INTENTION-DRIVEN ROBOTIC HAND REHABILITATION SYSTEM WITH INDIVIDUATED FINGER TRAINING FEATURE

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Intention-driven Robotic Hand Rehabilitation System with Individuated Finger Training Feature

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Certificate of Originality

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

__________________________ (Signed)

Evan Aditya Susanto (Name of student)

Declaration

I hereby declare that the original mechanical design of the hand exoskeleton robot used in this study, and its control system (both hardware and software) have been developed by Prof. Raymond K.Y. Tong and his team prior to the commencement of my PhD study. I, nevertheless, made all the modifications necessary both on the hardware and the software to allow specific finger control and measurement to suit the system for the study.

I also declare that all the other aspects of the study: the experimental design, software programs, data collection, data analysis, and other procedures described in this thesis were done by me with guidance from Prof. Raymond K.Y. Tong and some assistance from Mr. Newmen S.K. Ho (electronic design) and Miss Corinna Ockenfeld (data collection).

Abstract

Stroke is one of the most prominent causes of disability in the world and is relatively prevalent as well. Many individuals become hemiplegic as a result of stroke; and in many cases, they become very dependent to others and require long term care and rehabilitation. Loss of hand function as a result of stroke is one of the most impactful consequences that hinder stroke survivors from doing their activities of daily living (ADL) by themselves.

Different rehabilitation techniques have been developed to tackle this issue; while some studies have shown consistent results to improve arm function, not many have consistently shown hand and finger functions recovery (Langhorne et al. 2009). Constraint-induced movement therapy (CIMT) and robot-assisted training are the only two so far that are considered more promising (Langhorne et al. 2011). CIMT, however, has been criticized for only able to cater very selective population of stroke survivors with higher level of residual function. Robot-assisted rehabilitation, on the other hand, has focused more on larger and more proximal joints, such as shoulder and elbow, due the technical difficulties to facilitate more degrees of freedom (DOFs) required in the more distal joints like the fingers.

This study aimed to: (1) extend the hand exoskeleton robot system previously developed by our group to allow force assessment and control of individual finger,

(2) investigate finger characteristics after stroke, and (3) conduct a pilot randomized-controlled trial (RCT) to investigate the efficacy of the training using the system. For those purposes, here we propose the development of a hand exoskeleton robot with individual finger feature to cater the need of having a robot-assisted rehabilitation with hand gestures training. The device is a 5-DOF hand exoskeleton robot with 5 independent linear actuators, capable of facilitating individual finger movement assistance whenever necessary. The device is equipped with force sensors to measure MCP and PIP joint moments of each finger. The stability, linearity, and reliability of the joint moments measurement was tested and verified.

A preliminary study with six right hemiplegic, right-hand dominant, stroke survivors and six age-matched neurologically intact control subjects was conducted to provide brief information about muscle weakness and finger individuality after stroke. Results showed decreased muscle strength and finger individuality post stroke. Additionally, it was also revealed that finger flexion individuality correlated very well with the functional ability reflected by the clinical scores (Pearson's $r > 0.9$ for its correlations with ARAT and WMFT scores).

In the next part of my study, a pilot randomized-controlled trial with 19 chronic stroke subjects (14 males and 5 females, aged 53.2 ± 9.9 years old) was conducted.

The subjects were randomly distributed into two groups: the robot-assisted (robot) group or the non-assisted (control) group. Each subject was required to complete 20 one-hour sessions of the designated training. All subjects, regardless of the grouping, were to do the same task: moving a sponge with three different grips, i.e. hand grasp, three-finger pinch, and two-finger pinch. The robot group received intention-driven assistance from the device, while the control group was given no assistance as the linear actuators were detached from the device. The results showed that the robot group maintained its significant improvement of hand and upper limb functions 6 months after the training, indicated by improved ARAT (mean change = 14.00±5.75, $p = 0.044$) and FMA-SE (mean change = 3.44±2.01, $p = 0.020$) scores, while the control group did not show any significant improvement at the same time point.

This suggested the potential efficacy of the training and the feasibility of using it in a clinical setting for after stroke upper limb rehabilitation. In the future, we are also exploring the possibility of using this training as a complement to CIMT, apart from being a standalone upper limb rehabilitation technique; allowing individuals with stroke to receive this intervention first when their functional ability has not match the requirement of CIMT and possibly enroll in CIMT provided that they improved enough following the proposed robot-assisted fingers rehabilitation.

List of Publications

Susanto, E. A., Tong, R. K. Y., Kamper, D. G., Zhang, M. (in preparation). Fingertip Trajectory Selection. *Experimental Brain Research*.

Susanto, E. A., Tong, R. K. Y., Ockenfeld, C., & Ho, N. S. K. (2015). Efficacy of robot-assisted fingers training in chronic stroke survivors: a pilot randomized-controlled trial. *Journal of Neuroengineering and Rehabilitation, 12*(1), 42.

Susanto, E. A., Tong, R. K. Y., & Ho, N. S. K. (2015). Hand exoskeleton robot for assessing hand and finger motor impairment after stroke. *HKIE Transactions, 22*(2), 78–87.

Hu, X. L., Tong, K. Y., Wei, X. J., Rong, W., **Susanto, E. A.,** & Ho, S. K. (2013). The effects of post-stroke upper-limb training with an electromyography (EMG)-driven hand robot. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *23*(5), 1065–74.

Susanto, E. A., Tong, R. K. Y., Ho, N. S. K., & Hu, X. (2012). Hand Exoskeleton Robot as a Force Measurement Tool. In *The 9th IASTED International Conference on Biomedical Engineering*. Innsbruck, Austria: ACTAPRESS.*(with oral presentation)*

Ho, N. S. K., Tong, K. Y., Hu, X. L., Fung, K. L., Wei, X. J., Rong, W., & **Susanto, E. A.** (2011). An EMG-driven exoskeleton hand robotic training device on chronic stroke subjects: task training system for stroke rehabilitation. *IEEE ... International Conference on Rehabilitation Robotics : [proceedings], 2011.*

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First, I would like to thank God for all His grace and blessings, with which I am finally able to successfully complete this journey.

Just like many other PhD candidates before me, I started this journey towards obtaining my PhD degree not knowing the impact it would bring to my life. This journey has far been one of the most rewarding experiences I have ever had. Never have I imagined how this would dramatically alter the way I think and shape me to be the better researcher and the better person I am. As rewarding as it is for me, this has also been one of the most challenging journey in my life; one I could never accomplished without the encouragement and support from my family, friends, colleagues, and mentors.

I am and will forever be grateful to my supervisors, Prof. Raymond Tong and Prof. Ming Zhang, for the opportunity and guidance given to me. Throughout my 4 years of study, they have been great mentors for me; always providing great insights and advices to support my growth, both as a scientist and as a human being.

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While five months is really not a long time, my exchange at the Rehabilitation Institute of Chicago has been one of the most impactful experiences I have ever had. My sincere gratitude goes to Dr. Derek Kamper for his unwavering support and guidance. To him, and to Dr. Chris Jones, Dr. Dan Qiu, and Mr. Kai Qian, I would also like to express my earnest gratitude for the fascinating discussions we have and for the insights they share with me during my time there.

I would like to thank to all my friends for the encouragement, support, and care, without which this accomplishment would not be possible.

Last but definitely not least, for my parents and my three sisters, words could never describe how grateful and thankful I am to be your son and brother. I will always remember your selfless sacrifice that allowed me to pursue and complete this path. All these would not be possible without your unyielding prayers and support.

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6Mo	Six-month follow-up assessment
APB	Abductor pollicis brevis
ARAT	Action research arm test
BIC	Biceps brachii
CIMT	Constraint-induced movement therapy
CMC	Carpometacarpal joint
CPM	Continuous passive motion
CVA	Cerebrovascular accident
DIP	Distal interphalangeal joint
DOF	Degree(s) of freedom
ED	Extensor digitorum
EMG	Electromyogram
FCR	Flexor carpi radialis
FCU	Flexor carpi ulnaris
FDI	First dorsal interosseous
FDP	Flexor digitorum profundus
FDS	Flexor digitorum superficialis
FMA	Fugl-Meyer assessment

FMA-SE	Fugl-Meyer assessment (shoulder and elbow subscore)
FMA-WH	Fugl-Meyer assessment (wrist and hand subscore)
fMRI	Functional magnetic resonance imaging
FPB	Flexor pollicis brevis
HandSOME	Hand spring operated movement enhancer
HEXORR	Hand exoskeleton rehabilitation robot
HWARD	Hand wrist assistive rehabilitation device
IP	Interphalangeal joint
M1	Primary motor cortex
MCP	Metacarpophalangeal joint
MCID	Minimal clinically important difference
MDC	Minimal detectable change
MMSE	Mini mental state examination
MPB	Middle phalanx bar
MSS	Motor status scale
MVC	Maximum voluntary contraction
MVT	Maximum voluntary torque
PIP	Proximal interphalangeal joint
Post	Post-intervention assessment

PPB	Proximal phalanx bar
Pre1	First pre-intervention assessment
Pre2	Second pre-intervention assessment
RCT	Randomized controlled trial
ROM	Range of motion
TMC	Trapeziometacarpal joint
TMS	Transcranial magnetic stimulation
TRI	Triceps brachii
VR	Virtual reality
WMFT	Wolf motor function test
WMFT-FT	Wolf motor function test (functional tasks subscore)

Chapter 1

Introduction

1.1. Background

Stroke, also referred as cerebrovascular accident (CVA), occurs when there is a disturbance of the blood supply to the brain either due to blockage or leakage of blood flow. This causes lack of oxygen in the brain and subsequently damage to the brain itself. Individuals with stroke often experience hemiplegia with different levels of severity. Because of that, for stroke survivors, the occurrence of CVA can actually change their lives completely; with many of them losing their independency and start to rely on others to take care of themselves and do things they used to do by themselves previously.

One main factor affecting the independency of stroke patients the residual function of their hand and fingers (Nudo et al. 2001; Popovic et al. 2002). For daily activities, different types of hand and finger movements are very important. Lateral pinch, for example, is one very useful fingers' motion that is used normally for holding spoon and/or fork during self-feeding, holding pen during writing, etc. The extent to which CVA affect the motor function of the upper limb, in particular hand and fingers, thus becomes a major factor defining the independency level of the stroke survivors.

In relation to that, unfortunately, only 50% of stroke survivors are likely to regain some upper limbs functions (Broeks et al. 1999). While stroke is known to produce weaknesses in affected side of the survivor's body in general, distal muscles normally experience a more profound weakness when compared to more proximal muscles; causing finger movements to be predominantly weak (Colebatch & Gandevia 1989). Apart from weakness, a more essential issue in regards to finger characteristics after stroke is the control. Brunstrom and Zackowski et al mention that voluntary finger movement on stroke survivors are often accompanied by abnormal synergy of adjacent digits, wrist, elbow, and even shoulder (Brunnström 1970; Zackowski et al. 2004); making it very difficult for them to perform useful hand and finger functions that can enhance their independency level significantly.

A proposed reason for this phenomena is that hand and finger functions are not directly promoted by the increase in pure muscle force as they are for shoulder and elbow functions, but instead are more related to the coordination of the different muscles controlling the hand and its each digits (Lang & Schieber 2003; Raghavan et al. 2006). This argument is supported by the fact that abnormal synergy prevents the individuation of finger movement controls and may be present even after muscle strength recovery (Schieber et al. 2009).

