of the prosthetic hand are designed either mechanical or electromechanical system and are either body powered or electrical powered. The fabrication of prosthesis socket, terminal device and vibrating armband is elaborated in the sub section of this chapter.

3.1.1 Prosthetic Socket

To be effective, artificial arms should be worn by their users for periods in excess of 8 to 12 hours a day (Weir, 2003). Loose or tight socket can cause problem to the user. A loose-fitting socket results in moving stump inside the socket and does not move the prosthesis itself. If for an electrically powered prosthesis, if the electrodes don't have a good contact with the skin, the prosthesis will not work at all. Meanwhile a tight one can cause rubbing of the skin and create soreness and skin problem. Meanwhile, terminal device is the component of an upper extremity prosthesis that substitutes for the functions of the hand that helps to pick and drop objects.

Socket design from one transradial subject was used in this study. The socket was fabricated using BioSculptor CAD/CAM technology instead of traditional technique. The traditional technique uses direct casting on the patient residual limb meanwhile CAD/CAM technique performed via *FASTScan* and *BioShape* software by BioSculptor Technology Company. There are pro and cons between these methods and the details on the fabrication of prosthetics socket using CAD/CAM technique and traditional technique were elaborated below.

3.1.1.1 Socket Design by BioSculptor^{TM} CAD/CAM technology

BioSculptor^{TM} CAD/CAM technology enable prosthetist to fabricate prosthetic socket efficiently without the use of Plaster of Paris (POP) at short duration of time. This technology involve the direct scanning of the stump of patient, rectification using CAD/CAM software and milling of modified positive cast. The tools used are dual-camera scanning wand, miniature transmitter, optical stylus, mechanical stylus, sweep registration software and computer.

The sockets were fabricated at Centre for Prosthetics and Orthotics Engineering (CPOE), University of Malaya. The patient, 25 years old, male a transradial amputee with 95mm residual limb length from medial epicondyle which stump (36.5% from total length of forearm length) classified as short below elbow amputation level based on Figure 3.1. The subject met the inclusions criteria. The subject is currently using myoelectric prosthesis, has been using the same system for more than one year, active, able to perform activities of daily living without assistant, working and have a good medical condition. Subject who is familiar with myoelectric system was selected in order to ease the training and testing procedure activities of daily living.

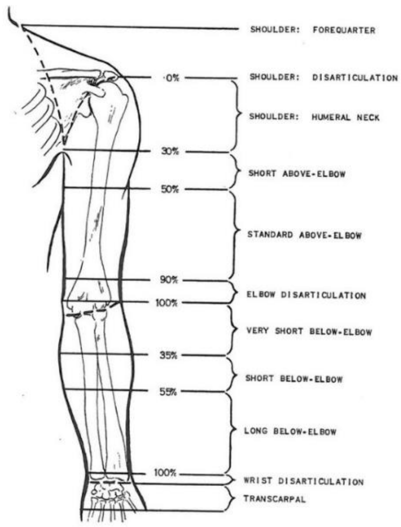


Figure 3.1: Amputee type based on amputation level

The stump of the transradial amputee subject was scanned using the BioScanner^{TM} software FASTscan. The camera are able to make 50 lines/second at the range of 23 inches radius (56cm) from wand to transmitter and the accuracy range absolute - 0.178mm RMS (0.005in). The BioScanner^{TM} dual-camera scanning wand (Figure 3.2) made up of two cameras to capture greater details, in a short period and in fewer sweeps.

Figure 3.2: Dual-camera scanning wand

A miniature transmitter was fitted directly on the body of the subject to compensate for any changes in position due to movement and ensuring an accurate scan without time consuming setup. Patient stump positioned at 45˚ flexion and advised to stay still for several minutes until scanning process is complete. The scanning was done slowly at proper distance from the residual limb. The scanning took approximately 7 minutes with total of 9 sweeps.

Reference marks on important landmarks and bony prominences were marked using mechanical stylus to acquire maximum precision. *FastSCAN* software was used to monitor sweeps made and to further improve quality, the software streamlines the final scan to equally distribute the scan sweeps and tightens seams between sweeps to produce smooth scan result.

Figure 3.3: Scanning process of subject's residual limb

The image of total sweeps is as shown in Figure 3.4. Sweeps registered and surface generated. The scanned model edited using RBF Surface Processing with 0.50mm Fit Accuracy and 1.00mm Mesh Resolution and file imported to ".obj." format. The obj. file then imported to BioShape software for further modification of the socket. The reference marks made using stylus labelled with BioShape software as Olecranon, Lateral and Medial Epicondyle, M1, M2 and M3 (Figure 3.5).

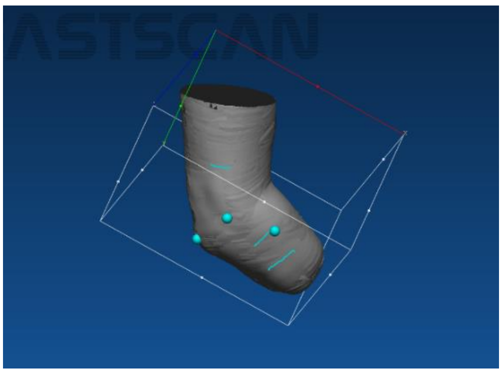


Figure 3.4: Sweeps on transradial subject using BioScannerTM on fastSCAN software.

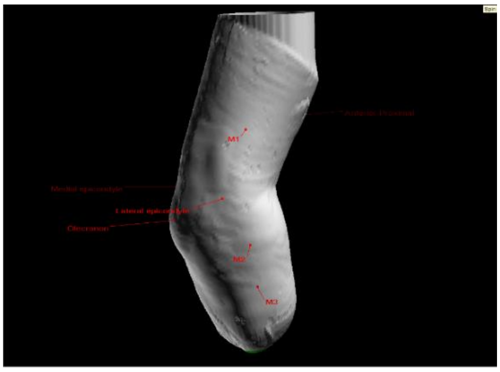
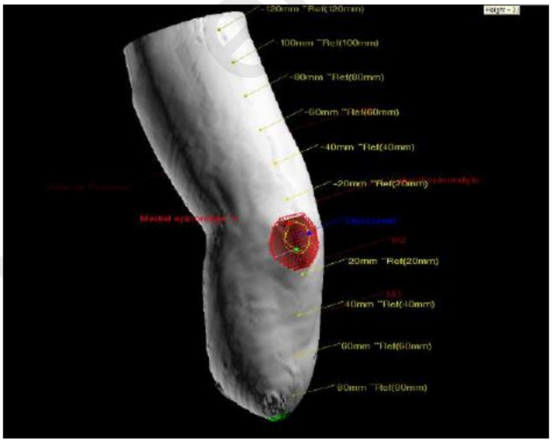


Figure 3.5: Labelling marks with BioShape software (M1: Proximal Trimline Mark; M2: Stylus Mark 20 mm inferior to Olecranon; M3: Stylus Mark 40 mm inferior to Olecranon; Olecranon, Medial Epicondyle, Lateral Epicondyle).

Additional dimensional reference marks were added with 20mm space between each reference marks started from the reference mark, the olecranon. Distance from Olecranon is shown in yellow colour in so that distant to proximal part will be negative and positive value towards the distal end. Build-ups of 1/8 inch were made for relief on bony sensitive areas. This build-ups made by increasing the height at blue, green and red nodes on as shown in Figure 3.6. The height were distributed equally on the surface. After that, surface of model was smoothen to get a better surface during carving on foam as shown in Figure 3.7.



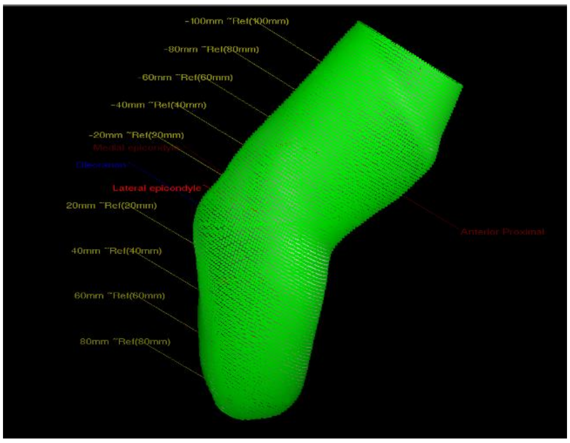


Figure 3.6: Buildups on olecranon area (1/8 inch at each colour nodes)

Figure 3.7: Smoothing procedure for all surface of cast.

In order to get a good position during carving/milling process and ease the draping procedure, the position of the positive cast was aligned in order to make the socket position 90˚ vertical (Figure 3.8). The anterior axis run from anterior proximal point to anterior distal point and the residual limb positioned exactly at 45˚ elbow flexion.

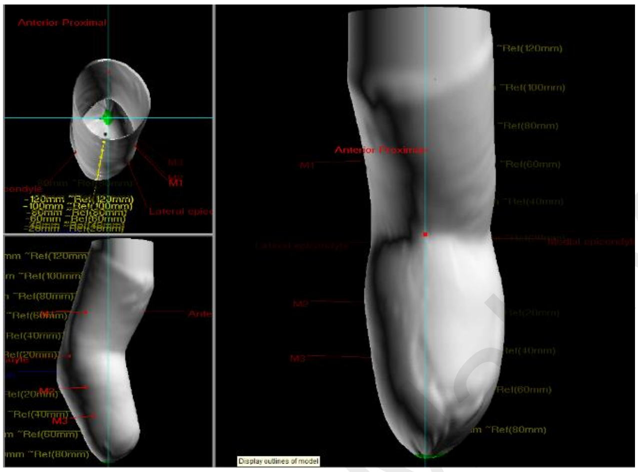


Figure 3.8: Alignment of positive cast

The measurement details of the cast including circumference, anterior-posterior and medial-lateral for every 20mm dimension (Table 3.1) were rechecked with the real subject. Five percent tension was made near the proximal trimline for the suspension of the socket, below the trimline mark, M1 and finally proceed with trimline. Trimline drawn on the positive cast and extension made for milling purpose (Figure 3.9).

Before proceed to the curving and milling process with BioMill™, best fit CAMFoam™ is selected based on the dimension of the cast. Position of the mandrill is adjusted so it is perfectly at the center of the cast design. The fault from this procedure will interfere the milling process. BK1 Foam selected, placed on the platform and the process started. The duration for carving procedure took about 1 hour and 12 minutes for 1 degree fine carving resolution. Terminal Device. After milling process, the socket draped as the same way with the traditional method and attached to the ready-made exoskeleton.

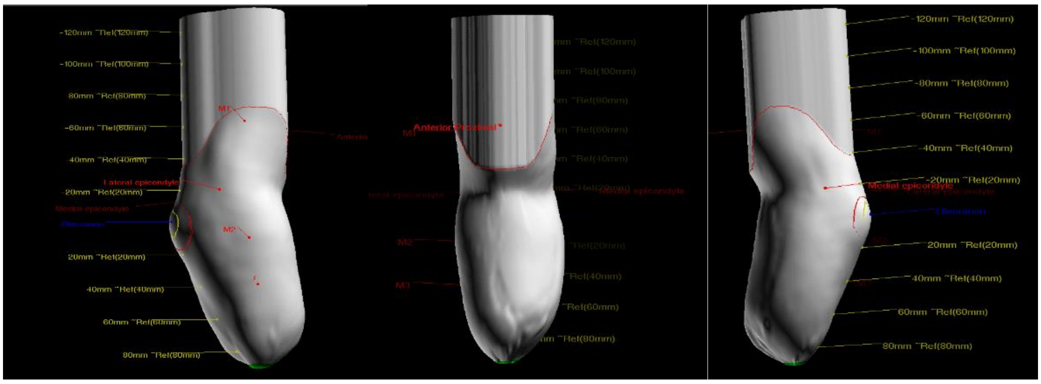


Figure 3.9: Sketch of proximal trimline on the positive cast

Table 3.1: Final Dimension of the positive cast. *Circ:circumference; A-P: Anterior-Posterior; M-L: Medial-Lateral

Reference Point	Circ (mm)	A-P (mm)	M-L (mm)
-120mm REF	252.7	76.4	76.9
-100mm REF	269	84.5	82.3
-80mm REF	274.7	90.2	81.8
Anterior Proximal	266.5	88.7	78.8
-60mm REF	266	88.7	78.5
M1	265.1	88.5	78.1
-40mm REF	252.7	83.4	71.6
-20mm REF	237.4	78.3	59
Medial Epicondyle	237.7	78.4	58.4
Lateral Epicondyle	239.3	78.9	58.5
Olecranon	260.9	84	71.9
M2	265.4	84.1	78.3
20mm REF	261.6	83.1	79.1
40mm REF	245.9	76.7	77.9
M3	244.3	76	77.5
60mm REF	219.1	68.9	68.2
80mm REF	136.4	43.8	41.2

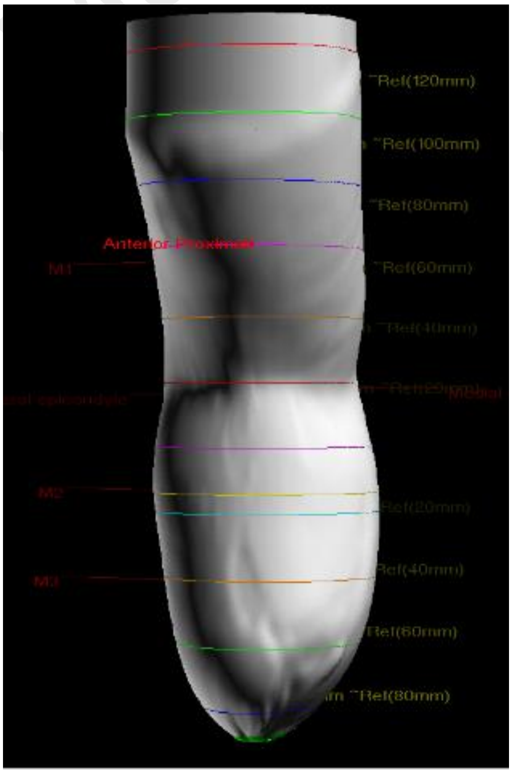


Figure 3.10: Milling process with BioMillTM

3.1.1.2 Comparison of Conventional and CAD/CAM Socket Fabrication Technique

As compared to the use of traditional method, CAD/CAM method via BioSculptor technology^{TM} allows the prosthetist to supply an absolutely intimate fit socket. An intimate fit is not tight; rather, it allows clinical data to be used in designing a well-fitting prosthesis. The system make the fabrication process to be more precise especially during modifications, more efficient and the prosthetists will have more quality time with clients. With CAD/CAM technology, patients have no longer to endure the mess and bother associated with plaster casting. Not only that CAD/CAM method are perfect for mass production and it save a lot of time rather than rectifying the plaster manually at workshop, checking the measurement, repeat rectifying process, smoothing and so forth. Modifying the cast will takes less time as rendering and smoothing can be made directly plus the process can be undo and redo.

