THUMB-TIP FORCE PREDICTION BASED ON HILL'S MUSCLE MODEL USING NON-INVASIVE ELECTROMYOGRAM AND ULTRASOUND SIGNALS

BY

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ABSTRACT

Restoring human limb that is lost during accident with prostheses is one challenging issue in engineering field. The loss of human limb, involving upper and lower limbs leaves great impact on human that it limits daily activities in many ways. There are many studies that have been done previously in making and improving prosthetic unit for amputees. Most of them are made to replicate the basic functionalities of the missing limbs and adopt more conventional passive controllers. As a result, the prosthetic unit range of motion is limited and the motion is unnatural. Hence, there is a need to develop model based controller for such system to address the problems. The goal of the research is to develop a semi-analytical model of a thumb that could be used to develop a model based controller. In this work, the information from the muscle characteristics is gathered. The electromyography signals from the four muscles responsible on thumb flexion are measured and recorded using biosignal measurement system. The thumb tip force is measured using thumb training system developed for the research. On top, information such as the length of the muscles and tendons is collected from the ultrasound probe and magnetic resonance imaging (MRI) machine to increase the data accuracy. These data are fed into Hill's muscle model and optimized by the particle swarm optimization (PSO) technique to map the relationship between thumb posture, thumb tip force and all the signals measured. The resulting thumb model developed using the method proposed in this research work has shown lower root mean square error (RMSE) as compared to previous method.

خلاصة البحث

ترميم جسم الإنسان المتعرض لحادث عن طريق إضافة أطراف اصطناعية يعد أحد القضايا الأكثر تحديا في مجال الهندسة. إن فقدان أجزاء من جسم الإنسان، سواء أكانت الأطراف العلوية أو السفلية يترك أثراً كبيرا على الإنسان نفسه، يظهر جليا في الحد من الأنشطة اليومية في نواح كثيرة. هناك العديد من الدراسات التي أجريت سابقا حول تصنيع وتحسين الأطراف الاصطناعية للمبتورين. ولقد صُنِّعَ معظمها لتكرار الوظائف الأساسية للأطراف المفقودة مع اعتماد وحدات التحكم السلبي التقليدية. ونتيجة لذلك، فإن نطاق الحركة للطرف الاصطناعي محدود، والحركة غير طبيعية. وبالتالي، هناك حاجة لتطوير وحدة تحكم على أساس نموذج لهذا النظام لمعالجة هذه لمشاكل. والهدف من هذا البحث، هو اقتراح نموذج شبه تحليلي للإبهام والذي يمكن استخدامه في تطوير وحدة تحكم على أساس نموذج. في هذا العمل، يتم جمع المعلومات المتعلقة بخصائص العضلات. ويتم قياس وتسجيل الإشارات الكهربائية من العضلات الأربعة المسؤولة عن ثني الإبهام وتسجيلها باستخدام نظام قياس الإشارات الحيوية. يتم قياس قوة طرف الإبهام باستخدام نظام تدريب الإبهام المطور خصيصا لهذا البحث. بالإضافة إلى ما سبق، يتم جمع المعلومات المتعلقة بطول العضلات والأوتار عن طريق لاقط الموجات فوق الصوتية وآلة اتصوير بالرنين المغناطيسي (MRI) لزيادة دقة البيانات. يتم تغذية هذه البيانات في نموذج هيل للعضلات (HILL'S MUSCLE MODEL) واستمثالها من خلال تقنية استمثال سرب الذرات (PARTICLE SWARM OPTIMIZATION PSO) لتعيين العلاقة بين هيئة الإبهام، قوة طرف الإبهام، وكل الإشارات التي تم قياسها. وقد أظهر نموذج الإبهام الناتج باستخدام الطريقة المقترحة دقة أفضل بالمقارنة مع الطريقة السابقة.

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APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Mechatronics Engineering.

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Muhammad Rozaidi Bin Roslan

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To my beloved family, teachers and friends who have provided valuable assistance

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In the name of Allah, the most compassionate and the most merciful,

I would like to take this opportunity to express my sincere appreciation and gratitude to my supervisor – Dr Sharul Na'im Sidek for his guidance, suggestions, critical comments and support which has enabled me to develop my research skills and complete this thesis.