These subsequently result in the lower number of stroke patients who can lead an independent life. Thus, upper limb, in particular hand and finger, rehabilitation is significantly essential to help individuals with stroke to regain their independency. Several rehabilitation techniques for upper-limb following stroke have been developed over the past few decades. Two most promising ones of them are: constraint-induced movement therapy (CIMT) and robot-assisted rehabilitation (Langhorne et al. 2011).

CIMT is done by constraining the less affected arm while performing intensive training and forcing only the use of the more affected arm to complete the tasks (Taub et al. 1999). The promising results obtained by CIMT have been attributed to the reversal of the behaviorally reinforced learned non-use and the expansion of the contralateral cortical area due to repetitive movements of the affected limb (Taub et al. 2002; McIntyre et al. 2012). However, there have also been controversies due to the very selective subjects recruitment in many CIMT studies; due to the very stringent and rigorous nature of the training, only those who were considered to be able to withstand such training were recruited as the participants in many CIMT studies (Langhorne et al. 2009).

The use of robotic system for rehabilitation, meanwhile, has been implemented in the past few decades and has been useful for the physical therapists.

Rehabilitation robot itself is also an emerging research field, proven by the exponential increase of the number of journal papers on this field throughout the past five years (Marchal-Crespo & Reinkensmeyer 2009).

Different control algorithms were also developed and implemented in those rehabilitation robots. Three of the most commonly implemented control algorithms are: continuous passive motion (CPM), assistance strategies, and challenge-based strategies (Marchal-Crespo & Reinkensmeyer 2009). CPM-based systems provide mechanical assistance to the patient to perform some predefined motions without any voluntary input from the patient himself. Systems with assistance strategies require voluntary input from the patient as the driving force of the robot's mechanical assistance. Meanwhile, opposite to the former two, systems with challenge-based strategies give a predefined resistance against the intended motion instead of providing mechanical assistance. This is intended to help the users increasing the paretic muscle force involved in the motion.

Nevertheless, while many of these systems have been studied and proven to be effective in certain senses, most of them focus the rehabilitation on more proximal joints such as shoulder, elbow, and some on wrist joint (Maciejasz et al. 2014). Robotic system for stroke rehabilitation systems that focuses on finger rehabilitation is very few at the moment, not to mention those that provide a feasibility to train each finger individually. By 2010, there were only 30 devices focusing on hand rehabilitation, and only 8 of them had been clinically studied (Balasubramanian, Klein, et al. 2010). The lack of such device certainly should be addressed, considering that the learned non-use phenomenon could possibly be prevented by repetitive use of the distal part of the arm and hence keeping its representation in the cortex (Oujamaa et al. 2009). Two possible factors hindering the development of such device are: (1) the challenge in the design due to the complex nature of hand and finger movements and its relatively many DOFs; and (2) the difficulty of controlling those movements experienced by the stroke survivors.

Hence, an intention-driven robotic hand rehabilitation system with individuated finger training feature for stroke patients is proposed in this study. This system aims to be able to both: (1) prevent learned non-use by assisting rehabilitation on hand and fingers, and (2) facilitate rehabilitation program that can complement CIMT by covering wider stroke population with its lower requirements and yet could help stroke survivors to regain enough motor function to be enrolled in the more demanding CIMT.

1.2. Objectives

1) To extend the hand exoskeleton system previously developed by our group to allow force assessment and control of individual finger.
2) To investigate finger characteristics after stroke.
3) To conduct a pilot randomized controlled trial (RCT) and investigate the efficacy of the fingers training using the hand robotic system.

1.3. Thesis Outline

This dissertation provides in-depth description about the development of intention-driven robotic hand rehabilitation system with individuated finger training feature. More specifically, a review of available literatures related to the topic is made available in Chapter 2 of this dissertation. Chapter 3 describes in detail the development of the hand exoskeleton robot used in the study and provides an evaluation on the device finger force sensing performance in terms of stability, repeatability, and flexion-extension linearity.

In Chapter 4, the utilization of the device on both neurologically intact individuals and stroke survivors to study hand and finger characteristics after stroke is described. This is a preliminary study that was originally meant to assess the suitability of the device for such purposes. Chapter 5, meanwhile, describes the utilization of the device for another purpose, namely stroke rehabilitation. In this chapter, the concept of robot-assisted fingers training using the hand exoskeleton robot is proposed; and this concept is implemented by utilizing different hand gestures in a task-oriented training.

The findings of all the studies described in Chapter 3 to Chapter 5 are then discussed as one full story in Chapter 6. Conclusions of the study as well as suggestions for future research directions then follow in Chapter 7. Finally, the list of references and the appendices are provided at the very end of this dissertation.

Chapter 2

Literature Review

2.1. Stroke

Stroke, or often referred as cerebrovascular accident (CVA), is a condition where there is a rapid loss of brain functions caused by disturbance of blood supply to the brain; a condition that results in the affected area being unable to function properly anymore. Depending on the affected area, the effects of CVA can vary from just a mild disability to death; some most common effects are hemiplegia and inability to formulate speech. There are two kinds of CVA based on its cause: ischemic stroke and hemorrhagic stroke. Ischemic stroke is caused by a blockage of blood supply to the brain. This type of stroke is the most common one and constitutes to about 87% of the total stroke cases (Go et al. 2014). On the other hand, hemorrhagic stroke, that accounts for the rest 13% only (Go et al. 2014), is due to the existence of leakage of blood in the brain.

Apart from being one of the major causes of disability, stroke is also relatively prevalent. By 2010, in United States alone, an estimated number of about 6.8 million people have had a stroke, and 129,476 stroke-caused mortality has been recorded in the same year (Go et al. 2014). Every year, approximately 795,000 stroke attacks occurred (which means a stroke attack occurs every 40 seconds in US on average), with around 610,000 of which are first attacks (Go et al. 2014). Locally, in Hong Kong alone, the prevalence has increased more than 100% from 11,062 in 1981 to 26,150 in 2002 and has been steady at around 25,000 incidents per year since then (Hospital Authority Statistics and Workforce Planning Department 2008; Hospital Authority Statistics and Workforce Planning Department 2013; Hospital Authority Statistics and Workforce Planning Department 1998). Now altogether with the stroke mortality rate that fluctuates around the figure of 3,000 throughout the same period from 1981 to 2012 (Hospital Authority Statistics and Workforce Planning Department 1998; Hospital Authority Statistics and Workforce Planning Department 2008; Hospital Authority Statistics and Workforce Planning Department 2013), there is a strong indication of significant increase in the number of people living with disability due to CVA. With such condition we are having nowadays, the importance of stroke rehabilitation has unarguably become more and more prevalent.

2.2. Hand Neuromechanics

As this dissertation focuses on robot-assisted hand rehabilitation after stroke, it is important to first understand the neuromechanics of human hand.

2.2.1. Hand Anatomy

Human hand is a complex neuromechanical system consisting of about 27 bones (excluding sesamoid bone), 29 major joints, 34 intrinsic and extrinsic muscles, and innervated by 3 major nerves with more than 40 sensory and muscular branches. The 27 bones in the hand comprises 14 phalanges, 5 metacarpals, and 8 carpal bones (see Figure 2.1); and in addition to that, there are sesamoid bones whose number varies between individuals (Schmidt & Lanz 2004; Marieb 2003).

As can be seen as well in Figure 2.1 below, human thumb consist of two joints, namely metacarpophalangeal joint (MCP) and interphalangeal joint (IP), while each of the four fingers has 3 joints: metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP), and distal interphalangeal joint (DIP). Each of the four fingers has 4 degrees of freedom (DOF): 2 on the MCP and 1 on each of the IPs. Meanwhile, despite having fewer joints, the thumb has 5 DOFs, one more than the other fingers. This is due to the fact that the carpometacarpal (CMC) joint of the thumb, or also known as the trapeziometacarpal (TMC) joint, is taken into account when describing the movement of the thumb. This TMC joint is capable to perform pronation - supination movement in addition to flexion-extension and abduction-adductions; making a total of 5 DOFs on the thumb.

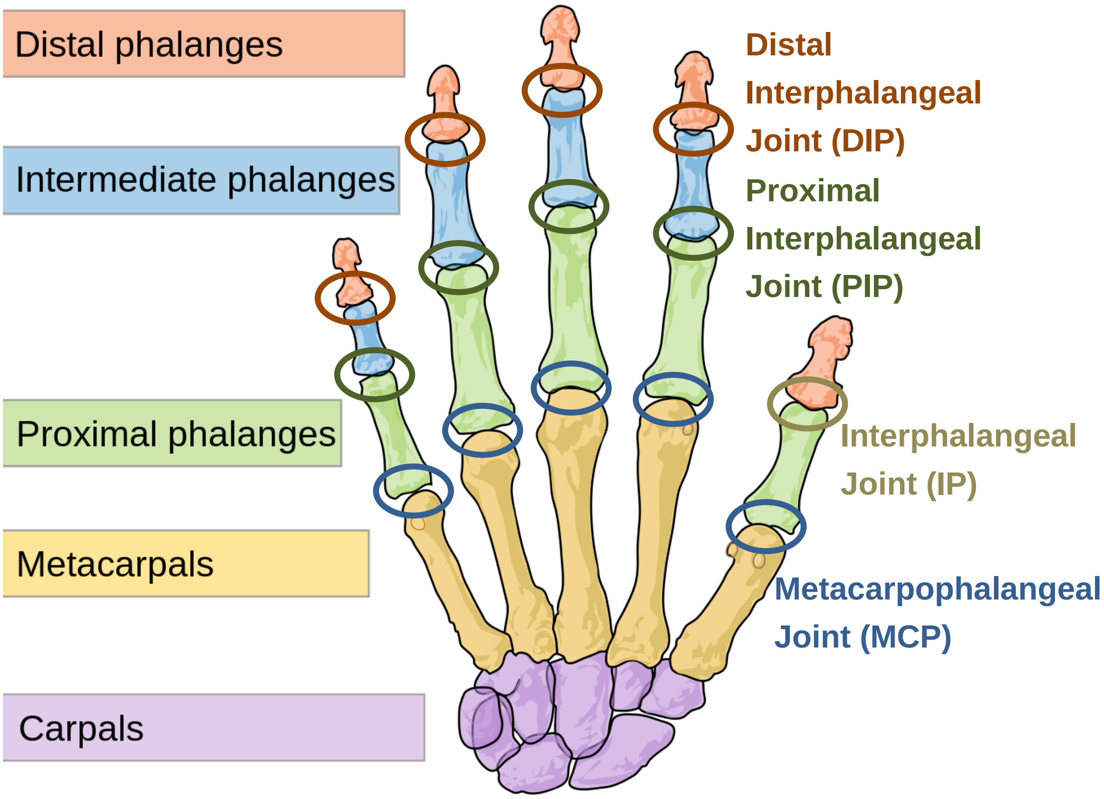


Figure 2.1. Bones and joints in human hand (adopted from *Wikimedia Commons* - by Mariana Ruiz Villarreal / modified from original with additional indicators and labels - http://commons.wikimedia.org/wiki/File:Scheme_human_hand_bones-en.svg).

Comprising five digits and having a cumulative of 21 DOFs, the complexity of our hand is virtually apparent. While theoretically each joint needs a pair of muscles for each DOF, it often is not the case in hand. For example, with 5 and 4 DOFs, respectively, for thumb and index finger, the hand only consists of 8 muscles to control the thumb and 7 muscles for the index finger; less than the theoretically necessary 10 and 8 muscles for thumb and index finger (Cooney et al. 1985). The implication of this is that it takes a combination of more than just two muscles to perform a single motion; increasing the complexity of the neuromechanical system of the hand.