Conveniently, patients who cannot travel to the prosthesis center can be scanned at their house, ward, or in a nursing home as the component fit into a compact in portable case that is smaller than a standard carry-on piece of luggage. Capturing the 3D shape for static object is much simpler than capturing a dynamic and complex object. The BioScluptor Innovative Solution comes with clear top scanning table in order to capture the plantar surface of the feet and for patient who are not able to stand for extended period of time.

However the problem with this system is that the trading of plaster models for 3D-renndered image on screen is a bit of an adjustment for the prosthetist and orthotist. With all benefits of the system, there are many practitioner who still did not adapt with this new technology. Although it will takes some time for the learning process but it is really worth. At some point in the not-so-distant future, the majority in this profession will use CAD on regular basis.

3.1.2 Terminal Device

In this section, process of developing myoelectric control terminal device prototype described in details include the design requirement decided for prototype, parts/electronic components used, circuit and programming works.

3.1.2.1 Design Requirement

The design requirement decided for this prototype, is classified into three part, a) User Interface and b) Mechanical Power; c) Safety; d) Control and Sensor Integration e) Manufacturability. For user interface the requirement that need to be meet by smartGrip at the end of the development process is that the batteries is easily swappable and rechargeable with one hand without no additional tool. SmartGrip easy to be don and doff without extra effort, lightweight and easy placement of the skin electrodes. The amount of energy consumed per unit time should be low and efficient.

Safety is one of important aspect in designing a prosthesis. SmartGrip must be safe to use and handle during operation. Water resistant material should cover all components for protection from common impact such for example moisture. The 12V DC Motor must not exposed for this safety purposes. The batteries and control unit is placed inside the hand exoskeleton or compartment with proper circuit installation. Isolator also used with the control unit to prevent any unexpected surges or spikes during operation.

For control and sensor integration the smartGrip comes with two sensors, the force sensor and myoelectric sensor. The sensor will generate analog reading for every millisecond for greater accuracy and quick respond time. Commonly available standard microprocessor which able to handle sensor input and motor output must be used (Arduino compatible microcontroller). Besides that, manufacturability which is the ability of manufacturing the device should be less than the hand available in the market as the study trying to produce a low cost yet efficient functional prosthesis. The entire cost for manufacture and assemble process of one complete terminal device must be less than RM 2000 at 1 unit quantity and 1500 per 100 quantity.

3.1.2.2 Electronic Components

Electric hand Terminal device was used. Improvement and adjustment were made on this available electric hand. The adjustment made on the motor, control unit, gripping control and prosthesis control. The prosthetic hand come with small connected gear that moves with every rotation of motor, clockwise to open and anticlockwise to close the hook. The device made up of a pair of active prong. The upper prong has maximum 6.87 cm opening span with maximum 72˚ opening angle. Meanwhile the lower prong has smaller maximum opening angle span of 4.30 cm and 45˚ opening angle. The motor connected to the plastic gears that move both the upper and lower prongs. The shape of the upper and lower prongs (Figure 3.11) is claw-like so that cylindrical object can be easily and safely grasp. Meanwhile for controlling smaller object, the tip of the hook is used. The tip of the hook has 0.5 cm x 0.5 cm area and this area is practical to reach out small object and especially to reach object at narrow area.

Figure 3.11: Electric Terminal Device

Two input sources and two output used in the prototype. The inputs are the muscle sensor and force sensor, and meanwhile output used is high torque 12V DC motor and high speed vibration motor. Faulhaber DC-Micromotor 6V (Figure 3.12) model 1024K006SR substituted inside cylindrical case of 12 mm diameter and 24.2 mm length positioned at the pivot of the hook. The model of the original motor is unidentified. There are some problem with the original motor as the motor would work a while, stop and restarted which is due to disconnected commutator contact. Besides, it generate heat after few minute of usage and some noise generated during the operation. Faulhaber 1024K006SR (Stall Torque = 4.6 mNm; no-load speed = 12,300 min-1 ; speed constant = 2017min-1/V and operating temperature range = -30 to 85℃) works very well with low-noise and good temperature control.

Figure 3.12: Faulhaber1024K006SR DC motor 6V

Arduino microcontroller is a programmable logic controller that has recently become the standard hobbyist and robot controller. Arduino family microcontrollers comes with power, digital and analog input/output pins which can be directly connected to various components. With variety features and user friendly, it comes with very reasonable price.

Thousands of code libraries and projects available from online websites. Moreover, there is no other microcontroller that offers the same amounts of analog input close to the size and cost of Arduino. Adafruit Feather 32u4 Basic microcontroller is small and can be inserted easily inside the exoskeleton and it is very lightweight, therefore contribute to the reduction of weight of mass of the prosthesis. The control unit receive feedback from the input sensors, analyse the data, read and execute the coded program.

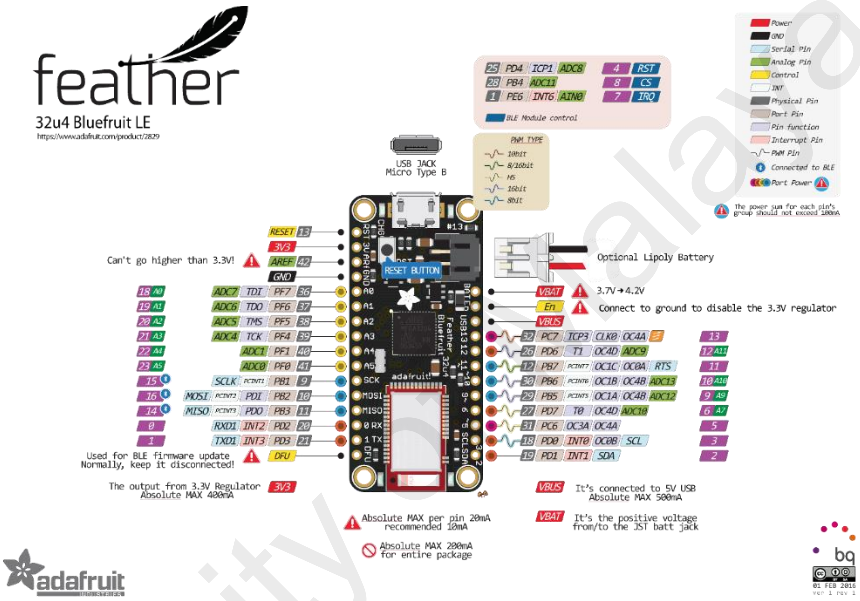


Figure 3.13: Adafruit Feather 32u4 basic microcontroller

Myoware Muscle Sensor, an all-in-one electromyography (EMG) sensor (0.82" x 2.06") from Advancer Technologies measuring the filtered and rectified electrical activity of the muscle. It comes in single-supply voltage of +3.1V to 5V, polarity protected power pins, indicator LEDs, and an On/Off switch. The sensor layout and pins are shown in Figure 3.14.

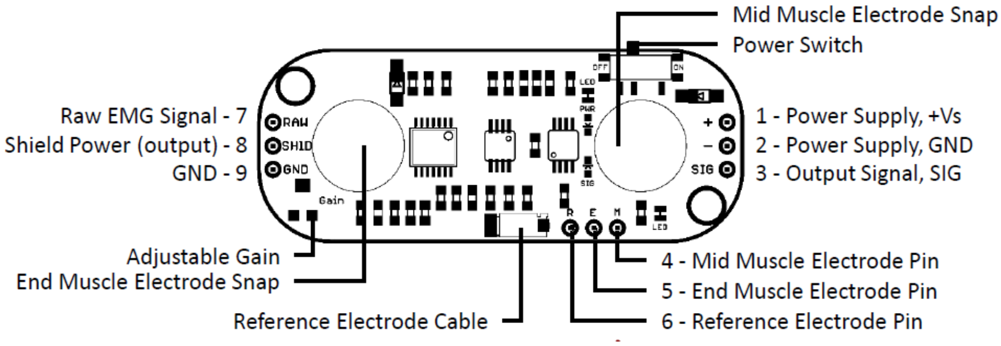


Figure 3.14: Myoware Muscle Sensor layout

The sensor is specially designed for microcontroller therefore the signal can be directly processed. The sensor primary output is not a raw data but rather an amplified, rectified and integrated signal that works well with microcontroller's analog-to-digital converter (ADC). The difference illustrated in Figure 3.15 (not the actual sensor output).

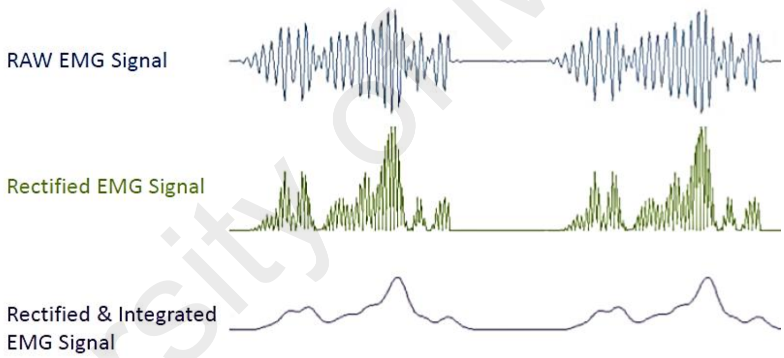


Figure 3.15: Illustration of raw EMG and EMG envelope

The Myoware muscle sensor measure, filters, rectifies and amplifies the electrical activities of a muscle and produces analog output signal that can be read and analyse by microcontroller/control unit. The sensor can be switch on when use and off when it is not used. The output range from 0 –Vs (Voltage of power source) volts depending the amount of activity in the selected muscle. The myoware do not need positive and negative voltage power supplies as it can be directly plugged into 3.3V or 5v from the microcontroller boards. The setup configuration of grid powered with power and output isolation is as shown in Figure 3.16. The isolation amplifier and power isolator provide isolation between user and electrical grid.

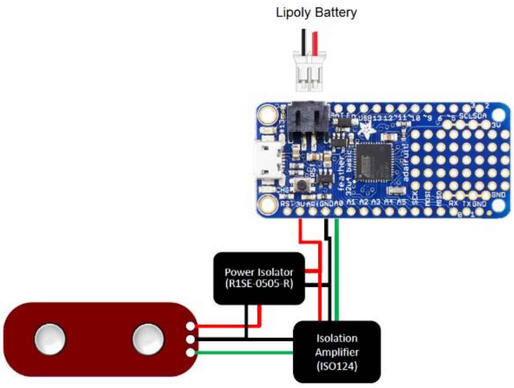


Figure 3.16: Setup configuration of MyowareTM Muscle Sensor

The Myoware™ sensor has embedded electrode connector so that electrodes can be plugged in easily without the needs of cable. It can be placed at any active muscle. User must determine the muscle group to target (e.g. biceps, forearm). The correct procedure to place the sensor is as shown in Figure 3.17. Prepare three new electrodes and snap them to the sensor's snap connector at bottom side of Myoware muscle sensor. Make sure the skin is clean and dry and next position those electrodes with one electrode exactly at the centre of muscle body, another one in the direction towards the end of muscle body and the reference electrode located on bony (e.g. elbow bone) or nonadjacent part near the targeted muscle.

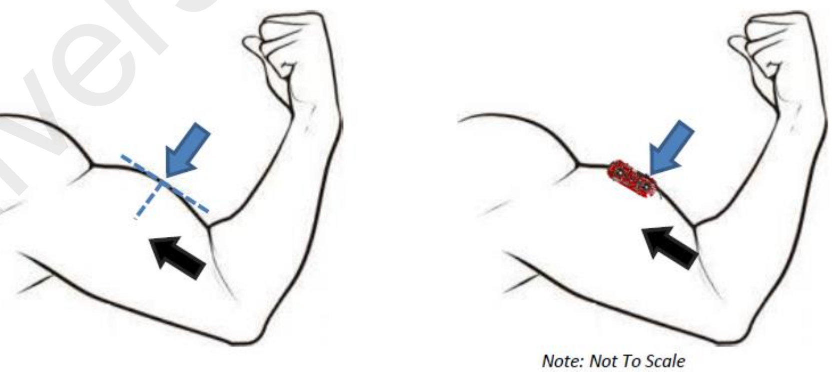


Figure 3.17: Example sensor location for Biceps

Electrode placement is important in order to obtain accurate and reliable raw EMG output. It has a vast effect on the strength of the signal Figure 3.18. The sensor must be aligned with the orientation of the muscle fibers, at the middle of muscle body. Placing

Myoware^{TM} sensor in wrong location will result in reduction of strength and quality of sensor's signal due to interference attributed to crosstalk.

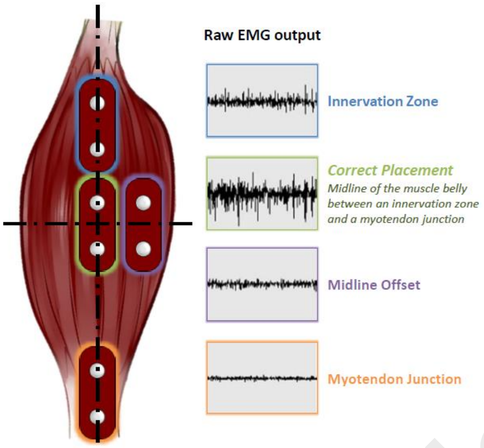


Figure 3.18: Correct position of electrode placement

One electrode must be placed at the body of muscle one at the end of muscle and the other end of electrode must be placed near to bones as reference to the analog value. It is save to use this sensor as it comes with protection of polarity protected power pins that protect the sensor chips from burning out when the power accidently connected backwards.