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LIST OF ABBREVIATIONS

A/D	Analog to digital
ADL	Activity of daily activities
ANN	Artificial neural network
AP	Adductor Pollicis muscle
AP	Action potential
APB	Abductor Pollicis Brevis muscle
APL	Abductor Pollicis Longus muscle
APL	The John Hopkins University Applied Physics Laboratory
CE	Contractile element
CSA	Cross sectional area
DARPA	Defense Advanced Research Projects Agency
DASDV	Difference absolute standard deviation
EMG	Electromyogram
EPB	Extensor Pollicis Brevis muscle
EPL	Extensor Pollicis Longus muscle
FDI	First Dorsal Interosseous muscle
FFT	Fast Fourier transform
FPB	Flexor Pollicis Brevis muscle
FPL	Flexor Pollicis Longus muscle
IP	Interference pattern
MAV	Moving average
MDF	Median frequency
MNF	Mean frequency
MNP	Mean power
MRI	Magnetic resonance imaging

MU	Motor units
MUAP	Motor unit action potentials
MPL	Modular Prosthetic Limb
OP	Opponens Pollicis muscle
PART	Partial decision tree
PEE	Parallel elastic element
PSO	Particle Swarm Optimization
RMSE	Root mean square error
ROM	Range of motion
SEE	Serial elastic element
sEMG	Surface electromyography
SVM	Support vector machine
VC	Vapnik Chervonenkis dimension
WAMP	Willison amplitude
WL	Wavefor m length

LIST OF SYMBOLS

A	Degree of nonlinearity
$a(t)$	Muscle activation level
f_1	Force length function
F_{CE}	Force of contractile element
$F_{CE_{max}}$	Maximum force of contractile element
F_{PE}	Force of parallel element
$F_{PE_{max}}$	Maximum force of parallel element
F_{muscle}	Force of a muscle
$F_{thumb-tip}$	Thumb-tip force
K	Gain of muscle
L_{CE_0}	Optimum length of contractile element
L_{max}	Maximum length of muscle
L_{ts}	Tendon slack length of muscle
S	Shape parameter
$s(n)$	Signal data
$u(t)$	Normalized processed EMG signals
ΔL_{CE}	Different in length of contractile element
ΔL_{PE}	Different in length of parallel element
$\Delta L_{PE_{max}}$	Maximum different in length of parallel element
$\emptyset$	Gaussian distribution

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

In doing activities for daily living, human hand has work in such wonders. The design of human's hand is complex and its dexterity allows human race to improve themselves. Hand is composed of wrist, palm and five fingers which are thumb, index, middle, ring and little fingers. There are many muscles responsible and work in unison to move a particular finger. Thumb is a unique finger compared to other fingers as it works as an opposable digit to all other fingers. There are nine muscles that control the movement of a thumb. Four of the muscles are located at the forearm and they are known as exterior muscles while the other five muscles are interior muscles and are located in the area of hand.