Muscles controlling the hand, based on the location of their muscle belly, can be categorized into two: (1) extrinsic muscles, whose muscle belly is located on the forearm (see Figure 2.2), and (2) intrinsic muscles, whose belly is on the hand itself (see Figure 2.3). Some of the extrinsic muscles of interests are flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), flexor carpi ulnaris (FCU), flexor carpi radialis (FCR), and extensor digitorum (ED).

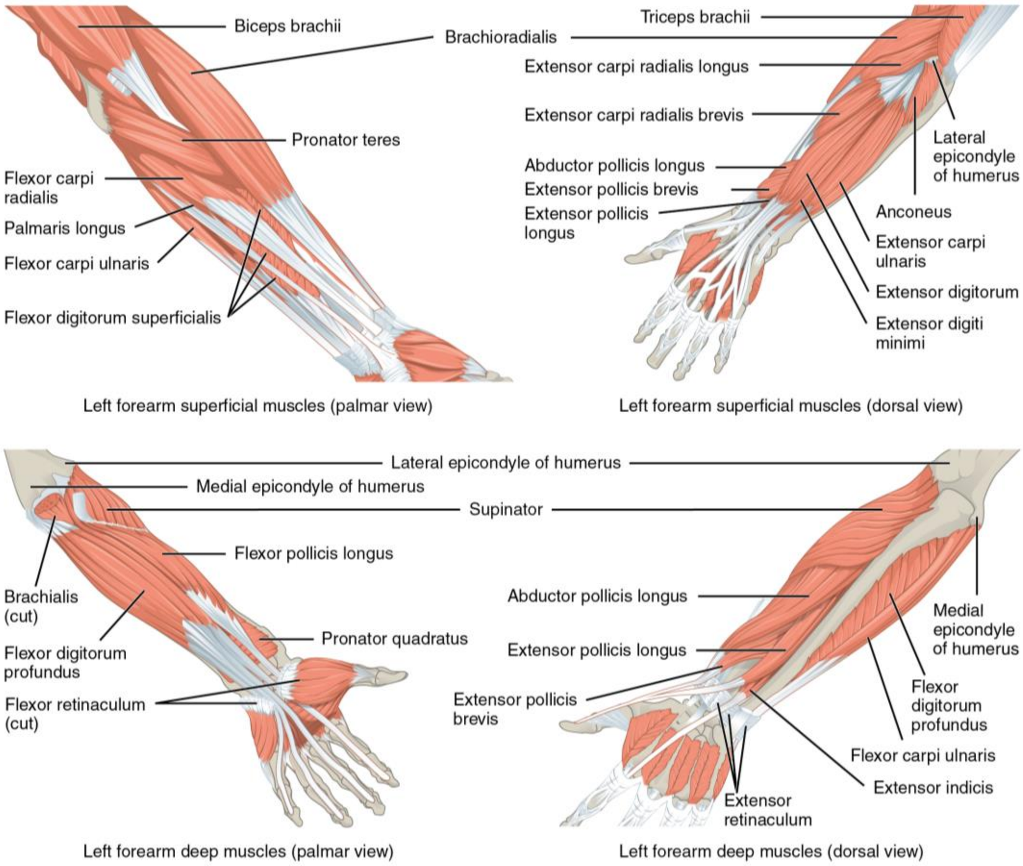


Figure 2.2. Extrinsic muscles of the hand (adopted from *Wikimedia Commons*- by CFCF / CC BY 3.0 / cropped from original - http://commons.wikimedia.org/wiki/File:1120_Muscles_that_Move_the_Forearm.jpg).

The FDS and FDP are the main flexors of the four fingers (except the thumb). Although their muscle bellies are located on the forearm, they both have long tendons that are connected all the way to the digit phalanges, enabling them to flex the four fingers. The FDP can be further divided into two: (1) the lateral aspect of FDP that connects to the index and middle fingers, and (2) the medial aspect of FDP that flexes the ring and little fingers. The FCU and FCR, meanwhile, are responsible for the ulnar and radial deviations of the wrist, respectively; and they both also flex the wrist. On the other hand, the ED is responsible for extending the four digits.

As for the thumb, its movements are mostly controlled by the intrinsic muscles, with some extrinsic muscles playing certain roles in its abduction and extension. Its flexion and abduction are mainly controlled by the flexor pollicis brevis (FPB) and abductor pollicis brevis (APB), respectively; and adductor pollicis muscle together with the first dorsal interosseous (FDI) muscle are responsible for its adduction.

All these muscles connect two bones and control the movement on the joint between the two bones by contracting and relaxing their fibers according to the commands received from the brain through the nerves that innervate them.

As can be seen in Figure 2.4, human hand is innervated by 3 nerves, namely median nerve, ulnar nerve, and radial nerve, each of which is responsible for different function of the hand. The median nerve mainly innervates muscles that are responsible for fine control of the hand, including but not limited to different kinds of pinches performed by the thumb, index finger, and middle finger. The FCR, FDS, and the lateral aspect of FDP are some of the muscles innervated by the median nerve. In contrast to that, the ulnar nerve innervates muscles like FCU and the medial aspect of FDP, which are responsible for power grasping. The radial nerve, on the other hand, is responsible for innervations of the wrist extensors, such as the ED, which stabilizes hand positions.

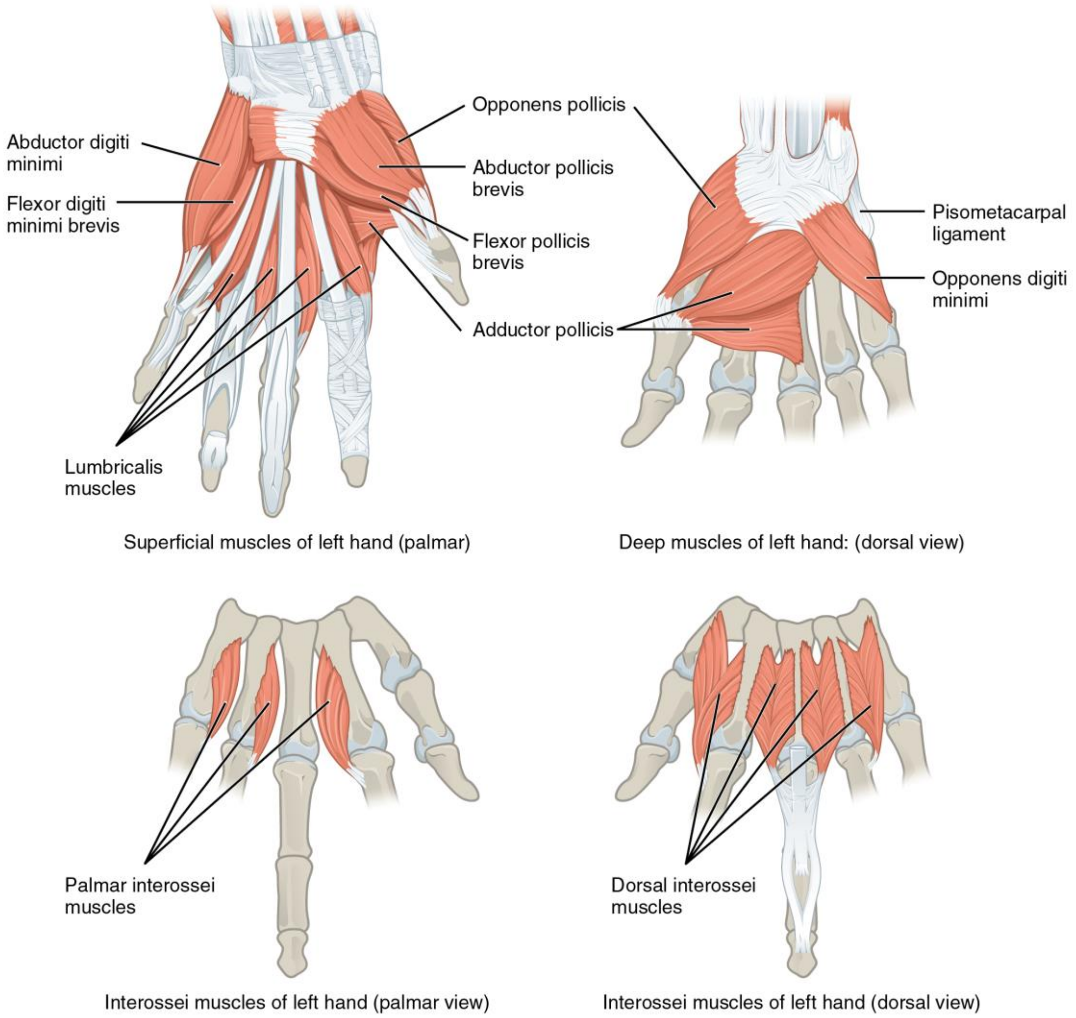


Figure 2.3. Intrinsic muscles of the hand (adopted from *Wikimedia Commons*- by CFCF / CC BY 3.0 - http://commons.wikimedia.org/wiki/File:1121_Intrinsic_Muscles_of_the_Hand.jpg).

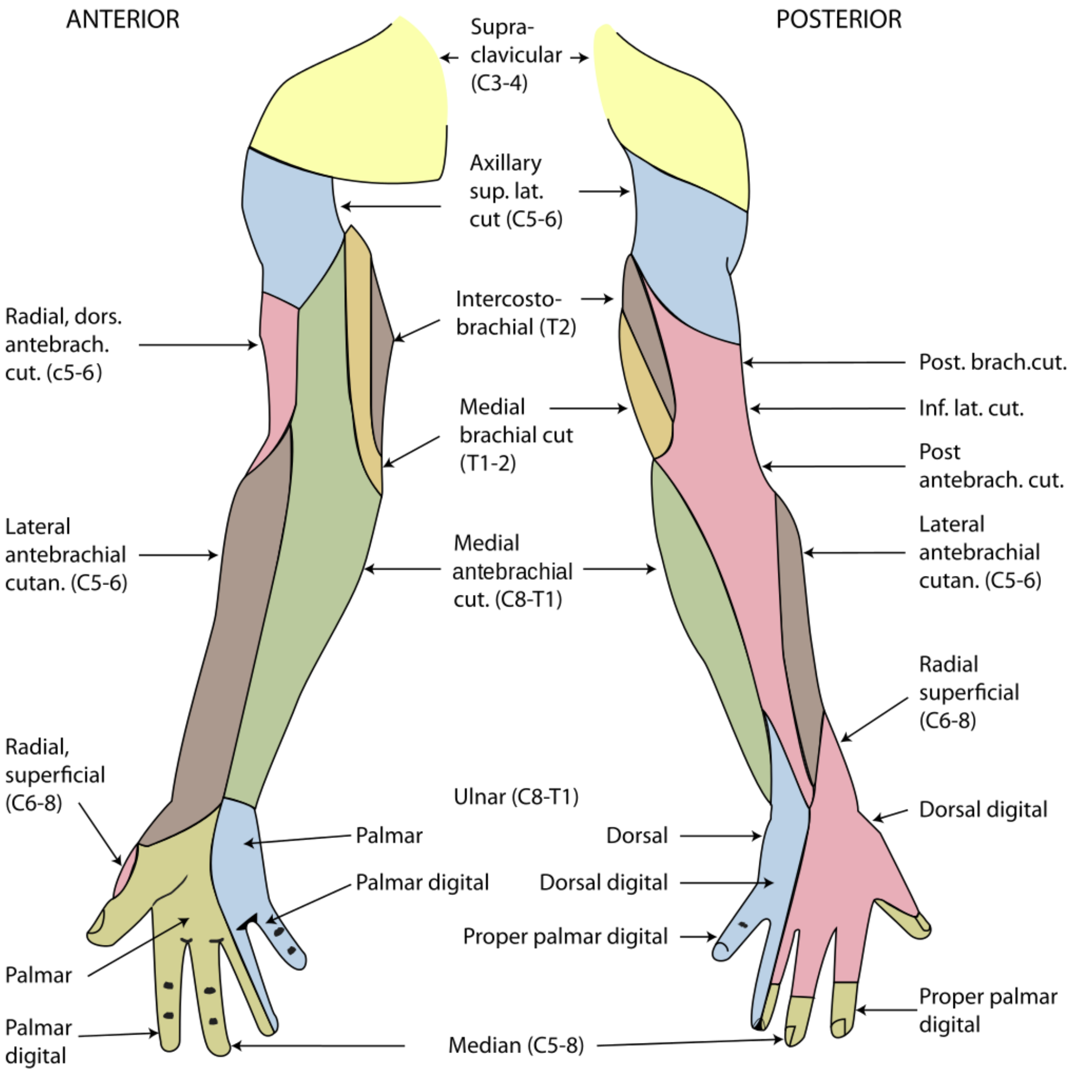


Figure 2.4. Innervation diagram of human (right) upper limb (adopted from *Wikimedia Commons* - by Mikael Häggström - http://commons.wikimedia.org/wiki/File:Gray812and814.png).