The second input, Force Sensing Resistor (FSR) was used (Figure 3.19). FSR is commonly known for it used in sensing a changes in force but not in sensing an accurate value of input. It can be replaced easily, durable and water resistant. The force used to monitor the changes of force exerted on object pinched by the electric hand. FSR made of conductive polymer that will change its resistance with change of force applied to the surface of the sensor. While applying force on the rounded area, the particles or ink inside the film move and touch conducting electrode and therefore changing the FSR resistance. The good features of FSR is its size, thickness of less than 0.5 mm, flexible, low cost and good shock resistance. The only drawbacks of FSR is its low precision as the measurement result will drift with time and usually differ 10% and more.

Figure 3.19: Force Sensitive Resistor (FSR)

Rechargeable lithium-ion polymer battery (Figure 3.20) was used. LiPos which comes in a soft package pouch is lighter than equivalent cylindrical cells of the same capacity. The lightweight features of LiPos battery is the advantage as the mass of prosthetic hand prototype require minimum weight to provide comfort to the user. Lithium-ion polymer battery capacity range between 2.7-3.0 V when discharged and 4.20-4.35 when fully charged.

Figure 3.20: Lithium Ion Polymer Battery - 3.7v 2500mAh

The battery attached with 2-pin JST-PH connector that comes with necessary protection circuitry that prevent over-charging or over-use and protect against output shorts of the battery. The voltage will go very high during over-charging and very low during over-use and at that phase, the battery will cut out.

3.1.3 Sensory Feedback

In order to establish sensory feedback in the system, sensory substitution method which is a non-invasive technique for circumventing the loss of one sense by feeding its information through another channel in this case vibration was used. A vibration motor (Figure 3.21) is one of the technology growing nowadays that vibrates when sufficient power is applied. It is a shiftless vibratory motor protected within housing with operating range is between 2 to 3.6V. The motor vibrate very high on 3V and the vibration become soft and noticeable once anchored to PCB.

Figure 3.21: Vibration Motor

Vibration motor comes with two terminal that can be directly connect to any DC power supply. In order to control it with Arduino microcontroller, some parts needed for the circuit setup include 1N4001 Diode, 0.1µF ceramic capacitor, 1KΩ Resistor and 2N2222 NPN Transistor (Figure 3.22).

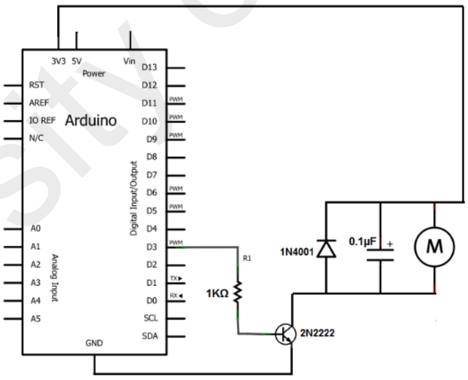


Figure 3.22: Schematic diagram for vibration motor citcuit

The motor may produce voltage spikes as it rotates and diode reverse biased was connected parallel to the motor to prevent these voltage from destroying microcontroller. The 0.1µF capacitor absorbs voltage spikes produced when the brushes, which are contacts connecting electric current to the motor windings, open and close and transistor 2N2222 provide amplification in the circuit as Arduino microcontrollers have weak current output and 1KΩ resistor placed in series with the base of the transistor.

The speed and vibration intensity controlled by increasing the delay to slower and decreasing the delay to amplify the vibration intensity. For the sensory feedback, the motor programmed if the force at the hook opening increasing, vibration will be more intense. Below 360 FSR analog value, the vibration is very low but beyond 380 the intensity become stronger. In order to provide comfort and safety to the user, the vibration sensor placed inside small pouch on elastic armband (Figure 3.23). The armband should be adjustable and can be wear by all size of user.

Figure 3.23: Ready-made Arm Band with small pouch

Increments of force at the hook opening detected by the force sensor will contribute to the sensory feedback made up of vibration sensor. In order to change the vibration mode for different force exerted by the terminal device we change the delay for the activation of motor. Vibration with more delay will produce mild and less noticeable vibration meanwhile short delay between actuator activation will produce more stronger and noticeable vibration. The vibration mode with more delay used for low grasping force and vibration mode with very short delay was programmed for high grasping force. Example of coding are shown in the Table 3.2.

Table 3.2: Arduino code for different vibrating mode

Mild Vibration	Strong Vibration

void setup()
{
pinMode(motorPin, OUTPUT);
}
 	
void loop()
{
digitalWrite(motorPin, HIGH);
delay(1000);
digitalWrite(motorPin, LOW);
delay(2000);
}
	void setup()
	{
	pinMode(motorPin, OUTPUT);
	}
	
	void loop()
	{
	digitalWrite(motorPin, HIGH);
	delay(1000);
	digitalWrite(motorPin, LOW);
	delay(500);
	}

Test was conducted on 10 random participants to get their respond on the vibration mode. Vibration motor placed inside armband and mild and strong vibration of the motor loaded. The participants asked to range the vibration mode between the scale of 1 to 5 (1 – Not noticeable at all; 2 – Less noticeable; 3 – Noticeable; 4 – Strong and 5 – Very strong feedback taken and recorded from the subjects.

3.2 Trial and Analysis

In this part, prototype trial and the analysis on two mechanical and one electrical terminal device was executed for the comparison of the performance of developed terminal device with terminal device that was available in the market.

3.2.1 Subject & Protocol

Three tests that require participation of subjects were conducted. The first test aimed to discover analog output signal detected by Myoware Muscle Sensor by different muscle contraction require the participation of 20 subjects. The second test was carried out after the prototype has been developed intended to obtain feedback from 10 random subjects about the control and operation of the hand through survey. For full operation of the hand, final test was conducted by recruiting one transradial amputee (from the University Malaya Medical Centre (UMMC), Kuala Lumpur) and two normal subject from Engineering Faculty, University of Malaya. They were invited to the Centre for Prosthetics and Orthotics Engineering, University of Malaya. The transradial amputee meets all the inclusion criteria which the subject is an upper limb amputee, used to electric hand system, healthy, no wound or ulcers on the residual limb, active and able to perform activities of daily living. All subjects were trained to use this prototype which named as 'smartGrip' three times a week with 2 hours for every session for 3 weeks.

All human test protocols were approved by the University of Malaya Medical Centre Ethics committee and verified by Certified Prosthetist and Orthotist (CPO) Cat I, and subject's written informed consent was obtained before the data collection. The transradial amputee fits his residual limb on the socket meanwhile the normal subject tied the prosthesis to their hand using Velcro (Figure 3.24). Feedback taken from the subjects.

Figure 3.24: Trial session of the prototype on subject (a) Transradial amputee (b) Normal subject (c) Prototype tied on normal subject by Velcro

QUEST (The Quebec User Evaluation of Satisfaction with Assistive Technology) questionnaire were carried out to evaluate user satisfaction with this assistive device. Standard QUEST questionnaire made up of 12 question including the user satisfaction with the assistive device and service. In this survey we eliminate service question as not related to the study. For each item, user must rate on their satisfaction towards the device using the following scale (Figure 3.25) of 1 to 5.

1	2	3	4	5
not satisfied at all	not very satisfied	more or less satisfied	quite satisfied	very satisfied

Figure 3.25: QUEST questionnaire scale

QUEST questionnaire were conducted by executing 10 random subjects to evaluate their satisfaction towards the control of the device. They were trained to use the hand (Figure 3.26) for 30 minutes and tried on grasping few objects and were asked to fill QUEST questionnaire form. The result of the QUEST questionnaire tabulated and analyzed.

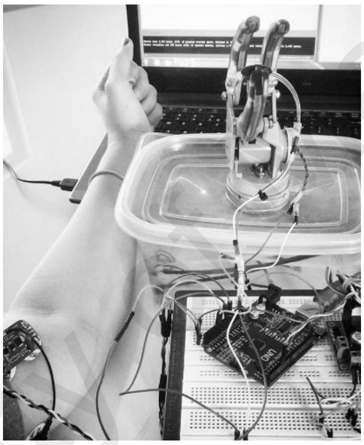


Figure 3.26: Test prior filling QUEST questionnaire form

Figure 3.27: Subject filling QUEST survey form.

3.2.2 Analysis of Myoware Sensor

Twenty random subject with different body mass, BMI and skin condition recruited to investigate value of analog reading generated for different contraction of muscle. The test conducted in order to get the value of optimal analog value to activate the Myoware muscle sensor. Sensor located at the biceps for all subjects. The subject asked to perform weak, medium, strong and very strong muscle contraction and the value of the reading recorded for 10 seconds. The average of the analog reading tabulated and plotted in graphical illustration. The information of the participants are as shown in the table below.

Table 3.3: Participants information of muscle sensors test

Subject	Sex	Age	Weight (kg)	Height (m)	BMI	Classification
s1	Male	23	60	1.62	22.86237	Normal
s2	Male	21	78	1.72	26.3656	Overweight
s3	Male	37	73	1.7	25.25952	Overweight
s4	Male	20	64	1.69	22.40818	Normal
s5	Male	41	61	1.77	19.47078	Normal
s6	Male	19	55	1.73	18.37683	Underweight
s7	Male	19	80	1.67	28.68514	Overweight
s8	Male	27	100	1.7	34.60208	Obesity
s9	Male	25	74	1.69	25.90946	Overweight
s10	Male	32	61	1.65	22.40588	Normal
s11	Male	22	60	1.73	20.04745	Normal
s12	Female	23	54	1.66	19.59646	Normal
s13	Female	23	61	1.52	26.40235	Overweight
s14	Female	23	50	1.53	21.35931	Normal
s15	Female	24	42	1.6	16.40625	Underweight
s16	Female	21	52	1.55	21.64412	Normal
s17	Female	19	66	1.7	22.83737	Normal
s18	Female	27	70	1.72	23.66144	Normal
s19	Female	18	49	1.52	21.20845	Normal
s20	Female	32	72	1.51	31.57756	Obesity

3.2.3 Analysis of Terminal Device

After done with the fabrication of the terminal device with sensory feedback, some terminal device tested. Two voluntary opening split hook, one voluntary opening hand, 3D printed hand and one electric hand (Figure 3.28) were analysed for the comparison with the developed prototype. Before the fabrication of prosthetic hand with sensory feedback, two-ways communication system between user and the device, improvement of one-way communication system developed named auto-adjusted prosthetic hand.

Hand terminal device (c) were eliminated because based on study by Gerwin Smit (2010), from test bench used, the hands have bad performance of activation forces (the hands require higher activation force) and mechanical work (the hand require 1.5–8 times more mechanical work) which is due to the friction inside the mechanism (Smit & Plettenburg, 2010). Meanwhile the 3D-printed hand (d) excluded from the study because of the motor used (5 servo motors) take up space inside the exoskeleton, and very less upper limb amputee using 3D-printed prosthesis. Two mechanical terminal device which are voluntary opening (VO) hook Otto Bock model 10A18 and Hosmer model 99P and one electrical hand were tested. As most of the upper limb amputee prefer to use this type of prosthetic hand, it is good to compare the developed prototype with this system as BP terminal device is part of standard terminal device used by the upper limb amputee.

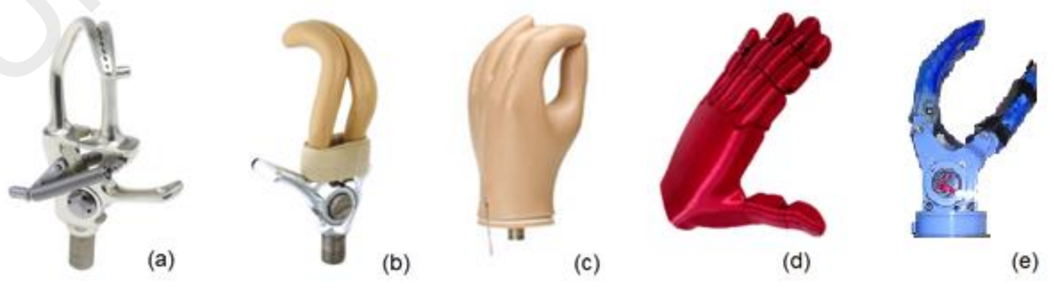


Figure 3.28: Terminal Device Tested (a) Otto Bock model 10A80 hook (Otto Bock; Duderstadt, Germany), (b) Hosmer model 99P hook (Hosmer; Campbell, California), (c) Hosmer Soft VO hand (Hosmer), (d) 3D-printed hand with 5 motors and (e) electric hand

3.2.3.1 Improvement of One-Way Communication System

The improvement of the one-way system utilized an auto adjusted system where the terminal device itself adapt to the situation. The system involved the use of force sensor placed at the hook opening, skin sensor, microcontroller, terminal device motor and battery. At this time, the sensory feedback system with sensory substitution via vibration mode by vibration motor was still under development.

The system operated with the activation of the myoware muscle sensor located on active muscle on user's residual limb. Myoware muscle sensor measure, filter, rectify and amplify the electrical activity of the muscle and produce analog output signal that can be read by microcontroller. If the microcontroller received an analog output signal greater than program threshold value then the terminal device will close but open if the analog output signal received is less than programmed threshold value. The threshold is set based on individual medium muscle contraction. Based on the result of analog output signal produced by different muscle contraction in Figure 4.3, value of 110 was selected to be used as threshold as the user do not need to really contract their muscle to operate the terminal device. Meanwhile the value for weak muscle contraction is not selected as the control of the hand will become unreliable as the hand will close and open by itself.

While closing, the system works by setting up the pre-threshold and threshold value for the force sensor. Force sensor detects force applied on the sensor surface and translated to the resistance value in the form of analog output signal that can be read by microcontroller. The force range from 0 (no force detected) to 1000 (the highest force can be detected). We set the pre-threshold value (analog value 100) and threshold value (analog value 700). The terminal device will start to close slowly once the force sensor detects the analog value of more than pre-treshold value. In order to prevent high force applied on object, he terminal device will stop to pinch when the analog value detects by force sensor is beyond the threshold value. Flowchart of the auto-adjusted system with improved one-way communication system is shown in Figure 3.29.