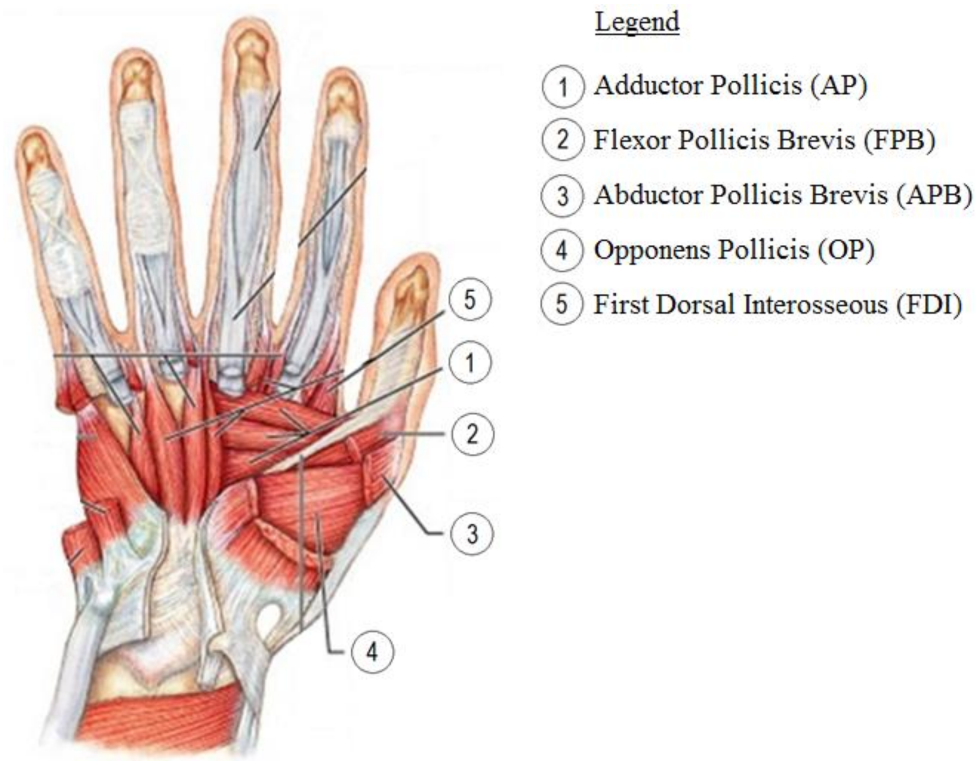

Figure 1.1: Thumb's muscles on human's hand

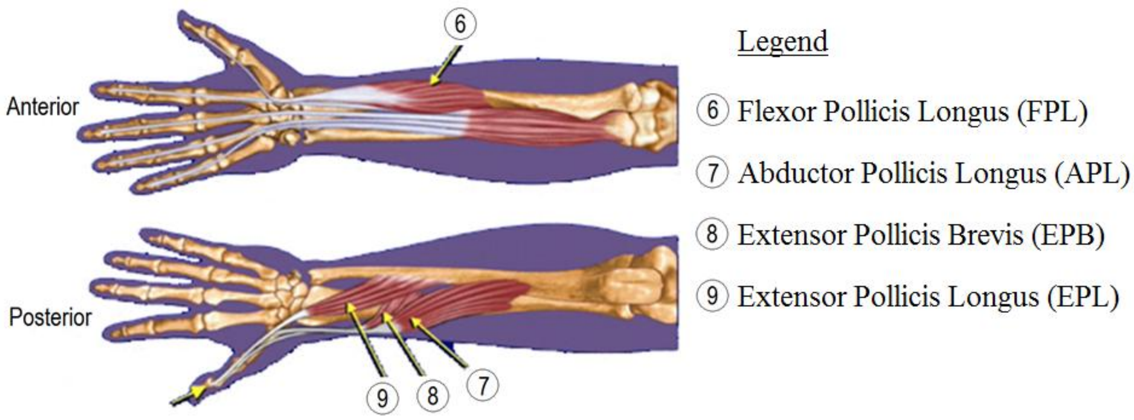

Figure 1.2: Extrinsic muscles of thumb

Figure 1.1 and Figure 1.2 depict all the muscles that are related to finger (thumb) movements. Figure 1.1 shows the location of the muscles on hand, they are Adductor Pollicis (AP), Flexor Pollicis Brevis (FPB), Abductor Pollicis Brevis (APB), Opponens Pollicis (OP) and First Dorsal Interosseous (FDI) which help moving the thumb and located on hand. From Figure 1.2 shown Flexor Pollicis Longus (FPL), Abductor Pollicis Longus (APL), Extensor Pollicis Brevis (EPB) and Extensor Pollicis Longus (EPL) which help moving thumb and resided on forearm.

The unique design and function of the thumb somehow can be greatly affected by traumatic accidents or diseases that could result in thumb amputation or paralysis. The functionality of the thumb and hand would deteriorate, and thus, would cost lack of performance in the activities of daily living (ADL).

The number of road accidents was in an alarming rate which according to Malaysian Institute of Road Safety Research (MIROS, 2015), more than 25 million registered vehicles were involved in road accidents through the year of 2014. Some road accidents affected the upper extremities including thumb which is vital for job implementations that require precise hand coordination. The effects of losing parts of the body or its functions may result in unemployment or if there is a job vacancy, jobs offered may be unrelated to one's passion and would eventually lead patient to a great depression.

For most of the cases, medical treatment cannot restore the function of the hand, thus the only alternative for the patient is to use prosthetic hand. Many commercial prosthetic hands can be found commanded by mechanical movement, switches and force sensitive devices on hand to move the fingers and forearm. More recent prosthetic hand leveraged on the sensed Electromyogram (EMG) signals generated by the muscle left after amputation. The EMG signals are sensed through electrode pad, and the microprocessor processes the signal activation and command the actuator accordingly.