2.2.2. Nervous System Pathways

The nerves responsible for hand motor control, and particularly finger individuation, receive signals from a number of different neural pathways and there have been debates as to which neural pathways contribute to which properties of hand motor control.

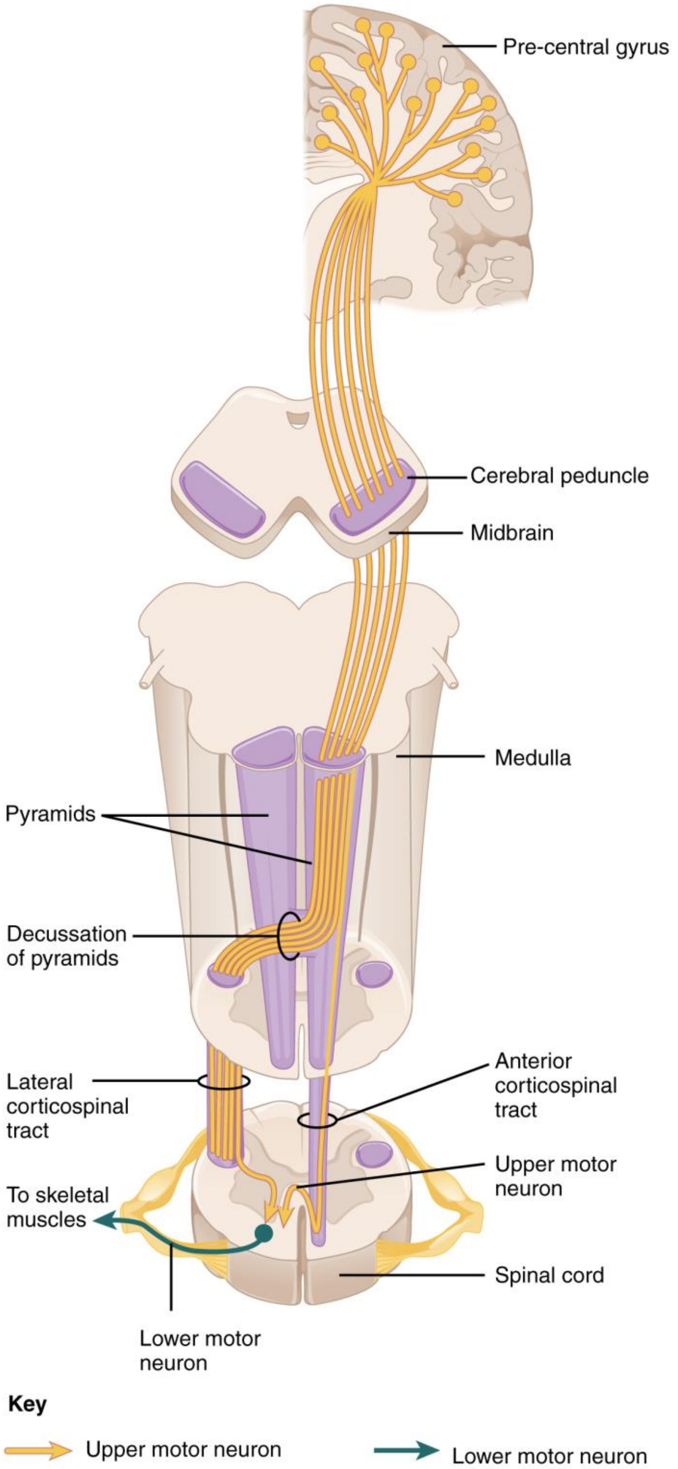


Figure 2.5. Corticospinal pathway (adopted from *Wikimedia Commons* - by CFCF / CC BY 3.0 - http://commons.wikimedia.org/wiki/File:1426_Corticospinal_Pathway.jpg).

One neural pathway that seems to be more widely accepted by most scientists to contribute in hand motor control, however, is the corticospinal tract, which is originated from the motor cortex, going through the medulla, where most of it crosses over to the lateral corticospinal tract, and ending up in the spinal cord (see Figure 2.5). Additionally, the corticospinal motor neurons have been found to have a direct synaptic connection to the alpha motor neurons for the fingers and thumb, which further emphasizes its role in the hand motor control.

In addition to the corticospinal tract, reticulospinal tract is known to play an important role in motor control as well. The reticulospinal tract can be further divided into two: medial (or pontine) and lateral (or medullary). The medial and lateral reticulospinal tracts are originated from the reticular formation in the brainstem across the pons and the medulla, respectively. Contrary to the corticospinal tract that mainly crosses over to the contralateral side, the reticulospinal tract mainly descends to the ipsilateral side although the lateral reticulospinal tract does descend bilaterally. These descending projections from the reticulospinal tract is responsible for mediation of postural control as well as facilitation and inhibition of voluntary movements (Siegel & Sapru 2010).

2.2.3. Finger Individuality

It has been known that human develop finger individuation over time. At birth, infants are only able to perform a reflexive whole hand grasp. The development of voluntary grasping after 2-3 months, digit individuation and fingers-thumb oppositions after 8 months, and full hand manipulation after 2 years then follows. Development of reaching-to-grasp coordination goes between 14 and 24 weeks, and development of fine digit manipulation continues until the age of 10 (Gordon 2001).

While the whole story is yet to be revealed, there have been quite a number of studies on finger individuation and its mechanisms. Danion et al. has shown that transcranial magnetic stimulation (TMS) on the cortical hand area of the primary motor cortex (M1) was able to increase individual finger force with a strong dependence on the background force of the instructed finger and with minimal to no dependence on the other fingers' forces (Danion et al. 2003). This ability of TMS to perform selective activation of individual digit suggests that the individuation control originates from the cortex.

Another study used functional magnetic resonance imaging (fMRI) to contrast the cortical activation pattern during synergistic task (with simultaneous flexion or extension on thumb and all fingers) to that during non-synergistic task (with thumb flexion performed simultaneously with fingers extension and vice versa). The results that revealed different activation pattern between suggest that, in addition to the primary motor cortex, there are other control mechanisms that might be involved in the control of finger individuation (Ehrsson et al. 2002).

2.3. Motor Deficits and Brain Plasticity after Stroke

Having understood the mechanics of the hand and the neural systems that controls the hand, here we will look into the impact of stroke on them.

2.3.1. Motor Deficits

Researchers have been extensively studying motor deficits after stroke both in upper limb as a whole and in hand and fingers specifically. It was revealed that stroke impaired its survivors' hand functionally and in some cases altered it structurally. Functionally, individuals with stroke suffer from hemiplegia and experience a significant reduction in their muscle strength (Kamper et al. 2003; Kamper et al. 2006; Triandafilou et al. 2011), loss of muscle coordination (Gowland et al. 1992), and more specifically, loss of finger dexterity and individuality (Nowak et al. 2007; Lang & Schieber 2003; Raghavan et al. 2006) on their affected side. Structurally, stroke may even cause muscle atrophy and may alter the biomechanics, fiber type, and fatty infiltration of the muscle (Kamper et al. 2001; Triandafilou & Kamper 2012). On top of that, stroke also alters reflexes in its survivors; inducing over-activity that results in spasticity (O'Dwyer et al. 1996; Kamper & Rymer 2000).

The stroke induced reduction in muscle strength, or often also referred as muscle weakness, is defined as the inability to produce enough tension in a muscle to perform a desired movement or maintain a certain posture, which subsequently also leads to motor impairment in many individuals with stroke (Ada et al. 2003; Chae et al. 2002). It has been suggested that muscle weakness is mainly caused by the inability to recruit sufficient skeletal motor units due to neural pathways interruption after stroke (Gracies 2005a; Gracies 2005b). Additionally, other factors such as paretic muscles' atrophy (Ng & Shepherd 2000), reduced firing rates and loss of agonist motor units (Rosenfalck & Andreassen 1980; McComas et al. 1973), fast contracting fibers' atrophy and slow contracting fibers' hypertrophy (Edström 1970), also contribute to the development of muscle weakness.

Especially in upper limbs, distal muscles are found to develop more severe muscle weakness following stroke compared to proximal muscles (Colebatch & Gandevia 1989). In the distal end of the upper limb, i.e. fingers, muscle weakness develops in both flexor and extensor muscles (Kamper et al. 2003), albeit of different level with extensor muscles are clinically observed to be more affected than flexor muscles (Ryerson & Levit 1997). Kamper et al suggest that the development of muscle weakness in both flexor and extensor muscles in fingers is mainly due to the central nervous system being unable to activate agonist muscles (Kamper et al. 2006).

Another factor of motor deficit post-stroke, loss or reduced of muscle coordination, is usually signified by co-contraction of antagonistic muscles. Gowland et al attribute this to the inability to both recruit agonist muscles' motor units and inhibit antagonist muscles' motor units in individuals with stroke (Gowland et al. 1992). The elevated antagonistic muscle activity level is also considered to play a major role in the co-contraction of antagonistic pairs which subsequently also results in the alteration of muscle activation pattern; hence, causing the inability to individually activate agonist muscle groups (Kamper & Rymer 2001; Cruz et al. 2005).

More specifically, in terms of digit coordination, individuals with stroke also lose their ability for multi-digit control. They show inefficient trajectories in kinematic grasp patterns (Cruz et al. 2005; Raghavan et al. 2010; Nowak et al. 2007) and experience difficulties in generating and maintaining appropriate grip force (Cruz et al. 2005; Dafotakis et al. 2008; Seo et al. 2010; Raghavan et al. 2006). Unnecessary muscle coactivation is also evident in individuals with stroke, likely due to an increase in neural drive to antagonistic muscles (Kamper & Rymer 2001; Kamper et al. 2003). This excessive coactivation among different muscles subsequently also lead to the abnormal muscle synergy observed in individuals with stroke (Roh et al. 2013). Furthermore, Li et al also suggest that stroke causes loss of strength and increase of enslaving force, i.e. the force produced by a non-instructed finger while another finger is instructed to perform maximum voluntary torque (MVT) (Li et al. 2003); effectively reducing the finger individuality and hindering its survivors from performing multifinger tasks.