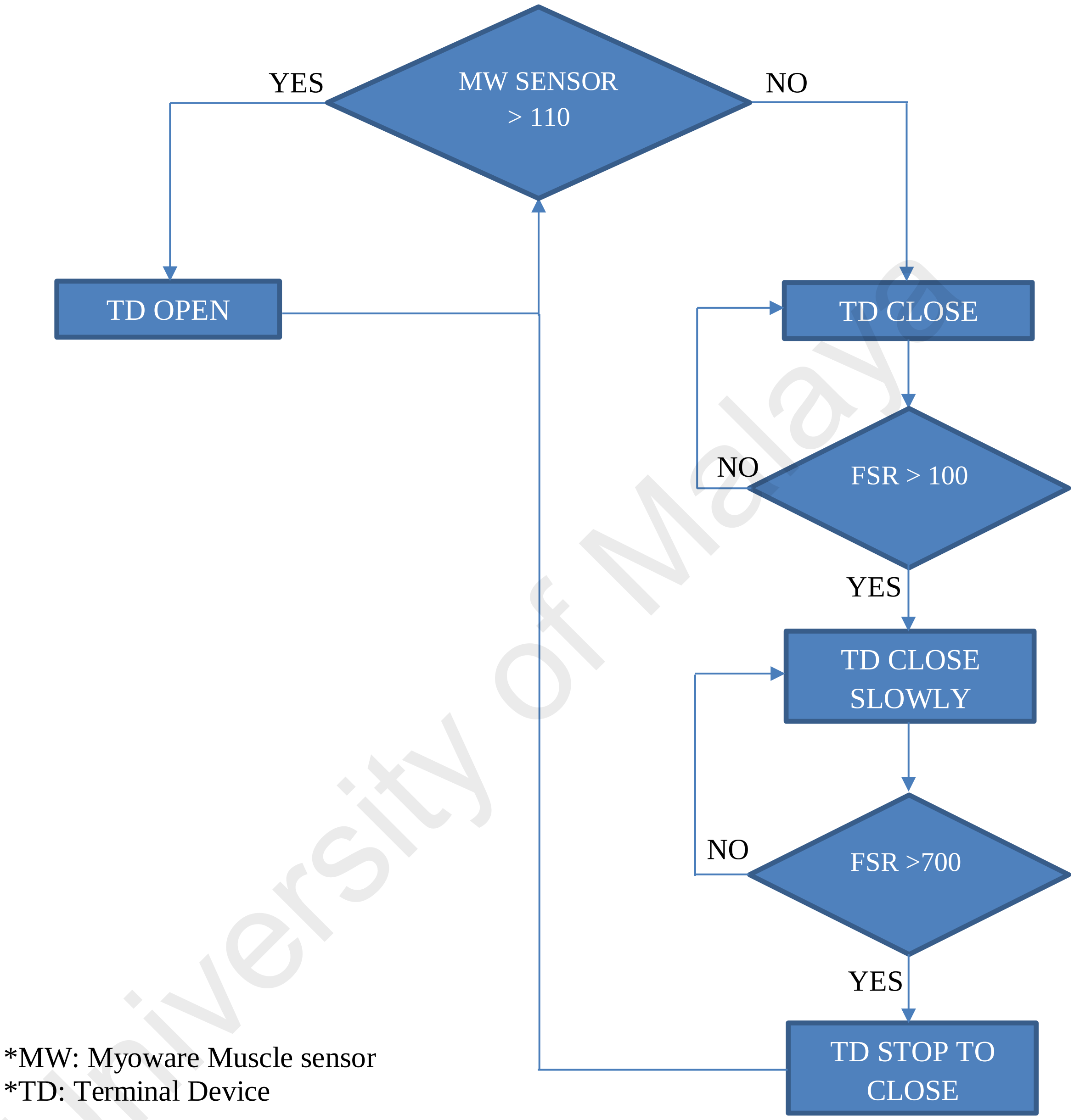


Figure 3.29: Flowchart of Auto-adjusted (improved one-way communication) terminal device.

3.2.3.2 Opening Angle

The testing setup for mechanical and electrical terminal device are different. Mechanical TD used test bench took to open meanwhile, electrical terminal moved with the supply of external power. Test bench tool for mechanical TD test made up of hole for hook connection and spindle at the other end. Stainless cable attached from the spindle to the TD attachment point and it is rolled manually for every 5 mm vertical opening of the hook. At every 5 mm hook opening, vertical length between two reference mark dots, *a*; incline length, *c* and cable length, *l* were measured and recorded. The summary of test 1 illustrated in (Figure 3.30). Meanwhile for the electric TD, microcontroller connected with the motor driver and motor, coding on Arduino software loaded so that opening angle can be measured at every opening angle.

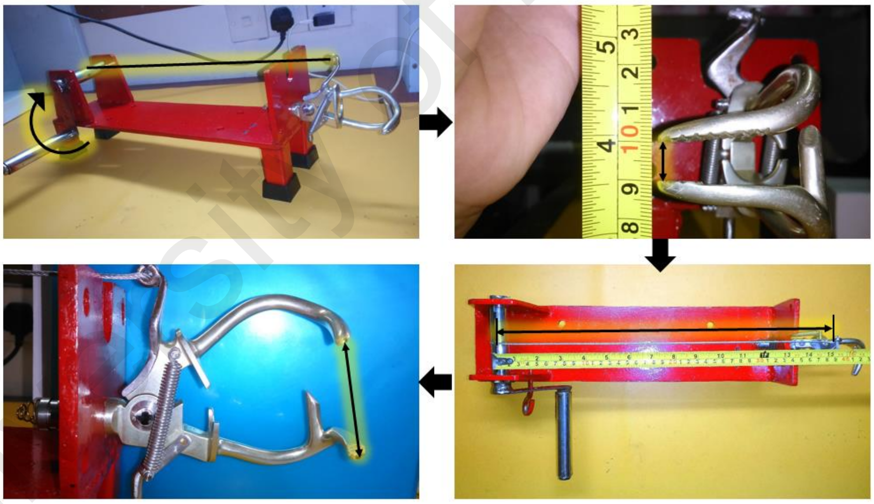


Figure 3.30: Setup for Test 1 (Mechanical terminal device)

From the measurement recorded, the horizontal distance between reference marks, *b*; cable excursion, *e*; opening angle, Θ and opening span, *C* were obtained. From illustration in (Figure 3.31), the length of *a*, *b* and *c* translated into a right angle triangle. Using Pythagoras' theorem the incline length or hypotenuse *c* is related to *a* and *b* by Eq. (1).

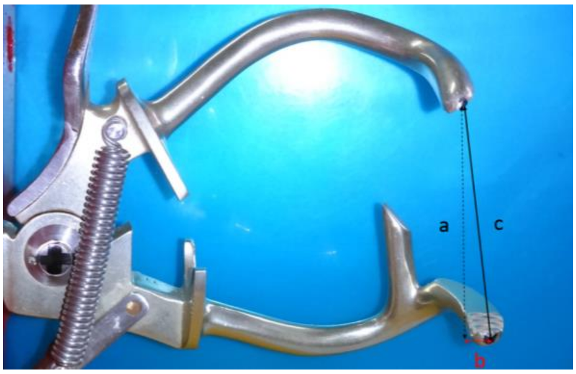


Figure 3.31: vertical length (a); horizontal length (b); and incline length (c)

$$a^2 + b^2 = c^2 \tag{1}$$

From Eq. (1), we are able to calculate the value of horizontal length, b as b and c are dependent values. The horizontal length is proportional to hypotenuse and vertical length. Sine rule Eq. (2) was used to find value of angle in triangle dimension. From derivation of sine rule, Eq. (3) enabled us to calculate the expected opening angle for every increment of vertical length.

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \tag{2}$$

$$Opening\ angle = \Theta = 2\left[\sin^{-1}\left(\frac{\frac{c}{2}\sin 90}{r}\right)\right] \tag{3}$$

Eq. (4) was used to calculate the opening span for both hook once the opening angle ϴ obtained.

$$Opening\ span = C_H = \frac{\Theta}{360^{\circ}} \times 2\pi r \tag{4}$$

The opening angle during 100% hook opening is measured and every 5 mm increment of vertical length using goniometer and calculation using the derivation of sine rule (3) for all tested hook. The opening angle should be measured between passive and active movable prongs for mechanical hook and two active prongs for the electrical hand with reference from tip to the axis of rotation of the terminal device. The value of opening angle for each terminal device simplified in the graphical representation.

3.2.3.3 Pinch Force Test

In the second test, ‘pinch force test’ aims to discover force changes during opening of the hook was conducted by placing Force Sensitive Resistor (FSR) directly at the lateral and tip section of the hook (Otto Bock model 10A18 and Hosmer 99P), distal and medial section of electric terminal device and tip of the finger of the 3D-printed prosthesis. Cube with 5mm thickness was placed one by one at all section together with FSR sensor (Figure 3.32).

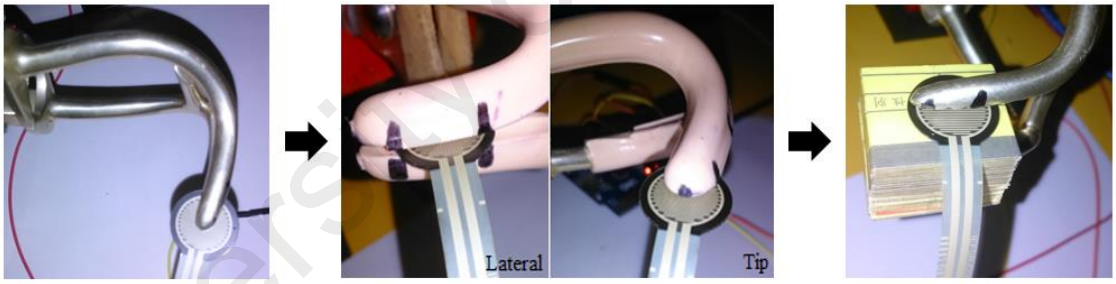


Figure 3.32: Setup for Test 2: Pinch Force

The analog data acquired was recorded from serial monitor of Arduino software for 10 seconds. Arduino coding for converting analog reading to force in Newton unit with one second delay between the analog readings was loaded on the software. In order to obtain highest force accuracy, part calibration using gain and offset trimming method was utilized by adjusting the reference voltage and feedback resistor so that the responses will be closer to nominal curve. Besides that, the actuation time was kept consistent for each test and the data will be recorded only if the reading on serial monitor was stable between minimum of two values. The forces (n=10) for every additional 5 mm cube placed between the hook were calculated and analysed using SPSS analysis software.

3.2.3.4 Pull Test

Pull Test conducted by placing wood piece (thickness = 10 mm) in between the fully closing without any threshold programmed terminal device. Spring scale that works by Hooke's Law which states that the force needed to extent a spring is proportional to the distance that the spring extended from it reset position was used in this test. The spring scale (maximum scale of 10 kg) hooked on the wood and pulled manually and slowly (Figure 3.33). The measurement on the spring scale recorded until the wood slip between the prototype openings. The results recorded and analysed.

Figure 3.33: Pull Test

CHAPTER 4: RESULTS & DISCUSSION

4.1 Prototype

The terminal device made up of control unit and battery inside the exoskeleton, force sensor, skin electrode and vibration motor inside the arm band (Figure 4.1). The performance of all parts and components analyzed and discussed in this section.

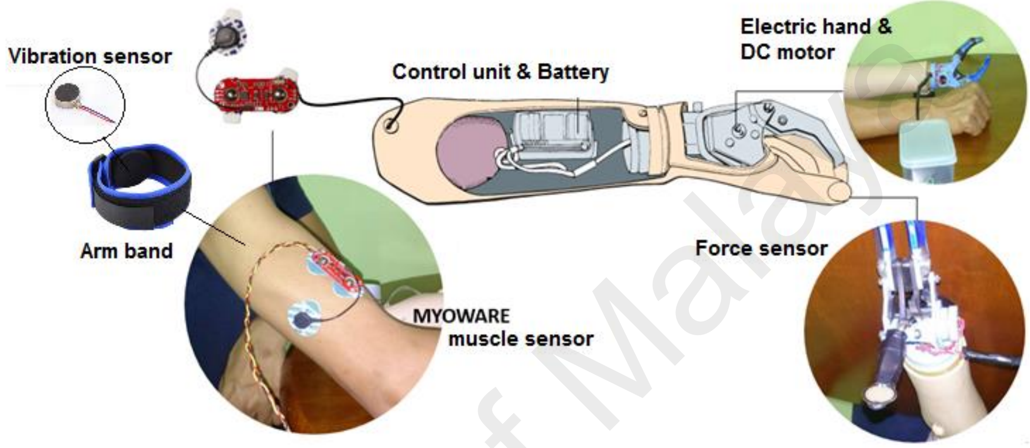


Figure 4.1: Parts and components of smartGrip prototype

The function of the following components and parts are as following:

- Control unit receive feedback from sensors (Myoware muscle sensor and force sensor), analyses the input data and send commands to the actuator (DC motor and vibration motor).
- The rechargeable LiPo battery supply power to the DC motor, vibration motor, microcontroller and sensors.
- The electric hand driven by DC motor helps to open and close the electric hand. The DC motors spin clockwise to open and counterclockwise to close the terminal device. It received commands from the control unit during operation.
- Force sensor detects force supplied to object and translate into vibration by mini vibration motor. The intensity of vibration is proportional to the force supplied on object.

- Myoware muscle sensor/ skin sensor measures, filters, rectifies and amplifies the electrical activities of muscle and produce analog output signal that can be read and analyse by microcontroller.
- Vibration sensor as sensory feedback allows the user to feel the object they hold and allows them to control how much force they want to supply on object. User will feel mild vibration with low force supplied on object but more stronger and noticeable vibration with increase in grasping force.
- Arm band, an elastic and custom made arm band locate vibration sensor and wear around arm.

4.2 Operation Flowchart

Prototype operate with the stimulation of myo muscle located at the arm or any active muscle on residual limb. In order to operate them, the user needs to contract their muscle until it reach certain level (threshold programmed). If the myoware muscle sensor detects the analog output value greater than program threshold value, the terminal device will start to open but closes if the analog reading is less than program threshold value.

While the terminal device closing, if the force sensors at hook opening detects force applied on object due to grasping activity of the terminal device, the level of force supplied will be equivalent to the vibration intensity generated by the vibration motor. With vibration produced, the user are able to control how much force they need to grasp an object. The flow repeated with the reading of the skin sensors. The flow chart of the operation is shown in (Figure 4.2).