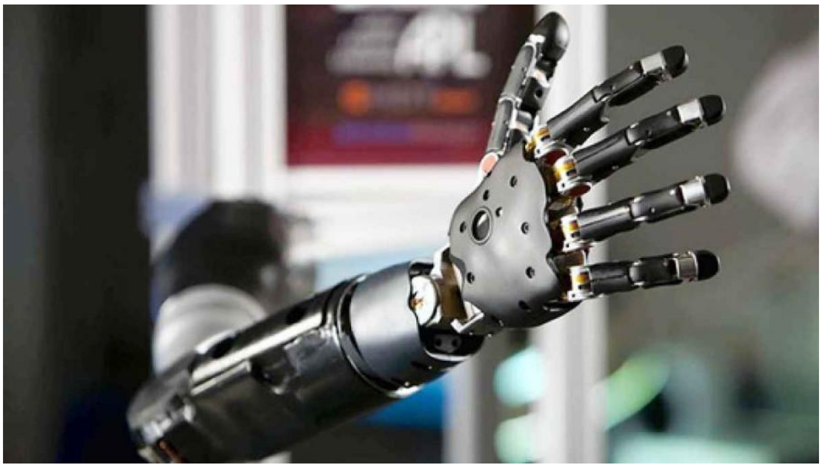

Figure 1.3: DARPA's prosthetic hand, Modular Prosthetic Limb (MPL)

There are several prosthetic hands that are based on EMG signals available. The latest prosthesis sponsored by Defense Advanced Research Projects Agency (DARPA), Modular Prosthetic Limb (MPL) is shown in Figure 1.3, it was co-developed and led by The John Hopkins University Applied Physics Laboratory (APL). The distinctive features of the design include MPL control system modalities that consist of reduction in order control, Cartesian, joint and muscle space control.

The MPL control system modalities are designed to maximize the patient's interface flexibility and modalities control that is available. Reduction in order of control that is part of MPL control system modalities allows mapping of suitable formation of fingers' position although the patients does not control all the degree of freedom (DOF) that are available on the MPL. The Cartesian space control correlates the motor cortex of human brain with the hand position's movements. The joint space control allows the patients to move an individual joint in a time. The muscle space control allows control from peripheral nerve signals to move a joint into a direction commanded.

The APL is working hard in envisioning an advance prosthetic hand that can be controlled solely by thoughts and can mimic real muscle movements (Michael M. Bridges et al., 2011).

There was a previous work done on thumb-tip force model which used Hill's muscle model (Won-II Park et al., 2012). This study reported thumb mathematical modelling, but using marker on skin surface to predict length of muscle and since the reading is based on the estimated value, the accuracy of the final model can be further improved. The markers are attached on the skin of subject and cameras captured the images of the markers' position and the images were processed by computer to predict the position of the muscles and the length of each muscle. Markers usually used to locate the position of human body in space at specific period either for body motions (Roy Tranberg, 2010) and for joint rotations (E. Ceseracciu et al., 2014). Other method of measuring muscle must be proposed in this research work in order to collect a better data.

In order to have precise control on prosthetic hand like one similar to natural body movement, concept of mathematical modelling that assigns input variables related to a system and correlate them to the predicted output can be employed. The system is designed with variables and constant that can be controlled or fixed in order to achieve the output targeted. The modelling saves a lot of cost in development as by using calculation and simulation, it allows better comprehension on the system that will be built later on. In modeling muscles, Hill’s muscle model is often being used because of its simplification and effectiveness. Other mathematical models of the same functionality include Huxleys, Ogden, Monte, Carlo, Kevin and Katnelson.

The research on thumb modelling is still new and previous prosthetic hands such as Bebionic and i-limb are on low level controller where the controller is still depending on sets of pre-defined functions and unable to do vast possible motions and configurations of fingers and thumb. The Bebionic and i-limb use this approach to simplify the process of the controller. To improve current controller of prosthetic hand, studies on the relationship of the EMG signal to the characteristics of each individual muscle need to be done, then analytical model of thumb-tip force can be developed. This model can be used to develop model-based controller for the thumb of prosthetic hands.