The situation is made worse by the development of spasticity in the stroke survivors. Approximately 19% of stroke survivors develop spasticity within 3 months after the stroke onset (Sommerfeld et al. 2004) and 38% of them develop it within the first year of stroke (Watkins et al. 2002). Spasticity is considered very complex and therefore it is difficult to formulate its exact definition. One that is most commonly used and widely accepted is the one by Lance, which defines spasticity as “a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyper-excitability of the stretch reflex, as one component of the upper motoneuron syndrome" (Lance 1980; Sommerfeld et al. 2004). This definition is further refined by Lance in 1990 by adding the remarks: “spasticity does not include impaired voluntary movement and an abnormal posture” (Lance 1990; Sommerfeld et al. 2004). Spasticity in stroke is caused by the imbalance between excitatory and inhibitory input to alpha motor neurons due to the damage in the central nervous system (CNS); this causes a hyper-excitability of the stretch reflex and subsequently leads to the development of spasticity (Brown 1994; Mayer 1997). While it is still controversial, it has been suggested that there is a correlation between spasticity and motor function, as indicated by the high correlation between Ashworth Scale (a clinical scale to measure spasticity) and the drawing test (a quantitative metric of movement ability) (Eder et al. 2005). Additionally, it has also been reported that reduction in spasticity could lead to motor function improvement (Hesse et al. 1996; Francis et al. 2004). Despite this controversy, it appears widely accepted that spasticity is indeed a major obstacle in motor function rehabilitation after stroke (Bobath 1990).

2.3.2. Brain Plasticity

As devastating as the motor deficits after stroke may sound, our brain possesses huge potential for recovery with its plasticity. The brain plasticity, or often also referred as the neural plasticity, is the ability of the brain to reorganize itself both functionally and structurally after any internal and/or external changes. Hence, in the case of brain damage following stroke, the plasticity of the brain can help to induce motor recovery.

It has been suggested that the brain reorganization evidently induced by stroke rehabilitation follows a specific pattern (Ween 2008):

1. Early shift of activation towards the contralesional side
2. Participation of motor learning structures
3. Reshaping of the activation into a refocused perilesional pattern which is

usually accompanied by a better recovery, or a widespread distributed pattern.

Several more studies also supported the notion that perilesional activation correlates strongly with motor recovery, and that ipsilesional activation is correlated with faster or better recovery compared to contralesional activation (Nelles et al. 1999; Calautti et al. 2001; Loubinoux 2003).

With motor recovery relying much on brain plasticity, Kleim and Jones propose 10 key principles of neural plasticity that should be followed in order to make the most of it to benefit stroke rehabilitation (Kleim & Jones 2008):

1. *Use it or lose it* – any brain function will degenerate if not used.
2. *Use it and improve it* – more frequent use of a brain function will enhance itself.
3. *Specificity* – the kind of training determines the kind of recovery resulted.
4. *Repetition matters* – more repetition of a task will induce a longer-lasting change in the brain.
5. *Intensity matters* – appropriate intensity is required to induce neural plasticity.
6. *Time matters* – the sensitivity of neural plasticity is time-dependent.
7. *Salience matters* – the training has to be salient in order to induce neural

changes.

8. Age *matters* – neuroplasticity is easier to induce in younger brain.
9. *Transference* – neuroplasticity induced by a therapy may assist the acquisition of similar functions.
10. *Interference* – neuroplasticity induced by a therapy may also hinder the acquisition of other functions.

Having understood the key principles of brain plasticity to take advantage of, it is of paramount importance to incorporate these key principles to the stroke rehabilitation program in order to obtain better recovery.

2.4. Stroke Rehabilitation

In the past few decades, researchers have been trying to develop new techniques for stroke rehabilitation both to replace and/or to complement conventional therapies such as physical and occupational therapies provided in the hospitals or rehabilitation centers. Some of them include: bilateral training (Coupar & Pollock 2010), high intensity therapy (Kwakkel et al. 2004), repetitive task training (French et al. 2007; French et al. 2010; Kwakkel et al. 2004), electrostimulation (Langhorne et al. 2009; Pomeroy & King 2006; Kwakkel et al. 2004), mirror therapy (Thieme et al. 2012), constraint-induced movement therapy (CIMT) (Langhorne et al. 2009; Sirtori et al. 2009), and robot-assisted training

(Langhorne et al. 2009; Mehrholz et al. 2008; Mehrholz et al. 2012). Langhorne et al reviewed numerous studies and classified different rehabilitation techniques into either “beneficial or likely to be beneficial” or “uncertain benefit” techniques. For upper-limb rehabilitation after stroke, two techniques that are classified as “beneficial or likely to be beneficial” are: (1) CIMT or modified CIMT, and (2) robot-assisted training for upper limb function (Langhorne et al. 2011).

2.4.1. Constraint-Induced Movement Therapy (CIMT)

Constraint-induced movement therapy (CIMT) is arguably one of the promising methods for upper limb rehabilitation post-stroke with studies showing impressive improvements post-training (Taub 1976; Taub et al. 1998; Taub et al. 2002; Langhorne et al. 2011; Wolf et al. 2010; McIntyre et al. 2012). It is a rehabilitation technique that involves restriction of the less affected arm 90% of the waking hours; hence forcing the patient to make concentrated and repetitive use of the more affected arm to do the required tasks (Taub et al. 1999). The training is done very intensively for about 2 weeks.

This training is derived from a series of behavior studies by Taub et al on monkeys. They found out that after the monkeys have one of their limbs deafferented, they try to use the deafferented limb and fail. With following attempts lead to more failures, and often pain as well as other aversive consequences, they soon learn that their deafferented limb is no longer useful for them and start to suppress the use of it (Taub 1976; Taub et al. 1999). Even after a couple of months, where recovery processes take place and the deafferented limb has become potentially useful, the tendency to suppress the use of the deafferented limb, or also referred as the learned nonuse, persists and they never learn the potential usefulness of it (Taub et al. 1999). Nevertheless, if the intact limb is restricted by a device, the use of the deafferented limb could be promoted. The monkeys are then forced to use the deafferented limb to do their activities of daily living (Taub et al. 1999; Taub et al. 1993). Early removal of the movement restriction device, however, would lead to only temporary effect and the suppression behavior of the deafferented limb use would soon take over again; hence, the deafferented limb has to be constrained for long enough a period for it to be strong enough and for the monkeys to overcome the learned nonuse (Taub et al. 1999; Taub et al. 1993). Using the same idea, CIMT aims to counter the learned non-use process from setting in by forcing the use of paretic limb itself.

In short, the underlying mechanisms governing recovery post-CIMT can be summarized into two: (1) the reversal of the behaviorally reinforced learned non-use; and (2) the expansion of the contralateral cortical area due to repetitive movements of the affected limb (Taub et al. 2002; McIntyre et al. 2012). However, there have been debates that the high efficacy of CIMT is mainly attributed to the very selected population of stroke survivors who are less impaired and/or able to tolerate prolonged constraint recruited in CIMT studies (Langhorne et al. 2009). The very intense and strenuous nature of CIMT does seem to limit its applicability to general stroke survivors.

2.4.2. Robotic Rehabilitation for Stroke

Robotic devices, on the other hand, have been adept complements to conventional therapy due to their ability to facilitate repetitive movement training with high intensity and precision (Langhorne et al. 2009; Langhorne et al. 2011). Many of them can be customized to meet patient’s needs, making it more suitable for stroke survivors with wide range of impairment level. With rehabilitation robot being an emerging field, the number of journal paper on this field throughout the past five years has experienced an exponential increase (Marchal-Crespo & Reinkensmeyer 2009). Some most renowned rehabilitation robots are the MIT-Manus (Hogan et al. 1992; Krebs et al. 1999; Krebs et al. 2004), ARM Guide (Reinkensmeyer et al. 2000), MIME (Lum et al. 2006; Lum et al. 2004), HWARD (Takahashi et al. 2005), RUPERT (Balasubramanian, Buchanan, et al. 2010) and PolyJBot (Tong et al. 2009; Hu et al. 2007; Hu et al. 2009).

Nevertheless, while many of these systems have been studied and proven to be beneficial, most of them focus the rehabilitation on more proximal joints such as shoulder, elbow, and some on wrist joint. Robotic system for stroke rehabilitation systems that focuses on finger rehabilitation is not too many at the moment, not to mention those that provide a feasibility to train each finger individually. Here we discuss some examples of the few rehabilitation robots with such features (see also Figure 2.6):

- Hand Exoskeleton Rehabilitation Robot (HEXORR)

  The HEXORR comprises two modular parts, one part attaches to the user's thumb and the other to the user's four fingers. Each of the two modular component is capable of assisting flexion and extension independently (Schabowsky et al. 2010). The device also supports three different kinds of algorithms: continuous passive movement, active unassisted movement, and active force assisted movement. A recent study using the HEXORR revealed improved ROM as well as improved scores for the hand component of FMA and ARAT (Godfrey et al. 2013).

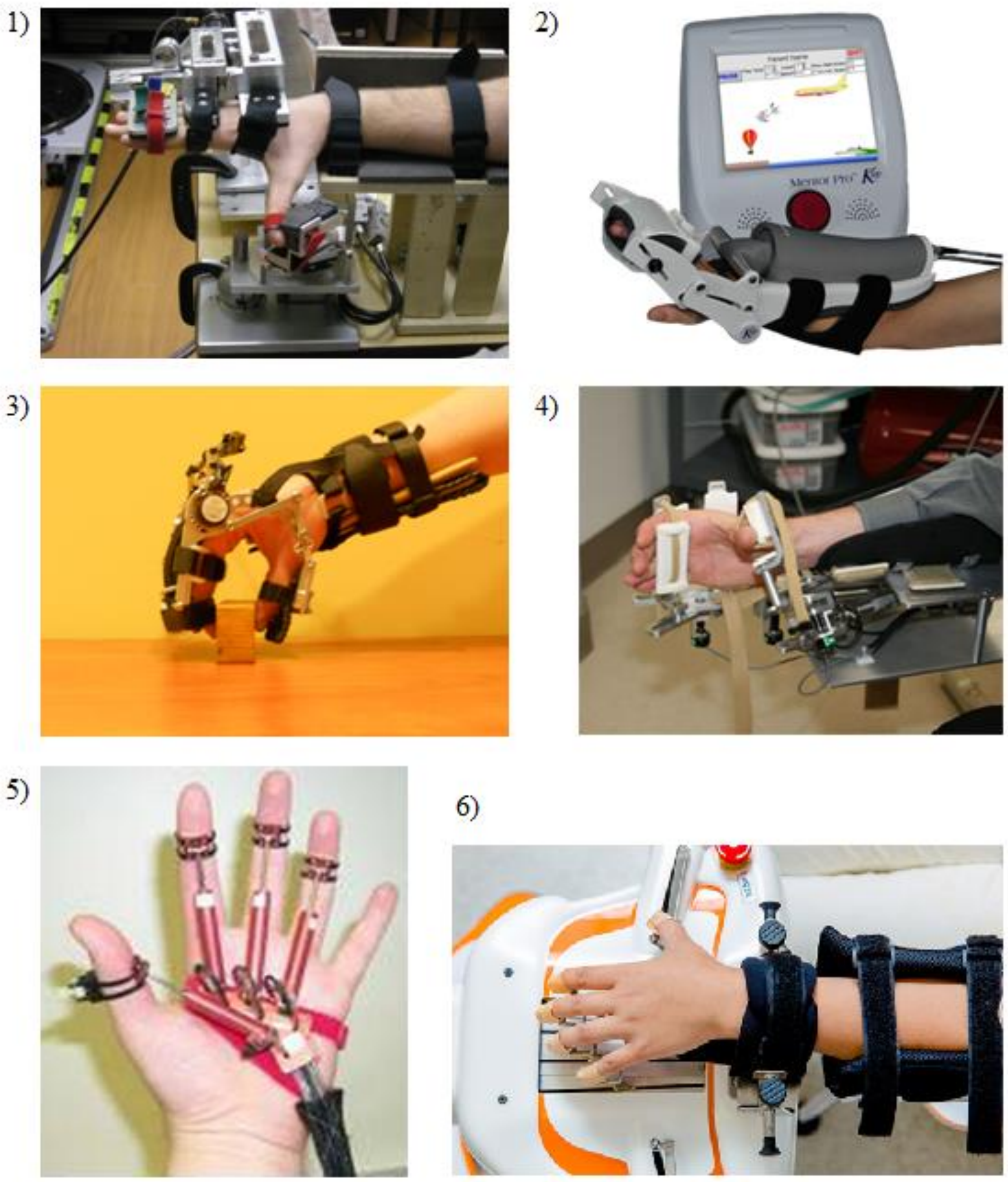


Figure 2.6. Pictures of different existing hand rehabilitation devices: 1) HEXORR; 2) Hand Mentor; 3) HandSOME; 4) HWARD; 5) Rutgers Hand Master II; 6) Amadeo.