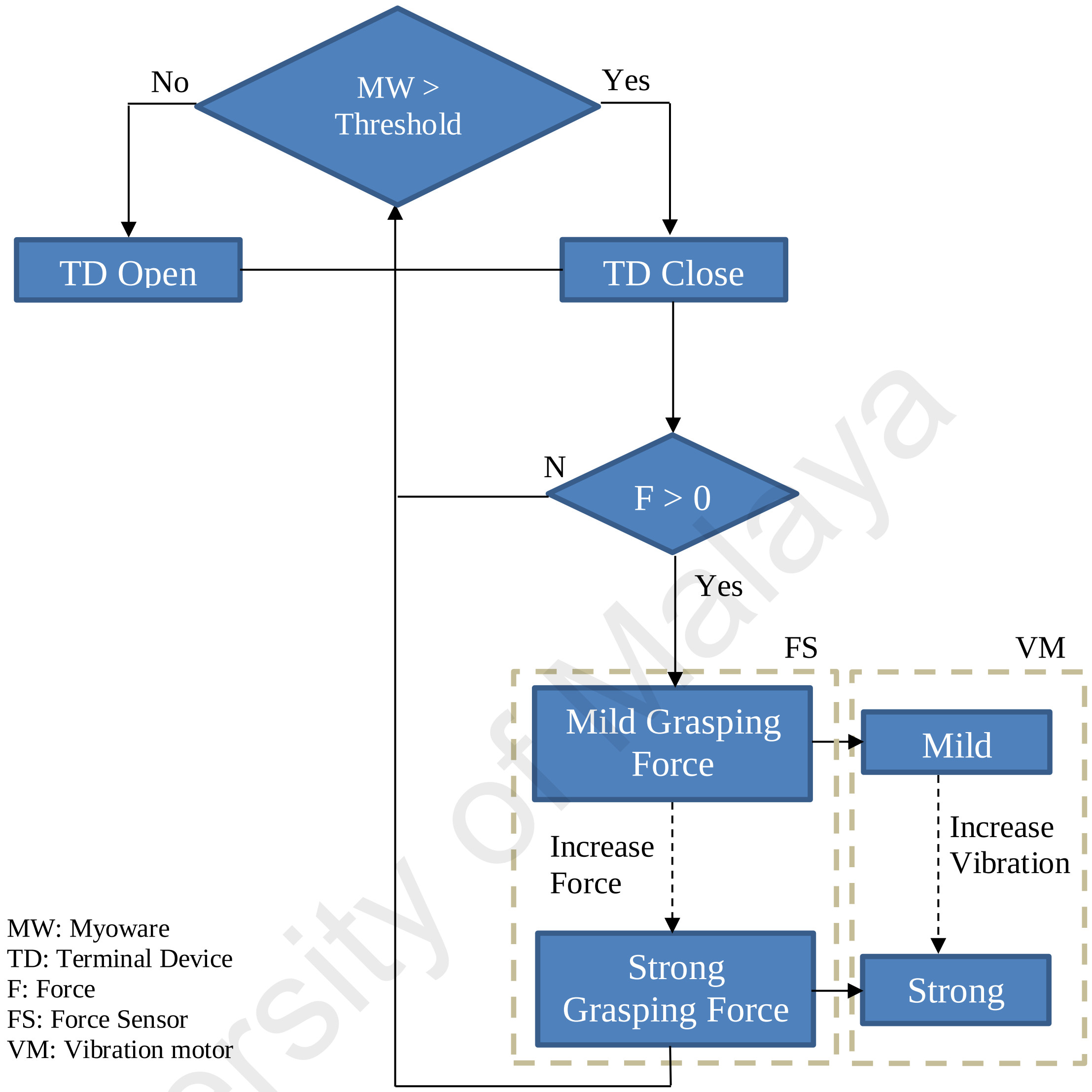


Figure 4.2: Flowchart of terminal device operation

4.3 Prosthetic Socket

The amputee fits his residual limb inside the socket fabricated by BioSculptor Technology. The socket comes with suspension at the proximal part, supracondylar and no other belt type suspension needed to hold the socket in place. Meanwhile for the normal subject, the prototype was tied on the user arm using Velcro.

4.4 Myoelectric Sensor

Test conducted to measure what value to be program to activate the muscle sensor. Different person generated different amount of force which may be related to the volume and mass of muscle, skin surface and other factors. The result of the test plotted in Figure 4.3. Average of 62.5 analog value recorded during weak muscle contraction, 110 medium muscle contraction, 208 strong muscle contraction and 371.3 very strong muscle contraction.

Medium muscle contraction of 110 was chosen as threshold value to activate the terminal device. It is selected as the user do not need to really contract the muscle to operate the hook therefore can prevent muscle fatigue. Value of weak muscle contraction was also not selected because the prosthetic control will become unreliable as the hook may open and close by itself. Meanwhile the value of strong and very strong also not used as threshold value as the user will need to really contract the muscle and can cause muscle problem.

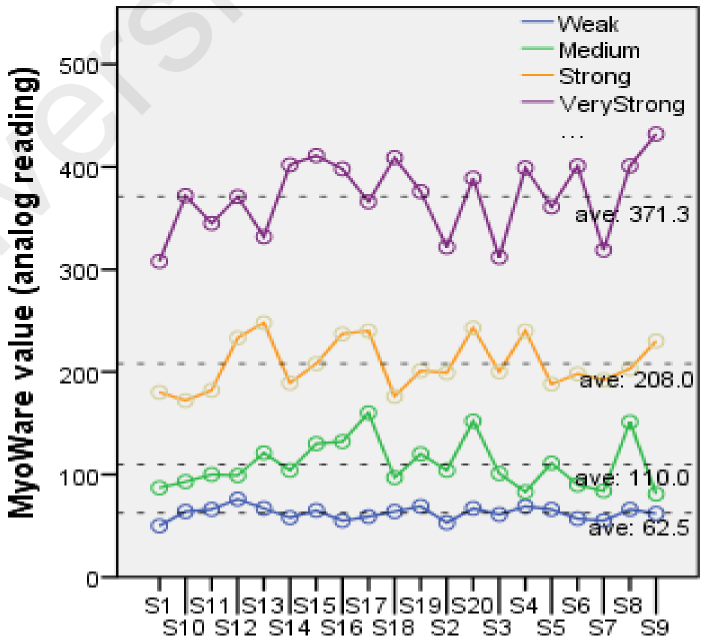


Figure 4.3: Myoware muscle sensor value for muscle contraction.

4.5 Sensory Feedback

From the test when the mild vibration loaded on the vibration motor, 70 % of them responded that the vibration is Less Noticeable, 20 % Noticeable and 10 % Not noticeable at all. But, when stronger vibration applied, 80% of the participant said that the vibration is noticeable with 20 % reported that the vibration is strong (Figure 4.4). Therefore minor adjustment made by increasing the delay for the mild vibration so that it is noticeable by the user. The level for strong vibration was not increase as increments of vibration will reduce the comfortability of the armband.

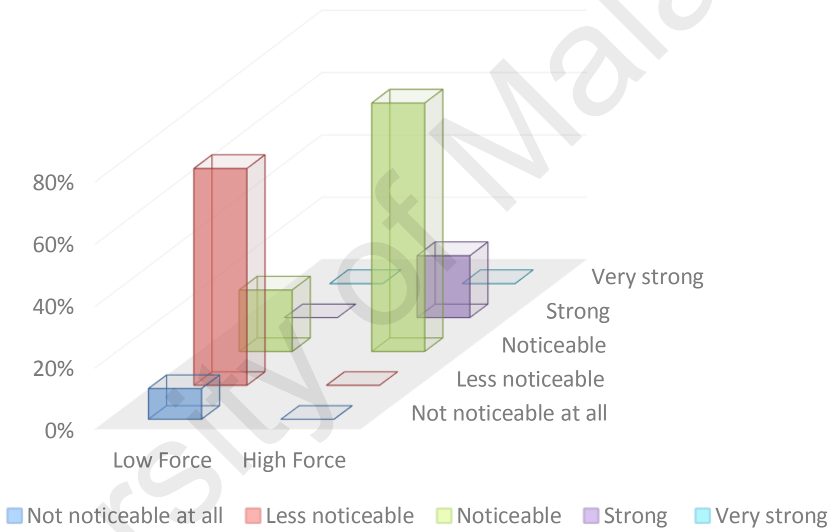


Figure 4.4: Result of vibration motor test

4.6 Opening Angle

Opening angle of the hook is the angle between passive prong and the movable active prong. An increase in the opening of hook will increase the angle between passive and active prongs. Prior 10mm vertical opening of the hook, the tip of active prong is in vertical position perpendicular to the tip of passive prong, therefore it is possible to calculate the expected angle for 5mm vertical increment of hook. The expected opening angle calculation for each 5mm vertical increment for all terminal device are shown in (5). From Eq. (3) we hypothesized that the opening angle, Θ (Θ_{H1}: 3.58˚; Θ_{H2}: 5.73˚;

Θ_{H3}: 54.8°) will increase for every 5mm increment in hook opening. Based on the results, the average angle of sector for H1 was 4.32% greater than expected Θ. Meanwhile the average angle of sector for H2 was 42.98% which was greater than expected Θ. (Θ_{aveH1}: 3.735° Θ_{aveH2}: 8.193°). The data for incremental angle for H1 is less dispersed and closer to the mean value compared to H2 (σ_{H1}: 0.60; σ_{H2}: 2.57). The expected angle for full opening for H1 and H2 is 40.81° and 49.28° respectively but the results showed an extra of 10% opening angle between prongs for H1 and 50% for H2 (H1: 44.82°; H2: 73.74°). Calculation for full opening angle is shown below (6).

For H1; For H2; (6)

$$\Theta_{H1} = 2[sin^{-1}(\frac{\frac{61}{2} sin\,90}{80})] \qquad \Theta_{H2} = 2[sin^{-1}(\frac{\frac{60}{2} sin\,90}{50})]$$

$$\Theta_{H1} = 44.82^\circ \qquad \Theta_{H2} = 73.74^\circ$$

For Electric hand (H3), both prong are moveable (Figure 4.5). The expected opening angle based on the derivation of sine rule for every 5 mm electric hand (e) opening is 54.8°. The lower prong can move from 0 – 45° and the other prong moves from 0 – 72° single axis. Both prongs move in (until 0°) to close and move out to open. Electric Hand H3, has the widest opening angle, followed by Hosmer 99P, H2 and H1.

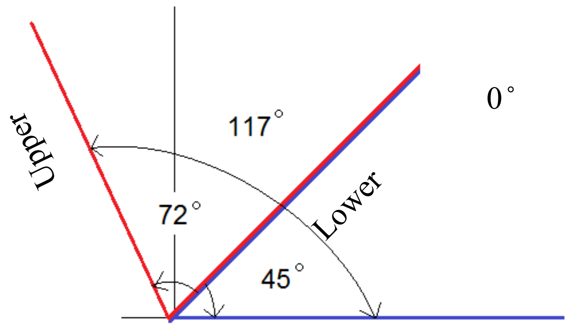


Figure 4.5: The opening angle of electric terminal device

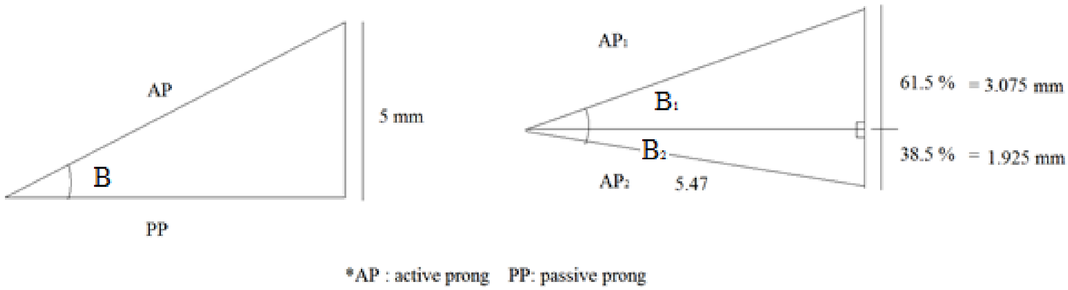


Figure 4.6: Opening angle for terminal device with one and two active movable prongs

Active & Passive Prongs

H1

$$B = \sin^{-1}\frac{b.\sin C}{c}$$

$$B = \sin^{-1}\frac{5.\sin 90}{80}$$

$$\underline{\boldsymbol{B = 3.58^{\circ}}}$$

H2

$$B = \sin^{-1}\frac{5.\sin 90}{50}$$

$$\underline{\boldsymbol{B = 5.74^{\circ}}}$$

Two Active Prongs (AP_1 & AP_2)

H3

$$B = B_1 + B_2 \qquad (5)$$

$$B_1 = \sin^{-1}\frac{b.\sin C}{c}$$

$$B_1 = \sin^{-1}\frac{3.075.\sin 90}{5.47}$$

$$B_1 = 34.2^{\circ}$$

$$B_2 = \sin^{-1}\frac{1.925.\sin 90}{5.47}$$

$$B_2 = 20.6^{\circ}$$

$$B_1 + B_2 = (34.2 + 20.6)^{\circ}$$

$$\underline{\boldsymbol{B = 54.8^{\circ}}}$$

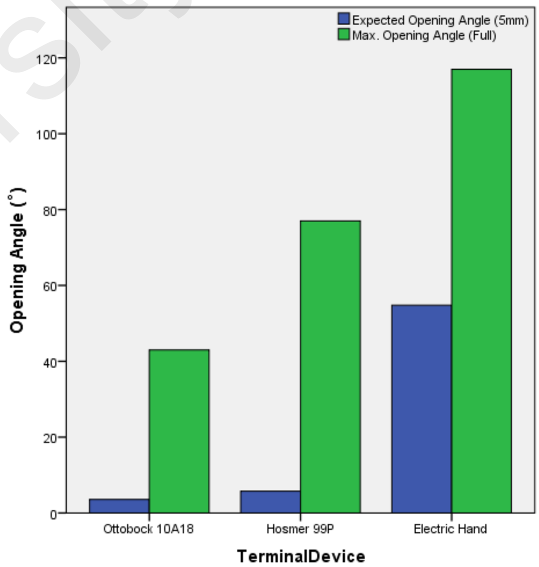


Figure 4.7: Expected opening angle for every 5mm vertical increment and maximum opening angle

Table 4.1: Opening span during 100% opening

Terminal Device	Prong arm, *r* (mm)	Full opening (˚)	Opening span during full opening, (mm)
H1	80	44.82	$2\pi(80)\ x\ \frac{44.82}{360}$ = 62.58 mm
H2	50	73.74	$2\pi(50)\ x\ \frac{73.74}{360}$ = 64.35 mm
H3	54.7	117.0	$2\pi(54.7)\ x\ \frac{117}{360}$ = 111 mm

(7)

From (7) we found electric hand, H3 has greater opening span. The tip of the H3 covered more than H1 and H2. From circumference formula of 2πr (2 x π x radius), it is clear that the longer the radius the greater the circumference (opening span) but the maximum opening angle of H2 and H3 which is greater than H1 made the tip of H2 and H3 covered more circumference than H1. As compared to normal hand range of motion (ROM) between thumb and digits (second through fifth digits), according to American Academy of Orthopedic Surgeons, MCP joint has 0˚ to 45˚ of hyperextension and 0˚ to 90˚ flexion. Imagine if thumb acts as passive prong and fingers MCP joint act as active prong (DIP and PIP in full extension), no work can be possibly done if the angle between prongs is 90˚ or more. Figure 4.8 illustrate the direction of force if Ottobock model 10A18 has greater than 90˚ opening angle.