1.2 ELECTROMYOGRAM SIGNAL PHYSIOLOGY

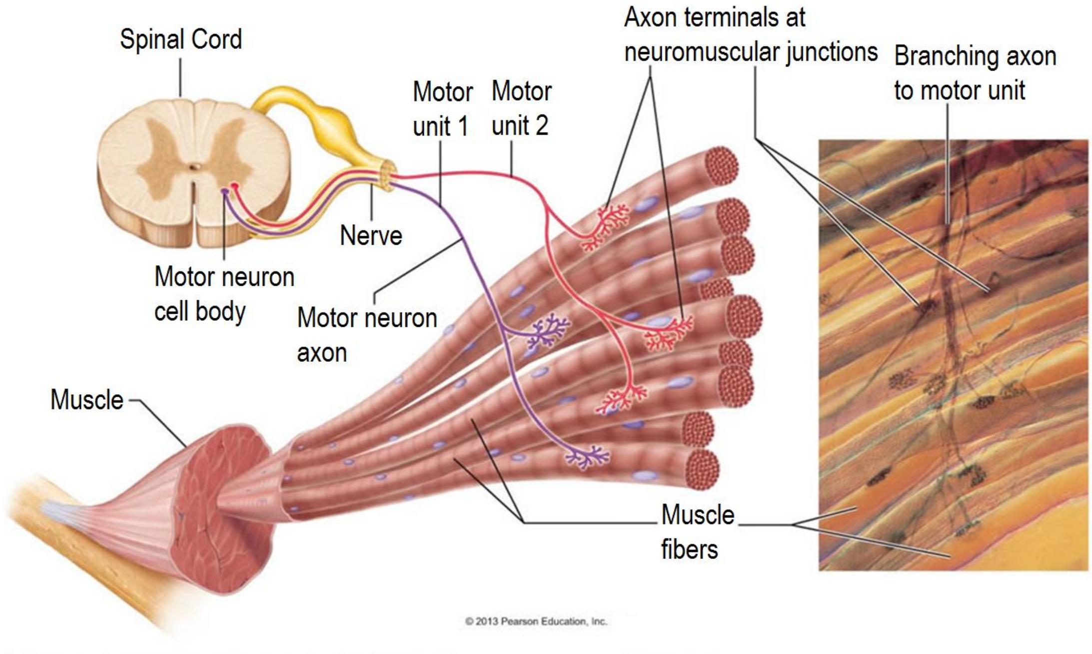

Figure 1.4: Neural path to muscle (Pearson Education, 2013)

The electromyogram (EMG) signal is an electrical signal produced when muscle contracts and it shows a representation of neuromuscular activity. In a bunch of muscles cells, there are many Motor Units (MUs) on the surface of skin used by electrodes to read Motor Unit Action Potentials (MUAP) together with noise. By increasing the muscle force through muscle contraction, the MUAP and the firing rates increased thus produce Interference Pattern (IP). The firing pulses are taken as a random function of time and it is non-Gaussian (Akash Kumar Bhoi, 2012). Figure 1.4 shows the source of EMG signals of muscles which are originated from nerves that carry electrical signals sourced from brain through spinal cord to the respective muscles.

In 1922, researchers found that oscilloscope can display electrical signals generated by muscles. This was the starting point where interfacing of electronics with human body made possible. However, limited amount of information can be extracted from the EMG signals since it is stochastic or random in nature (Raez, Hussain and Yasin 2006). Around 1930s to 1950s, the technique to measure EMG signals was improved much further. Clinical use for EMG signals started around 1960s. EMG activity was recorded by Hardyck, Petrinovich and Ellsworth from laryngeal which was a voice box muscle when a subject was reading aloud in 1966. Around 1980s, a smaller and lighter EMG measurement devices were produced (Raez et al., 2006). EMG signals continue usefulness its wonder when recently it was used to study and diagnose muscular dystrophy. It is also now being used widely in physiology, physiotherapy, motor control and biomechanics research in laboratories across the globe. EMG signals are now used to analyze muscle performance, muscle fatigueness and muscle diseases. Together with technology that is ever growing, the robotics is now combined with electromyography to help replace limb of amputees with prostheses.

Figure 1.5: g.USBamp device, biosignal amplifier

In recording the data of EMG signals from targeted muscles, EMG signal amplifier; g.USBamp biosignal amplifier was used in the work as depicted in Figure