- Hand Mentor

Commercially developed by Kinetic Muscles Inc. (USA), this device provides controlled resistive force on the user's hand and wrist (Koeneman et al. 2004). The Hand Mentor makes use of an artificial, pneumatic muscle to flex and extend wrist and finger (MCP) joints simultaneously based on the EMG signal obtained from the EMG surface electrodes attached to user's arm. Several studies and a case report have shown increased clinical scores, in this case WMFT score, and active ROM post-intervention (Frick & Alberts 2006; Rosenstein et al. 2008; Kutner et al. 2010).

- Hand Spring Operated Movement Enhancer (HandSOME)

  Developed by the same group from Catholic University of America (CUA) that built the HEXORR, the HandSOME aims to compensate finger flexor hypertonia post stroke by using a series of elastic cords to provide extension torque to the finger joints (Brokaw et al. 2010). This device has shown to be able to increase ROM and functional ability, measured by a task modeled after the Box and Blocks test (Brokaw et al. 2011).

- Hand Wrist Assistive Rehabilitation Device (HWARD)

  Similar to Hand Mentor, HWARD is also meant for wrist and hand therapy. The difference, however, is that HWARD provides more flexibility with 3 DOF as opposed to the single DOF of Hand Mentor, supporting flexion and extension of the wrist, the thumb's MCP joint, and the four fingers' MCP joints altogether (Takahashi et al. 2005). The design of HWARD also allows the user to interact with real object while simultaneously being assisted by the device. Intervention study with this device has shown improved FMA and ARAT scores as well as task-specific increased sensory motor cortex activation (Takahashi et al. 2008).

- Rutgers Hand Master II

This device is a haptic force-feedback glove actuated by pneumatic pistons on the palm of the hand (Bouzit et al. 2002). This glove is usually used in a VR environment by taking advantage of its capability of providing haptic feedback in a form of contact forces (Deutsch et al. 2004). Studies using this glove have reported better clinical scores, increased ROM, and increased paretic digits' extension speed (Merians et al. 2002; Boian et al. 2002).

- Amadeo

Developed by Tyromotion GmbH (Graz, Austria), this device is a mechatronic device for hand rehabilitation purpose that is equipped with capability to move individual finger separately. It is an 5 DOF end-effector-based system that takes end-point (fingertip) position and force as the inputs (Hwang et al. 2012; Sale et al. 2014; Maciejasz et al. 2014). This device has also been tested on acute, subacute and chronic stroke survivors, and has shown improvements on different clinical scores such as

FMA and Jebsen-Taylor test (Stein et al. 2011; Maciejasz et al. 2014; Hwang et al. 2012; Sale et al. 2014).

- Hand Cable-Actuated Rehabilitation (HandCARE)

  The HandCARE is a cable actuated hand rehabilitation device that takes finger force as its control input. This device can provide assistance for opening and closing movements of each finger and can accommodate different hand shapes and finger sizes with its instrumented cable loop attachment. The unique 5-clutch system implemented in the HandCARE allows independent movement of each of the 5 individual finger despite having only 1 actuator (Dovat et al. 2008). Pilot study has been conducted on 2 subjects, and both subjects improved their Chedoke-McMaster Impairment Inventory. Subject S1 improved from stage 3+ to stage 4, while subject S2 improved from stage 3++ to stage 5 (Dovat et al. 2010).

Maciejasz et al recently also published a thorough review article surveying different upper limb rehabilitation devices available at the moment. The same trend about the relatively smaller number of rehabilitation devices focusing on the distal joints is also observed in the article, albeit to a lesser extent due to the inclusion of commercial devices of which clinical studies may not have been conducted (Maciejasz et al. 2014).

Chapter 3

Study I: Development of Hand Exoskeleton Robot with Individuated Finger Feature

This chapter discusses the modifications made to the original hand exoskeleton robot developed by Tong et al (Tong et al. 2010; Ho et al. 2011)in order to suit the objectives of the study, and the tests done to validate its measurements. The works described in this chapter has been reported previously in the 9th IASTED International Conference on Biomedical Engineering in Innsbruck, Austria in 2012 (Susanto et al. 2012).

3.1. Introduction

Development of upper limb rehabilitation robots throughout the past few decades seems to focus more on larger and more proximal joints like the shoulder and elbow. A recent review revealed that there are more rehabilitation robots working on proximal joints than those designed for distal joints rehabilitation (Maciejasz et al. 2014). The challenge with more degree-of-freedoms (DOFs) required for the more distal part of the upper limb such as hand and fingers, appears to hinder the development of such device.

Hence, the first challenge towards the conception of holistic upper-limb rehabilitation after stroke began with finding an appropriate device to suit our purpose. In 2007, our group developed hand exoskeleton robot featuring 5 linear actuators providing assistance to 5 individual fingers (Tong et al. 2010; Ho et al. 2011), which until now remains one of the only few rehabilitation devices with such features (Maciejasz et al. 2014). While its original system does not facilitate individual finger control, its design allows modifications to enable such features. Considering the limited choices available and the accessibility of those devices, we decided to make use of the hand exoskeleton device and modify it to suit our purpose. This chapter describes the device as well as the modifications made to it and evaluates its performance.

3.2. Design

3.2.1. Device Criteria

In order to facilitate the task-oriented holistic upper limb rehabilitation after stroke, a robotic device with an ability to assist movements on all the joints in the upper limb, from shoulder all the way to DIP joints, is necessary. However, while the task-oriented training itself involves movements on all the joints, the target populations of chronic stroke survivors mostly have more residual functions on their proximal joints and less on their distal joints. And as it has been suggested that active voluntary training is promotes better recovery by overcoming learned non-use

(Taub 1976; Taub et al. 1993; Taub et al. 1994), and for the sake of the simplicity of the whole system, we decided provide assistance only on the finger joints; effectively eliminating the need of whole upper-limb robotic rehabilitation device.

Hence, for this study we will need a robotic device that would be able to: (1) provide assistance for finger movements in both flexion and extension directions, (2) actuate individual finger separately for fine motor control training (i.e. each digit is actuated by different motors), and (3) detect the intention of the user to move individual fingers to facilitate the control algorithm. In terms of range of motion (ROM), the device does not necessarily need to have a full flexion ROM on the finger joints as the users would be interacting with objects during the training. For such reason, a review of existing devices was conducted to see if there is any suitable device available, as has been presented in Section 2.4.2.

3.2.2. Hand Exoskeleton Robot

Having reviewed existing available devices, it appeared that there was no current device meets the requirement for this study. Even when considering only criteria (1) and (2), limited devices were available, one of which being our previously developed hand exoskeleton robot (Maciejasz et al. 2014). Hence, we decided to make use that hand exoskeleton robot and modify it to suit our needs instead.

The aforementioned hand exoskeleton robot was originally developed by Tong, K.Y., et al in 2007 and is shown in Figure 3.1 (Tong et al. 2010; Ho et al. 2011). The robot was capable of providing assistance to the user during hand grasping and hand opening. This device features five individual digits with a total of 9 joints: one MCP joint on the thumb and MCP and PIP joints on the other four fingers. Movements of MCP and PIP joints on the four fingers are always simultaneous with a four-bar linkage design.

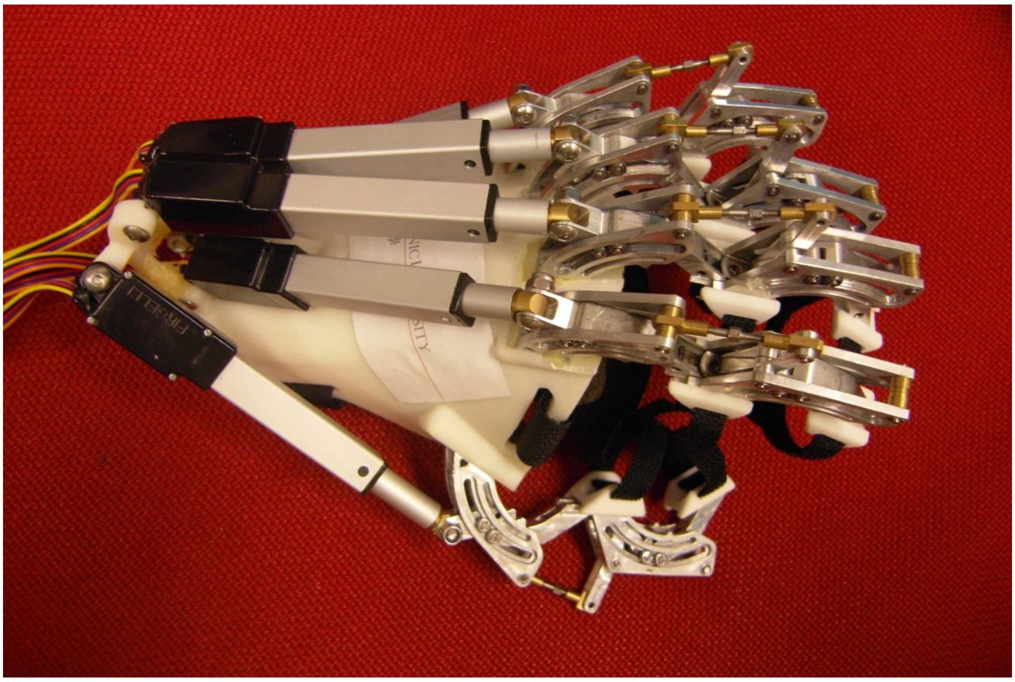


Figure 3.1. The hand exoskeleton robot originally developed by Tong et al.

The digits have a range of motion (ROM) of 55 degrees on the MCP joint and 65 degrees on the proximal PIP joint during the hand grasping and opening, The mechanical design itself is based on the concept of virtual centre; causing each phalanx of the hand exoskeleton robot, if well placed, to rotate around the actual respective MCP or PIP joint of the user. This enables the user to get assistance during the movement while at the same time keeping the movement as natural as possible (see Figure 3.2).