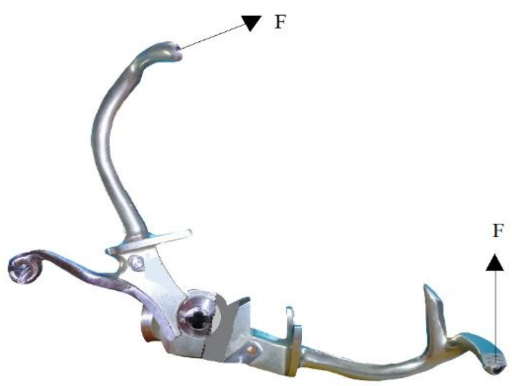


Figure 4.8: Illustration of the direction of force if Ottobock model 10A18 has greater than 90˚ opening angle.

Therefore, hook with wider opening is not necessary to be more efficient but in the case of Hosmer model 99P, extra motion of the tip of the hook can be considered as an advantage especially to grab bigger size object.

4.7 Pinch Force Test

Billock (1986) stated that the grasping surfaces of a mechanical hooks angle away from one another as the active finger moves in relationship to the stationary finger. Therefore the larger the object to be held in the mechanical hook terminal device, the less contact with the object and, consequently, the more force required to stabilize the object, dependent upon its shape (Billock, 1986). In order to further know this in detail, pinch force test was conducted by measuring force directly from the hook and hand by Force Sensitive Resistor (FSR).

The measurement of force was taken from two different positions which are on the lateral and the tip of the hook (H1: Otto Bock model 10A18; H2: Hosmer model 99P) and hand (H3: developed electric hand) as the analogue reading at both sections are different during different opening of the hook. For Electric Hand force also measured at tip and lateral section (Figure 4.9), but different from the mechanical hooks, H1 and H2. To increase the opening, 5mm cubes were added one by one at every section of the terminal device.

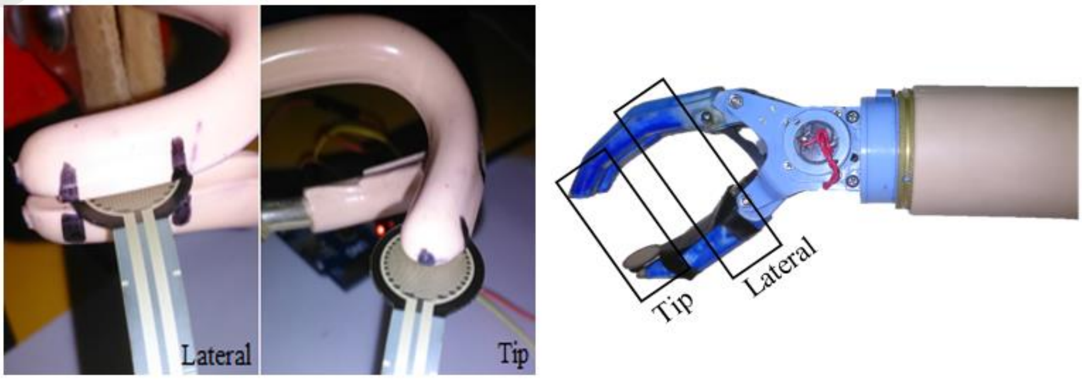


Figure 4.9: Tip and lateral section of H1, H2 and H3

Arduino software serial monitor showed gradual drop of force at lateral section for both hooks. A Pearson correlation coefficient was computed to assess the relationship between lateral force of a. There was a positive correlation between the two variables, r = 0.779, n = 110, p = 0.000. This means that both hooks started to have reduction in contact area with the sensor or to have additional space at the lateral contact of the hook. The results are therefore aligned with Billock (Billock, 1986). From observation, the contact point at lateral section was greatly reduced with the increase of hook opening. H1 supplied greater force during 0% hook opening and had better grasping for larger object while H2 had a good grasping for medium size object but less control for larger object.

As illustrated in Figure 4.10, the measurement of force at the tip section is different to the force at the lateral section of hook. A Pearson correlation coefficient was also computed to assess the relationship between lateral force of H1/H2 and tip force of H1/H2. There was a negative correlation between the two variables, r = -0.762, n = 110, p = 0.000 (H1) and r = -0.926, n = 110, p = 0.000 (H2). The value of F_T at different opening angle were quite constant for H1 which ranged between 2N to 3 N but increasing for H2 starting from 2N (number of cube: 0; 0mm) to 6N (number of cube: 10; 50mm). For the electric hand, the lateral force measure started from 5N which is higher than the value of lateral force of H1 and H2. The value for lateral force of H3 is quite constant between the forces of 4N to 5N. Meanwhile for the tip force it increasing starting from 5N to 7N which marks the highest of force measured.

Reduction of F_L of the hook cause an increase in the value of F_T. Therefore, we can assume that F_T is inversely proportional to F_L of the hook. The reason is related to the shape of the hook. When the hook is fully close, the lateral side of both prongs hook touched each other but there was small space observed at the tip of both hook and when the hook started to increase its opening, lateral section angled away and tip section angled in causing fully touch of both prongs at the tip section.

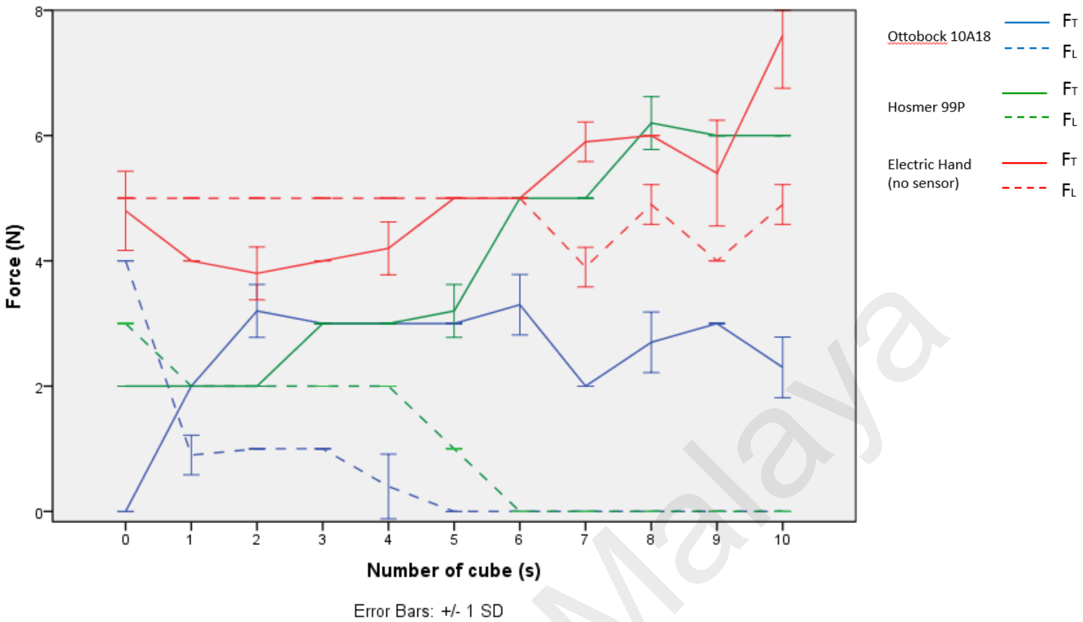


Figure 4.10: Lateral and Tip Force at different opening of the terminal device

For the electric hand, the force maintained at the middle section of the terminal device as the prongs exert equal distribution of force at different opening angle via rotation of DC motor. Meanwhile the force increased at the tip section of the electric hand is due to reduction of area of contact. From formula (8) with the same amount of force, the smaller the area of contact, the greater the pressure exerted. As the opening angle increasing, the tip of the hook angled away and the area of contact reduced and therefore the value of force sensor increased.

$$Pressure = \frac{Force}{Area} \tag{8}$$

To enable a number of activities of daily living, the devices should have a pinch force above 20 N (Keller, 1947; Van Der Niet Otr et al., 2010). From the result, the highest average force measured at the tip section of H3 but still less efficient in generating adequate force for activities of daily living. Based on the second test, it was found that Ottobock model 10A18, generated less than half of force supplied by Hosmer model 99P. Although Hosmer model 99P was a small adult size hook, but it was proven to generate greater force compared to adult size Ottobock model 10A18 (setting 1).

4.8 Pull Test

Pull test measure how much force can be overcome by the terminal device before the object slip from the tip of the terminal device. Wooden block of 10 mm thickness has rough surface therefore slippage of an object is not a big deal in this case. The spring scale was pulled slowly to prevent shock applied by the spring to the wooden block. The spring scale was pulled horizontally to prevent any additional gravity related force, therefore the pull test eliminate the gravity but manual pulling force. Based on the result of Pull Test, the terminal device capable to grip and restrain object with force less than 3.3 N, but not force beyond 3.7 N (Figure 4.11). This might change with the change in direction of force and the surface condition of an object.

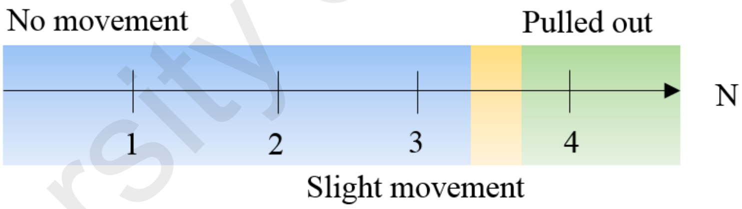


Figure 4.11: Pull Test result

4.9 Mass of prototype

Final weight of a prosthesis is critical to the success of any prosthetic fitting. In 1912, with invention of the lightest prosthetic body powered hook, user already complaints about the mass of the prosthesis at that time. The next hand was not becoming lighter but heavier with additional motors and batteries. Contrary to what one might think, one should not make an artificial limb replacement the same weight as the limb it replaces. Total arm replacements that exceed 3.5 kg (~7.5 lb) cannot be expected to be worn and used for a full day because of the discomfort associated with suspending that much weight from the body.

According to the study by Biddiss et al. the development of a more light-weight comfortable prosthesis is the most important design priority (E. Biddiss et al., 2007) and should be considerably lower to enable comfortable wearing (Smit et al., 2012). The average mass of human hand is 400 ± 90 g (J Shaperman, Setoguchi, & LeBlanc, 1992) and therefore the mass of smartGrip (Hand: 410 g | Battery 50 g) has significantly lighter compare to other terminal device measured by previous related study as shown in (Figure 4.12) and slightly lower than the average mass of hand.

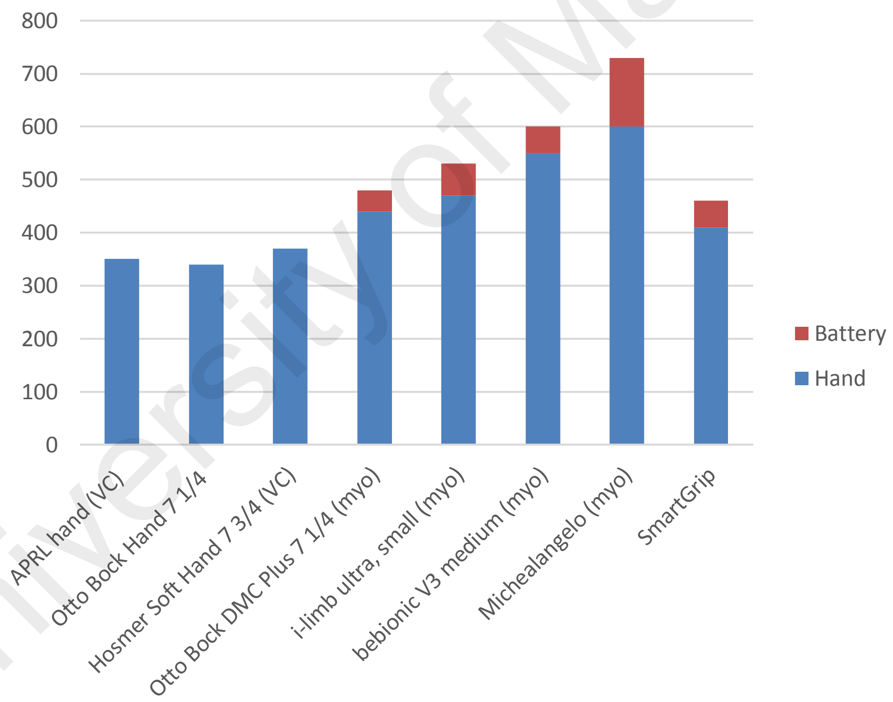


Figure 4.12: The mass of smartGrip compare to other commercially available body-powered hands and myoelectric hands. (Without cosmetic glove). The Figure also shows the mass of battery and hands. Adapted from "The lightweight Delft Cylinder Hand, the first multi-articulating hand that meets the basic user requirements," by G. Smit, D.H. Plettenburg and F. C. van der Helm, 2015, IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 23, pp. 431-440

4.10 Motor Performance

The common actuator used by most of terminal device operation for upper limb prosthesis is permanent magnet DC motor and stepper motor for most of elbow and wrist unit operation. Faulhaber motor 1024K006SR (6V) is a perfect fit for this application as it is tiny yet powerful. The dimension and motor specification are stated in the table below. It placed inside the case and connected to gears which move the hook outwards and inwards. The motors works very well with 2 hours of usage of prosthetic for activities of daily living. It is light and did not cause increase of the mass of the terminal device. Besides, Faulhaber 1024K006SR fits perfectly in the cylindrical case at the pivot of the terminal device, produce a near silent sound and does not produce heat during operation.