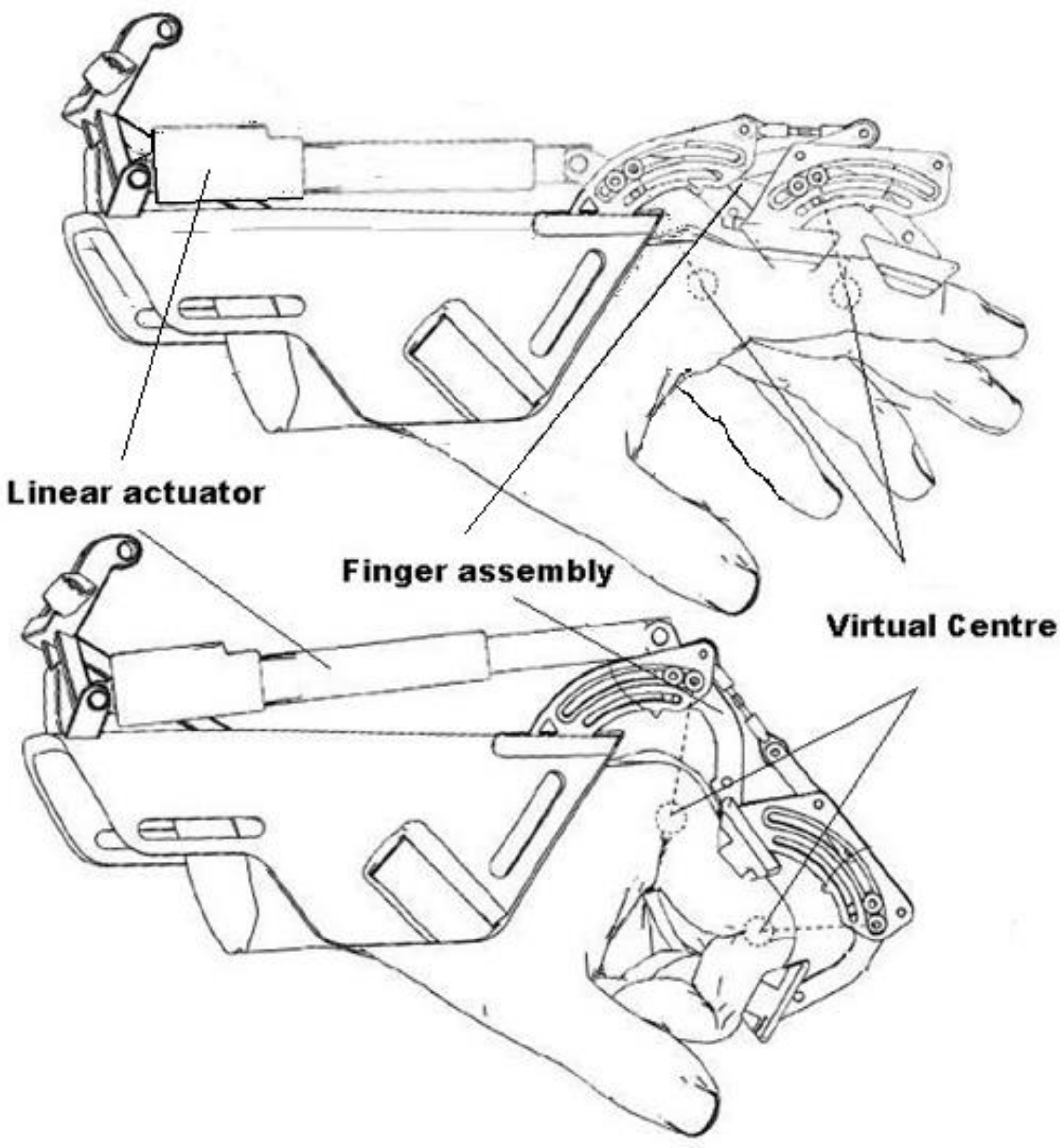


Figure 3.2. The mechanical design of the hand exoskeleton robot explaining the concept of virtual center.

Additionally, the hand exoskeleton robot itself is adjustable in terms of finger segments lengths in order to facilitate the high variance in hand sizes of its users;

permitting even wider a range of possible users.

Each digit is actuated by a single linear actuator Firgelli L12 (Firgelli Technologies Inc., Canada) placed right proximal to the digit and on the dorsal side of the exoskeleton base. The actuator is capable of providing 23N of force at its peak and has a backdrive force of 80N. All 5 linear actuators are driven by a 12V portable battery that is connected to the microcontroller unit and the motor drivers.

The device is attached to the user’s hand by means of Velcro straps. A couple of Velcro straps on the wrist and on the palm of the hand ensure the positioning of the device with respect to the user’s hand, while Velcro straps on the thumb’s proximal phalanx and the four fingers’ proximal and middle phalanges are meant to facilitate the device assistance during movements. The distal phalanges of the user are intentionally left open to provide sensory feedback during interactions with objects.

The device also features 6 EMG channels to detect contractions on the user’s muscle groups of interest, namely abductor pollicis brevis (APB), first dorsal interosseous (FDI), extensor digitorum (ED), flexor digitorum superficialis (FDS), biceps brachii (BIC), and triceps brachii (TRI). It uses these EMG signals to control its movement. All computations can be done in a single microcontroller unit.

3.2.3. Individuated Finger Feature Design

To facilitate individuated finger feature on the device, some modifications were made (see Figure 3.3). A total of nine full-bridge strain gauges ZF1000-2EB-T (Shenzhen Nanhua Electronic Technology Co., Ltd., China) were installed on the hand exoskeleton robot to provide a comprehensive overview of the user’s finger joint moments. One strain gauge measures the thumb MCP joint moment, and the other eight strain gauges measure the MCP and PIP joint moments of the rest four fingers. Additionally, five sliding linear potentiometers RS6011Y1401A (Alps Electric Co., Ltd., USA) were installed on each finger to provide position feedbacks to the system.

Each ZF1000-2EB-T strain gauge (Figure 3.4) was originally already in a form of full Wheatstone bridge and has a total resistance of 1000 ± 100 Ω. The bridge was powered by a 2.5 Volts power supply regulated by an INA 125 instrumentation amplifier (Texas Instruments Inc., USA) and the output of the bridge, which is the difference between the two mid-points of the two sides of the bridge, was inputted to the signal processing and data acquisition system (see Figure 3.5). On the other hand, the potentiometers were powered by 5 Volts power supply and its output was fed as an input to the signal processing and data acquisition system.

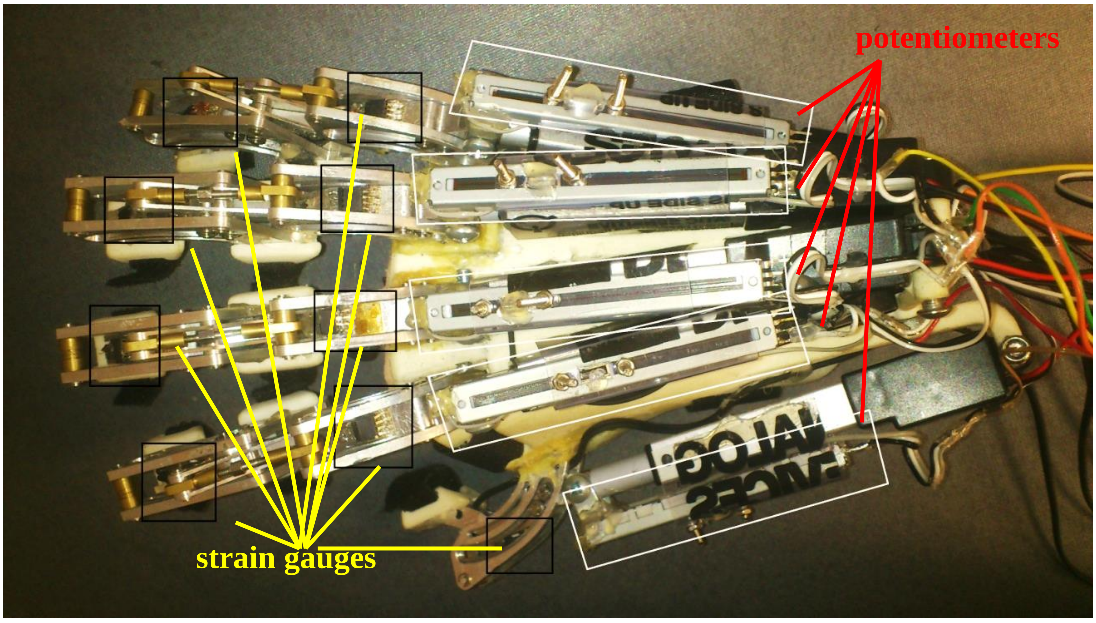


Figure 3.3. The modified hand exoskeleton robot used for this project. Highlighted in black (with yellow labelling) are the locations of the strain gauges and in white (with red labelling) are the locations of the potentiometers.

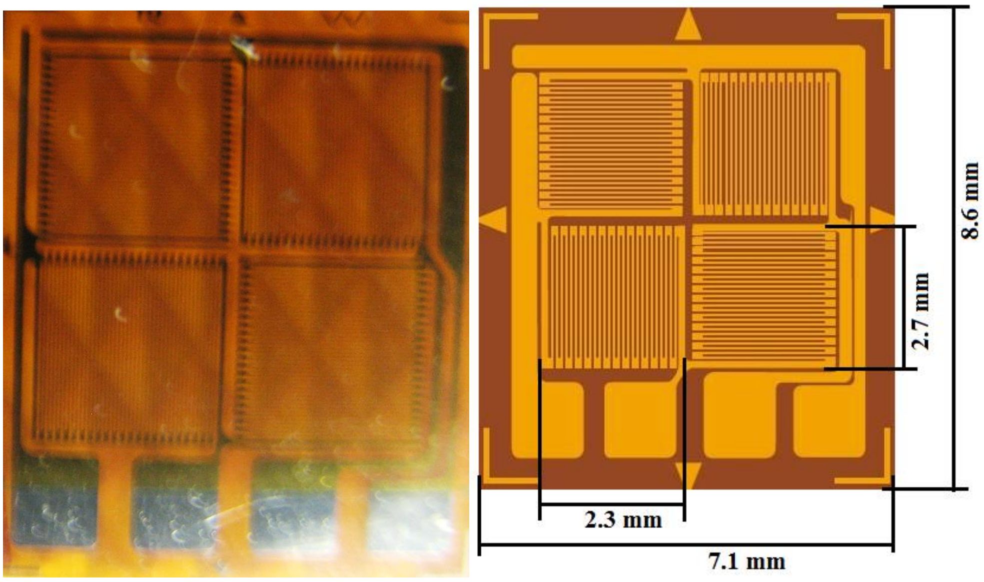


Figure 3.4. Picture of the ZF1000-2EB-T strain gauge used in this study (left), and its diagram (right).

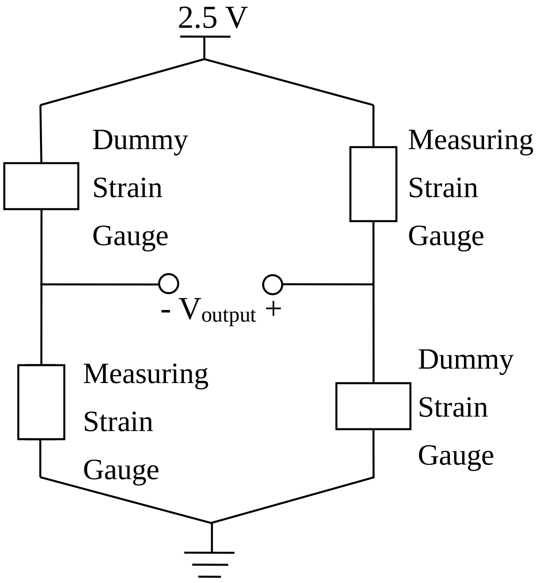


Figure 3.5. Picture of the full Wheatstone bridge diagram for each strain gauge.

Weighing barely 700 grams in total after modification, an increase of 200 grams from the original model, this hand exoskeleton robot should be light enough to be used as a rehabilitation training device by most stroke survivors.