Table 4.2: Faulhaber 1024K006SR specification

Motor specification	Value
Nominal voltage	6V
Efficiency max.	83 %
No load current	0,008 A
No load speed	12 300 min^{-1}
Stall Torque	4.6 mNm
Speed constant	2 071 min^{-1}/V
Current constant	0,217 A/mNm
Angular acceleration	384.10^3 rad/s^2

4.11 Subject Trial & Feedback

Two subject trial sets executed in this study. The first set involved one transradial amputee and two able bodies who trained to use smartGrip for period of 3 weeks with 2 session per week (2 hours per session). Meanwhile the second trial involved 10 random subjects who got the chance to try the prototype for 30 minutes to control and grasp some objects (Figure 4.13) and they were asked to fill up QUEST survey form at the end of the test.

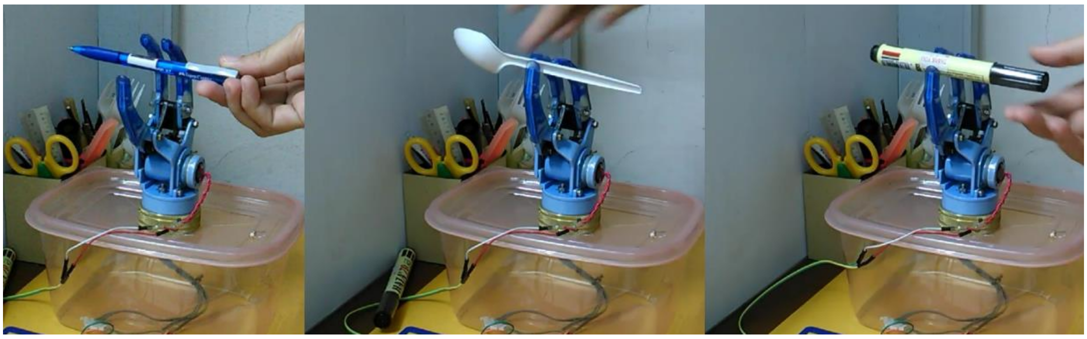


Figure 4.13: Trial set 2; 10 random participants grasping some object (Hard and soft object)

4.11.1 Subject Trial on Activities of Daily Living (ADL)

Based on the first set test, the hook is capable to grasp different size of object and very efficient on handling small object. The prototype can be used by any upper limb amputation level because the electrodes can be placed at any active residual muscle. The use of armband is flexible, it is adjustable and elastic and user can place it at any part of their arm according to the user comfort. It is comfortable as it eliminate the use of body harness, lightweight because it has comparatively less material than a hand shape, reduced number of motor and very light control unit. Besides that, the smartGrip is accurate, durable, low cost and low maintenance cost. As artificial hand cannot fell the object hold, being able to see the object they are holding is especially very important and this hook enable the user to see what object they trying to pick up. All the subjects are able to control any objects even with their eyes close with the presence of sensory feedback system. Some of the activities that can be carried out by smartGrip is as shown (Figure 4.14).

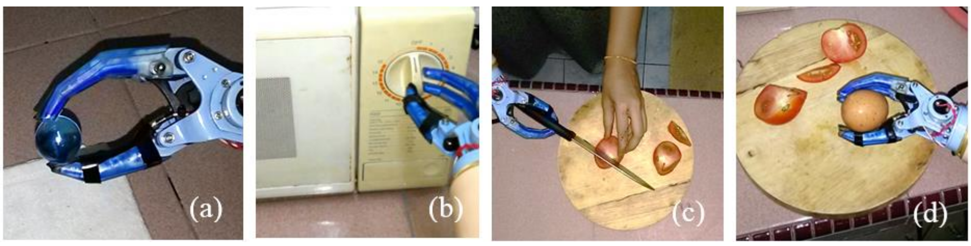


Figure 4.14: (a) the smartGRIP controlling slippery and small size object; (b) precise and accurate control; (c) Holds object securely; (d) Holds egg without cracking.

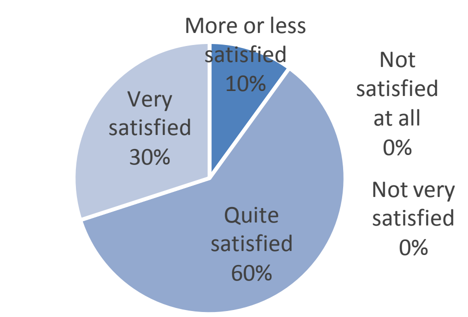
From the feedback of the subject, the transradial amputee who used to myoelectric system say that the hand is lighter than his current prosthesis. But the two able body subjects complaints the mass of the prosthesis is heavy and should be reduced. All subjects said that the opening and closing of the terminal device can be controlled easily after 2 session of practise. Not only that, from the feedback, they mentioned that the speed for closing and opening of the hook is too slow and therefore speed was increased by reducing the delay in the clockwise and counter clockwise rotations until all the subject satisfied with the operations. By having this system, user are able to control delicate and fragile object without having fear of damaging the object plus it has simple protocol of controlling the electric hook.

4.11.2 QUEST Questionnaire

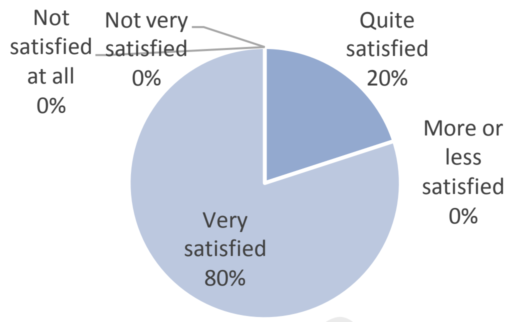
Based on the result of QUEST questionnaire (Table 4.3) more than 50 % of the participant very satisfied with the Effectiveness (90%), Durability (80%) and User Friendly (70%). For other categories, more than 50% of the participant quite satisfied with Dimension (60%), Weight (55%), Comfortable (55%) and safety (60%). There is no participant reported not satisfied at all or not very satisfied, only in ease in adjusting item, 30% reported not very satisfied and 50% more or less satisfied with the category. Twenty percent of the user were more or less satisfied with the user friendliness item, and 10 % for dimension. Overall, the total marks collected are good for the device only that some improvement need in aspect such as ease in adjusting, user friendliness, dimension and safety. 12 satisfaction items selected by the participants are Effectiveness (40%) follow by Comfort (25%), Safety (20%) and Ease in adjusting (15%).

Table 4.3: QUEST questionnaire results

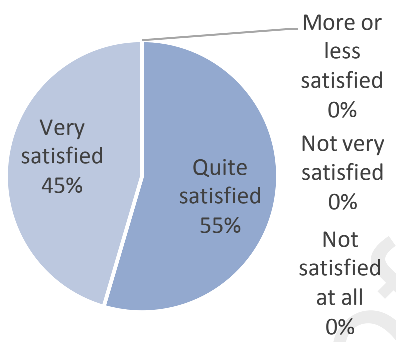
Dimension



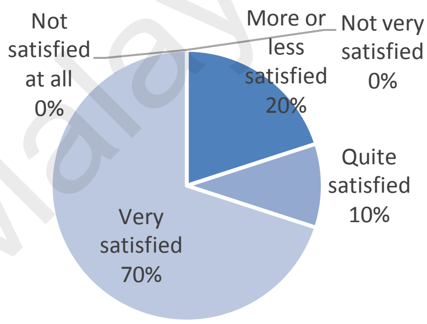
Durability



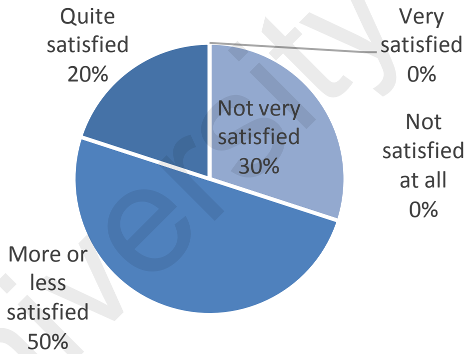
Weight



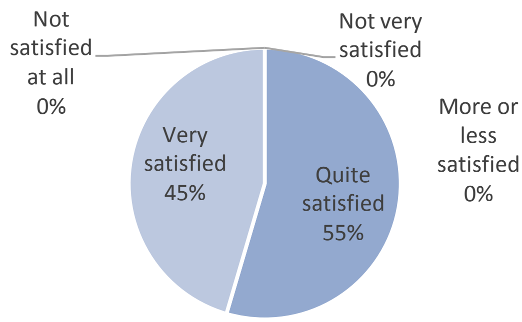
User friendly



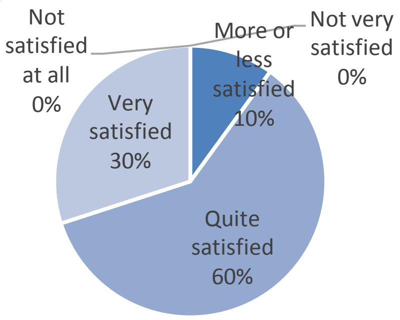
Ease in adjusting



Comfortable



Safety



Effectiveness

CHAPTER 5: CONCLUSION & RECOMMENDATION

5.1 Conclusion

This study present the 'smartGrip', a myoelectric control prosthetic terminal device prototype that utilised sensory substitution method in establishing sensory feedback system. SmartGrip terminal device solve the problem of myoelectric control prosthesis that are not able to sense amount of force supplied on object that usually end up squeezing object they hold by setting up two-way communication system between the prosthetic hand and the user. The smartGrip prototype has greater than 90˚ opening angle which regarded as an advantage especially to grasp bigger size objects. The study found the force at the tip section is inversely proportional to the force at the lateral section of the mechanical hook which related to the design of the canted prongs, but uniform force pattern discovered for smartGrip at the middle section due to equal distribution of force at that section and the reduction of area of contact at the tip section cause an increase in the pressure at the tip section. This increase in pressure will damage the object grasped by the terminal device. Although electric hand has the highest average force at the tip section but still less efficient in generating adequate force for activities of daily living. A complete electromechanical design of a prosthetic hand with sensory feedback have proven to increase functionality over currently available products. The developed prototype successfully established two way communication prosthetic terminal device that are able to monitor amount of force supplied on the object grasped as the force is translated into vibration mode that are identifiable by the skin of the user. Subjects were satisfied with smartGrip because it restore their sense of touch and at the same time capable to control amount of force supplied. Improvement need to be done in few aspects especially the ease in adjusting of the device. With neuroplasticity, the user are able to control the hand after several time wearing period and training.

5.2 Limitation of Study

The limitations of this study include:

- The number of upper limb amputee in Malaysia who is used to myoelectric system is very less. Most of them wearing either body-powered or cosmetic hand.
- The performance of the prototype should be compare to other available electric hand. Electric hand are expensive and very difficult to obtain.
- Much better microcontroller is supposed to be used.
- Force Sensitive Resistor (FSR) should be replace to more accurate force sensor.
- Sensory feedback noninvasively, by providing feedback on the skin needs a lot of training by the individual before the user get to use to the system.

5.3 Future Recommendation

This project has a lot of room for improvement in many different areas. The current hand, while working, could be made or design to be more aesthetically pleasing, have a wider range of motion, and could be made to be stronger and lighter. Improvement needed for the safety and ease of adjusting of the device. This project will be a platform for the development of electric prosthetic hand system in Malaysia. This study is significant because it contributes to the improvement on available prosthetic system and the testing of the product available in the market provide references for future development.

REFERENCES

Al-Ajam, Y., Lancashire, H., Pendegrass, C., Kang, N., Dowling, R. P., Taylor, S. J., & Blunn, G. (2013). The use of a bone-anchored device as a hard-wired conduit for transmitting EMG signals from implanted muscle electrodes. *IEEE Trans Biomed Eng, 60*(6), 1654-1659. doi: 10.1109/tbme.2013.2241060

Antfolk, C., D'Alonzo, M., Rosén, B., Lundborg, G., Sebelius, F., & Cipriani, C. (2013). Sensory feedback in upper limb prosthetics. *Expert Review of Medical Devices, 10*(1), 45-54. doi: 10.1586/erd.12.68

Bach-y-Rita, P. (1990). Brain plasticity as a basis for recovery of function in humans. *Neuropsychologia, 28*(6), 547-554.

Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychol Aging, 23*(4), 765-777. doi: 10.1037/a0013494

Biddis, E., & Chau, T. (2007). Upper-Limb Prosthetics: Critical Factors in Device Abandonment. *American Journal of Physical Medicine & Rehabilitation, 86*(12), 977-987. doi: 10.1097/PHM.0b013e3181587f6c

Biddiss, E., Beaton, D., & Chau, T. (2007). Consumer design priorities for upper limb prosthetics. *Disability and Rehabilitation: Assistive Technology, 2*(6), 346-357.

Biddiss, E. A., & Chau, T. T. (2007). Upper limb prosthesis use and abandonment: a survey of the last 25 years. *Prosthetics and orthotics international, 31*(3), 236-257.

Billock, J. N. (1986). Upper limb prosthetic terminal devices: Hands versus hooks. *Clin Prosthet Orthot, 10*(2), 57-65.

bin Tahir, A. Z. (2016). EMG sensor for robotic applications1.

Bowers, R. (n.d., December, 2014). Prosthetic Devices for Upper-Extremity Amputees. Retrieved April 24, 2016, from http://www.amputee-coalition.org/resources/prosthetic-devices-for-upper-extremity-amputees/

Bowker, J. H. (1992). *Atlas of limb prosthetics: surgical, prosthetic, and rehabilitation principles*: Mosby Inc.

Carey, S. L., Highsmith, M. J., Maitland, M. E., & Dubey, R. V. (2008). Compensatory movements of transradial prosthesis users during common tasks. *Clinical Biomechanics, 23*(9), 1128-1135.

Carlson, L., & Long, M. (1988). Quantitative evaluation of body-powered prostheses. *Chicago (IL): American Society of Mechanical Engineers, Dynamic Systems and Control Division*, 1-16.

Chatterjee, A., Chaubey, P., Martin, J., & Thakor, N. (2008). Testing a prosthetic haptic feedback simulator with an interactive force matching task. *JPO: Journal of Prosthetics and Orthotics, 20*(2), 27-34.

Childress, D. S. (1998). *Control strategy for upper-limb prostheses.* Paper presented at the Engineering in Medicine and Biology Society, 1998. Proceedings of the 20th Annual International Conference of the IEEE.

Christiansen, R., Contreras-Vidal, J. L., Gillespie, R. B., Shewokis, P. A., & O'Malley, M. K. (2013). *Vibrotactile feedback of pose error enhances myoelectric control of a prosthetic hand.* Paper presented at the World Haptics Conference (WHC), 2013.

Cipriani, C., D'Alonzo, M., & Carrozza, M. C. (2012). A miniature vibrotactile sensory substitution device for multifingered hand prosthetics. *IEEE transactions on biomedical engineering, 59*(2), 400-408.

Collier, M., & LeBIanc, M. (1996). Axilla Bypass Ring for Shoulder Harnesses for Upper-Limb Prostheses. *JPO: Journal of Prosthetics and Orthotics, 8*(4), 130-131.

Corin, J. D., Holley, T. M., Hasler, R. A., & Ashman, R. B. (1987). Mechanical Comparison of Terminal Devices. *Clinical Prosthetics & Orthotics, 11*(4), 235-244.

Dhillon, G. S., & Horch, K. W. (2005). Direct neural sensory feedback and control of a prosthetic arm. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13*(4), 468-472. doi: 10.1109/TNSRE.2005.856072

Farrell, T., & Weir, R. (2005). *Pilot comparison of surface vs. implanted EMG for multifunctional prosthesis control.* Paper presented at the 9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.

Geethanjali, P. (2016). Myoelectric control of prosthetic hands: state-of-the-art review. *Medical Devices (Auckland, N.Z.), 9,* 247-255. doi: 10.2147/MDER.S91102

Green, C. S., & Bavelier, D. (2008). Exercising Your Brain: A Review of Human Brain Plasticity and Training-Induced Learning. *Psychology and aging, 23*(4), 692-701. doi: 10.1037/a0014345

Head, J. (2014). *The effect of socket movement and electrode contact on myoelectric prosthesis control during daily living activities.* University of Salford.

Heckathorne, C. (1992). Components for adult externally powered systems. *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles, 2*, 151-174.

Heckathorne, C. W., & Childress, D. S. (1981). relationships of the surface electromyogram to the force, length, velocity, and contraction rate of the cineplastic human biceps1. *American Journal of Physical Medicine & Rehabilitation, 60*(1), 1&hyhen.

Hučko, B., Uherčík, F., & Horvát, F. (2014). Improved Kinematics for Upper Limbs Prostheses. *Procedia Engineering, 96*, 164-171. doi: http://dx.doi.org/10.1016/j.proeng.2014.12.137

Jacobsen, S., Meek, S., & Fullmer, R. (1984). *An adaptive myoelectric filter.* Paper presented at the IEEE Transactions on Biomedical Engineering.

Jang, C. H., Yang, H. S., Yang, H. E., Lee, S. Y., Kwon, J. W., Yun, B. D., . . . Jeong, H. W. (2011). A Survey on Activities of Daily Living and Occupations of Upper Extremity Amputees. *Annals of Rehabilitation Medicine, 35*(6), 907-921. doi: 10.5535/arm.2011.35.6.907

Jorgovanovic, N., Dosen, S., Djozic, D. J., Krajoski, G., & Farina, D. (2014). Virtual grasping: closed-loop force control using electrotactile feedback. *Computational and mathematical methods in medicine, 2014*.

Kaczmarek, K. A. (2000). Electrotactile adaptation on the abdomen: Preliminary results. *IEEE Transactions on Rehabilitation Engineering, 8*(4), 499-505.

Kaczmarek, K. A., Webster, J. G., Bach-y-Rita, P., & Tompkins, W. J. (1991). Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE transactions on biomedical engineering, 38*(1), 1-16.

Keller, A. D. (1947). *Studies to determine the functional requirements for hand and arm prosthesis*: Department of Engineering University of California.

Kolb, B., & Whishaw, I. Q. (1998). Brain plasticity and behavior. *Annual Review of Psychology, 49*(1), 43-64. doi: doi:10.1146/annurev.psych.49.1.43

Kyberd, P. J., & Chappell, P. H. (1994). The Southampton Hand: an intelligent myoelectric prosthesis. *Journal of rehabilitation research and development, 31*(4), 326.

Lawton, M. P., & Brody, E. M. (1969). Assessment of Older People: Self-Maintaining and Instrumental Activities of Daily Living. *The Gerontologist, 9*(3 Part 1), 179-186. doi: 10.1093/geront/9.3_Part_1.179

LeBlanc, M., Setoguchi, Y., Shaperman, J., & Carlson, L. (1992). Mechanical work efficiencies of body-powered prehensors for young children. *Child. Prosthet Orthot Clin, 27*(3), 70-75.

LeBlanc, M. A. (1985). Innovation and improvement of body-powered arm prostheses: A first step. *Clin Prosthet Orthot, 9*(1), 13-16.

McKenzie, D. S. (1965). The russian myo-electric arm. *J Bone Joint Surg Br, 47*, 418-420.

Miller, L. A., Lipschutz, R. D., Stubblefield, K. A., Lock, B. A., Huang, H., Williams, T. W., . . . Kuiken, T. A. (2008). Control of a Six Degree-of-Freedom Prosthetic Arm after Targeted Muscle Reinnervation Surgery. *Arch Phys Med Rehabil, 89*(11), 2057-2065. doi: 10.1016/j.apmr.2008.05.016

Millstein, S., Heger, H., & Hunter, G. (1986). Prosthetic use in adult upper limb amputees: a comparison of the body powered and electrically powered prostheses. *Prosthetics and orthotics international, 10*(1), 27-34.

Murguialday, A. R., Aggarwal, V., Chatterjee, A., Cho, Y., Rasmussen, R., Rourke, B. O., . . . Thakor, N. V. (2007, 13-15 June 2007). *Brain-Computer Interface for a Prosthetic Hand Using Local Machine Control and Haptic Feedback.* Paper presented at the 2007 IEEE 10th International Conference on Rehabilitation Robotics.

Napier, J. R. (1956). The prehensile movements of the human hand. *Bone & Joint Journal, 38*(4), 902-913.

Otto Bock. (2013). Hooks. Retrieved August 3, 2016, from http://www.ottobock.com.tr/en/prosthetics/products-from-a-to-z/hooks/

Ovadia, S. A., & Askari, M. (2015). Upper Extremity Amputations and Prosthetics. *Seminars in Plastic Surgery, 29*(1), 55-61. doi: 10.1055/s-0035-1544171

Parker, P., Englehart, K., & Hudgins, B. (2006). Myoelectric signal processing for control of powered limb prostheses. *J Electromyogr Kinesiol, 16*(6), 541-548. doi: 10.1016/j.jelekin.2006.08.006

Plemons, J. K., Willis, S. L., & Baltes, P. B. (1978). Modifiability of fluid intelligence in aging: a short-term longitudinal training approach. *J Gerontol, 33*(2), 224-231.

Plettenburg, D. H. (1998). *Basic requirements for upper extremity prostheses: The Wilmer approach.* Paper presented at the Engineering in Medicine and Biology Society, 1998. Proceedings of the 20th Annual International Conference of the IEEE.

Popov, B. (1965). The bio-electrically controlled prosthesis. *J Bone Joint Surg Br, 47*, 421-424.

Riso, R. R. (1999). Strategies for providing upper extremity amputees with tactile and hand position feedback–moving closer to the bionic arm. *Technology and Health Care, 7*(6), 401-409.

Santello, M., Flanders, M., & Soechting, J. F. (2002). Patterns of hand motion during grasping and the influence of sensory guidance. *The Journal of Neuroscience, 22*(4), 1426-1435.

Saunders, I., & Vijayakumar, S. (2011). The role of feed-forward and feedback processes for closed-loop prosthesis control. *Journal of neuroengineering and rehabilitation, 8*(1), 60.

Schieber, M. H., & Santello, M. (2004). Hand function: peripheral and central constraints on performance. *Journal of Applied Physiology, 96*(6), 2293-2300.

Scott, R. (1990). Feedback in myoelectric prostheses. *Clinical orthopaedics and related research, 256*, 58-63.

Scott, R., & Parker, P. (1988). Myoelectric prostheses: state of the art. *Journal of medical engineering & technology, 12*(4), 143-151.

Sears, H., Iversen, E., Archer, S., Linder, J., & Hays, K. (2008). *Grip Force Feedback in an Electric Hand-Preliminary Results*.

Shannon, G. F. (1976). A comparison of alternative means of providing sensory feedback on upper limb prostheses. *Medical and biological engineering, 14*(3), 289-294. doi: 10.1007/bf02478123

Shaperman, J., Landsberger, S. E., & Yoshio, S. (2003). Early Upper Limb Prosthesis Fitting: When and What Do We Fit. *Journal of Prosthetics and Orthotics, 15*(1), 11.

Shaperman, J., Setoguchi, Y., & LeBlanc, M. (1992). Upper limb strength of young limb deficient children as a factor in using body powered terminal devices: A pilot study. *J Assoc Child Prosthet Orthot Clin, 27*(3), 89-96.

Simpson, D., & Kenworthy, G. (1973). The design of a complete arm prosthesis. *Biomedical engineering, 8*(2), 56-59.

Smit, G., Bongers, R. M., Van der Sluis, C. K., & Plettenburg, D. H. (2012). Efficiency of voluntary opening hand and hook prosthetic devices, 24 years of development? *JRRD: Journal of Rehabilitation Research & Development, 49 (4), 2012*.

Smit, G., & Plettenburg, D. H. (2010). Efficiency of voluntary closing hand and hook prostheses. *Prosthetics and orthotics international, 34*(4), 411-427.

Smit, G., Plettenburg, D. H., & van der Helm, F. C. (2015). The Lightweight Delft Cylinder Hand: First Multi-Articulating Hand That Meets the Basic User Requirements. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 23*(3), 431-440.

Taylor, C. L. (1954). The biomechanics of the normal and of the amputated upper extremity. *Human limbs and their substitutes*, 169-221.

Taylor, C. L. (1955). *The biomechanics of control in upper-extremity prostheses*: National Academy of Sciences.

Taylor, C. L., & Schwarz, R. J. (1955). The anatomy and mechanics of the human hand. *Artif Limbs, 2*(2), 22-35.

The National Amputee Statistical Database Annual Reports. (2004). Edinburgh.

Trost, F. J. (1983). A comparison of conventional and myoelectric below-elbow prosthetic use. *Inter-Clinic Information Bulletin Vol. 18*.

Ungerleider, L. G., Doyon, J., & Karni, A. (2002). Imaging brain plasticity during motor skill learning. *Neurobiology of learning and memory, 78*(3), 553-564.

Van Der Niet Otr, O., Reinders-Messelink, H. A., Bongers, R. M., Bouwsema, H., & Van Der Sluis, C. K. (2010). The i-LIMB Hand and the DMC Plus Hand Compared: A Case Report. *Prosthetics and orthotics international, 34*(2), 216-220. doi: 10.3109/03093641003767207

van Duinen, H., & Gandevia, S. C. (2011). Constraints for control of the human hand. *The Journal of physiology, 589*(23), 5583-5593.

Van Lunteren, A., & van Lunteren-Gerritsen, G. (1989). On the use of prostheses by children with a unilateral congenital forearm defect. *J Rehabil Sci, 2*(1), 10-12.

Verhaeghen, P., Marcoen, A., & Goossens, L. (1992). Improving memory performance in the aged through mnemonic training: a meta-analytic study. *Psychol Aging, 7*(2), 242-251.

Watve, S., Dodd, G., MacDonald, R., & Stoppard, E. R. (2011). Upper limb prosthetic rehabilitation. *Orthopaedics and Trauma, 25*(2), 135-142. doi: http://dx.doi.org/10.1016/j.mporth.2010.10.003

Weir, R. F., Troyk, P. R., DeMichele, G. A., Kerns, D. A., Schorsch, J. F., & Maas, H. (2009). Implantable myoelectric sensors (IMESs) for intramuscular electromyogram recording. *IEEE Trans Biomed Eng, 56*(1), 159-171. doi: 10.1109/tbme.2008.2005942

Wiener, J. M., Hanley, R. J., Clark, R., & Van Nostrand, J. F. (1990). Measuring the Activities of Daily Living: Comparisons Across National Surveys. *Journal of Gerontology, 45*(6), S229-S237. doi: 10.1093/geronj/45.6.S229

Willis, S. L., Tennstedt, S. L., Marsiske, M., Ball, K., Elias, J., Koepke, K. M., . . . Wright, E. (2006). Long-term effects of cognitive training on everyday functional outcomes in older adults. *Jama, 296*(23), 2805-2814. doi: 10.1001/jama.296.23.2805

Xiong, C.-H., Li, Y.-F., Ding, H., & Xiong, Y.-L. (1999). On the dynamic stability of grasping. *The International Journal of Robotics Research, 18*(9), 951-958.

Xiong, C., Ding, H., & Xiong, Y.-L. (2007). *Fundamentals of Robotic Grasping and Fixturing* (Vol. 3): World Scientific.

Zollo, L., Roccella, S., Guglielmelli, E., Carrozza, M. C., & Dario, P. (2007). Biomechatronic design and control of an anthropomorphic artificial hand for prosthetic and robotic applications. *IEEE/ASME Transactions On Mechatronics, 12*(4), 418-429.

Zuo, K. J., & Olson, J. L. (2014). The evolution of functional hand replacement: From iron prostheses to hand transplantation. *Plastic Surgery, 22*(1), 44-51.