3.2.4. Data Acquisition System

The output signal of the strain gauge bridge was fed back to the INA 125 to be amplified with a gain of 1000 times, while the EMG signals captured by the EMG electrodes were amplified by a two-stage amplifier with a total gain of 1000 times and with a band-pass filter of 10 Hz and 500 Hz in between. All amplifiers were powered by a 5 Volts power supply.

Next, all the three inputs to the system, namely the amplified strain gauges, amplified and filtered EMG, and potentiometers signals were connected to the

NI-USB 6218 DAQ Card (National Instruments, Corp., USA) to be sampled with a sampling rate of 1 kHz and a resolution of 16-bit. The strain gauge and potentiometer signals were then filtered with a moving average filter of 10 data points. All the signals were the recorded in the computer system and used as inputs to the system that controls the linear actuators of the hand exoskeleton robot.

All the digital signal processing was done using a custom-made program developed in LabVIEW (National Instruments, Corp. USA). The program, which is to be described in details in the next section, was also designed to show and record all the signals in real-time basis. The recorded data were used for further offline data analysis.

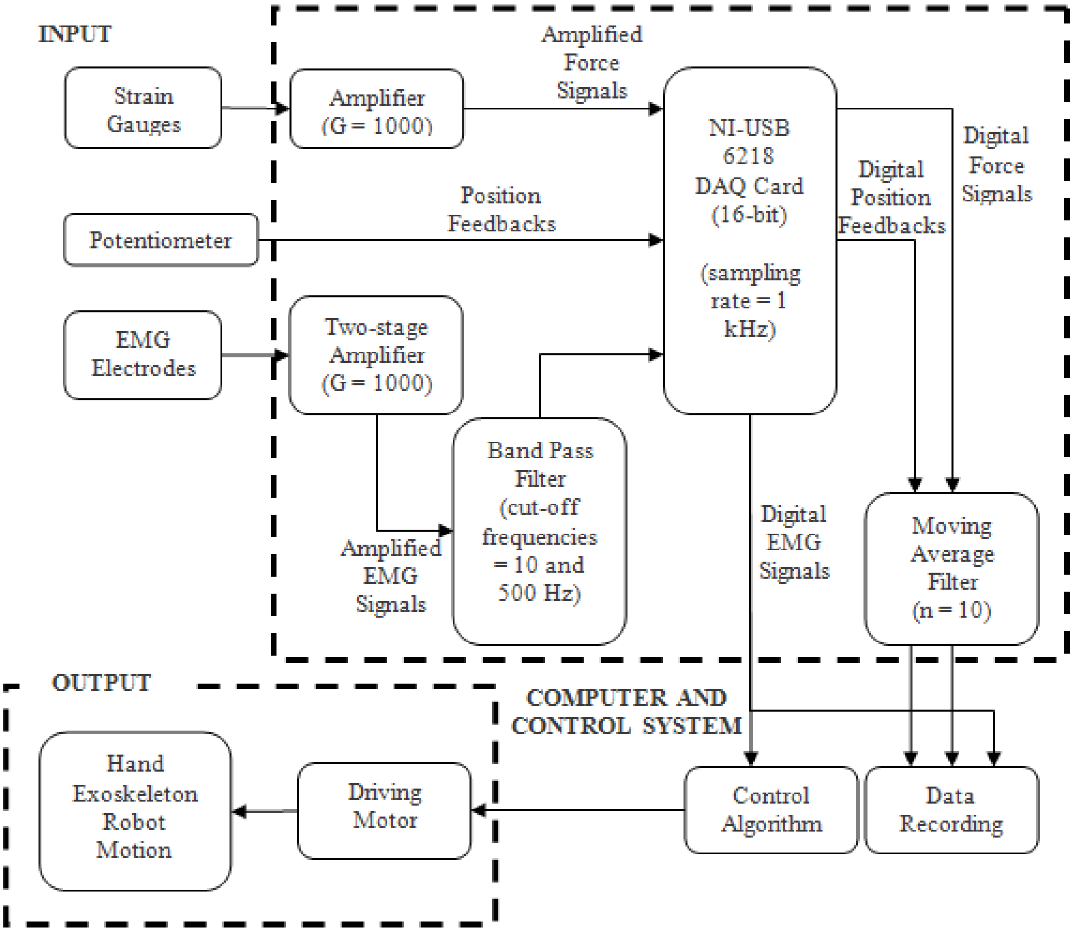


Figure 3.6. Schematic diagram of the system.

3.2.5. Software Architecture

The program developed for this study was written in LabVIEW (National Instruments, Corp. USA) environment and consisted of 3 independent processes, each of which is also often referred as a “loop”. The 3 independent loops, i.e. the data acquisition loop, the serial RX loop, and the serial TX loop, run simultaneously once the program is started. The serial communication process is divided into 2 loops, i.e. transmitter (TX) loop and receiver (RX) loop, mainly in order to reduce the potential delay of transmitting or receiving data due to the an ongoing process of receiving or transmitting data, respectively.

The data acquisition loop continuously collects EMG, strain gauges, and potentiometers digital signal from the NI-USB 6218 DAQ Card (National Instruments, Corp., USA) and simultaneously records these data into the computer hard disk. Further signal processing on those data was also performed within the data acquisition loop.

The EMG signal was further processed to obtain its envelope. DC offset removal was first done, followed by rectification of the signal. The envelope of the EMG signal was then obtained by applying moving average filter to the rectified EMG signal. The envelope of the EMG signal is required for easier interpretation of the signal and is to be shown online on the display. It can also be potentially used as an input for the control algorithm if desired. For offline analysis, however, only the originally acquired EMG signal is stored in the computer.

Moving average filter with $n = 10$ is also applied to both of the strain gauges and the potentiometers signals in this loop. After the filtering, the filtered signals are displayed online and stored in the computer system as well.


Path: C:\Users\Robot Hand\Documents\TrainingData

File Name: C:\Users\Robot Hand\Documents\

Type: Test

Measurement #: 1

Selector: Hand Grasping

Figure 3.7. Graphical User Interface (GUI) of the hand exoskeleton robot system program. Highlighted in red is the display for each joint moment. On the top, from left to right, are the PIP joint moments of the index, middle, ring, and little finger; on the bottom, from left to right, are the MCP joint moments of the thumb, index, middle, ring, and little finger. The 5 finger positions are shown in the bars highlighted in green; and the EMG level display for 6 muscles of interests, namely APB, FDI, FD, ED, BIC, and TRI, are highlighted in blue.

The serial RX loop is responsible to receive all the data coming from the microcontroller unit (MCU) controlling the hand exoskeleton device. It starts by first initializing the serial connection between the computer system and the MCU with a default baud rate set at 57600 bps. Once the serial connection is established, the loop continuously reads every data sent by the MCU.

Opposite to the serial RX loop, the serial TX loop is responsible to send commands to the MCU. This is required to be able to control the hand exoskeleton robot from the computer system (via the serial connection to the MCU). The control is done by sending 2 numeric characters to the MCU, which to be interpreted into different commands by the MCU. The commands recognized by the MCU are listed below in Table 3.1.

Table 3.1. Table of MCU commands and their interpretation.

Commands	Descriptions
Status	
98	Restart (soft) and print current status
96	Print current motor/finger positions
Initial settings	
00	Baseline level measurement
10	MVC level measurement
Passive movements	
30,52	Hand grasping (full motion)
31,53	Hand opening (full motion)
90	Hand grasping (incremental motion)
91	Hand opening (incremental motion)
32/34/36/38/42	T/I/M/R/L individual flexion (full motion)
33/35/37/39/43	T/I/M/R/L individual extension (full motion)
80/82/84/86/88	T/I/M/R/L individual flexion (incremental motion)
81/83/85/87/89	T/I/M/R/L individual extension (incremental motion)
54	Three fingers (T,I, and M) pinching (full motion)
55	Three fingers (T,I, and M) opening (full motion)
56	Two fingers (T and I) pinching (full motion)
57	Two fingers (T and I) opening (full motion)
Training modes	
40	Trigger mode (close direction)
41	Trigger mode (open direction)
50	Continuous mode (close direction)
51	Continuous mode (open direction)

When the program is stopped, all three loops are terminated and the serial connection is also closed.

3.2.6. Joint Moment Calculation

Meanwhile, the calculation of the joint moment is based on the following diagram shown in Figure 3.8 below.

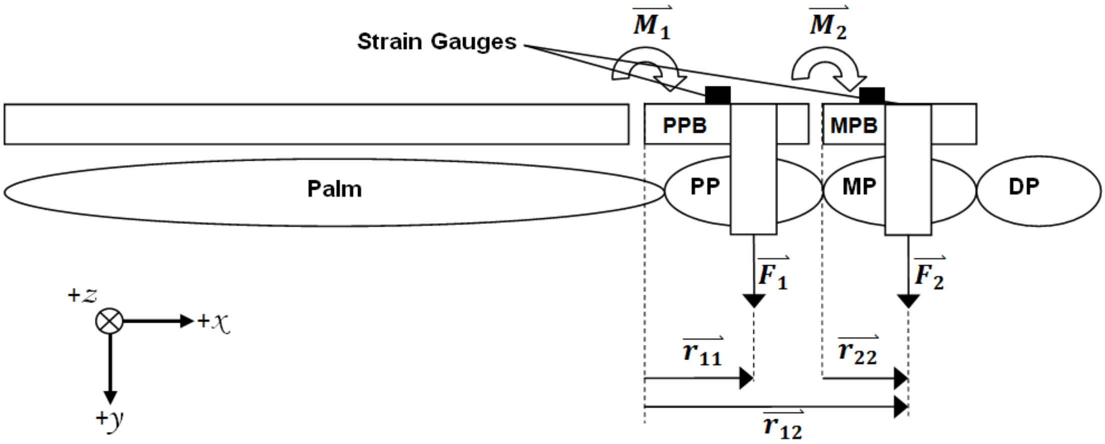


Figure 3.8. Diagram of the hand exoskeleton robot force sensing mechanism. PP, MP, and DP respectively refer to the proximal, middle, and distal phalanx of a finger; while PPB and MPB refer to the proximal phalanx bar and middle phalanx bar of the hand exoskeleton robot.

With all the strain gauges installed, for the four fingers, essentially the strain gauges installed in the proximal phalanx bar (PPB) are able to measure forces going to the +y direction on both proximal phalanx ($\overrightarrow{F_{1,y}}$) and on middle phalanx ($\overrightarrow{F_{2,y}}$); while the strain gauges on the middle phalanx bar (MPB) only measure $\overrightarrow{F_{2,y}}$. Knowing all the distances and the two moments on PPB and MPB (i.e. $\overrightarrow{M_{1,z}}$ and $\overrightarrow{M_{2,z}}$, respectively), we can calculate back the forces $\overrightarrow{F_{1,y}}$ and $\overrightarrow{F_{2,y}}$ by the following equations:

Equation 3.1

$$\overrightarrow{M_{2,z}} = \overrightarrow{r_{22,x}} \times \overrightarrow{F_{2,y}}$$

$$\overrightarrow{F_{2,y}} = \frac{\overrightarrow{M_{2,z}}}{\overrightarrow{r_{22,x}}}$$

Equation 3.2

$$\overrightarrow{M_{1,z}} = \overrightarrow{r_{11,x}} \times \overrightarrow{F_{1,y}} + \overrightarrow{r_{12,x}} \times \overrightarrow{F_{2,y}}$$

$$\overrightarrow{F_{1,y}} = \frac{\left(\overrightarrow{M_{1,z}} - \overrightarrow{r_{12,x}} \times \overrightarrow{F_{2,y}}\right)}{\overrightarrow{r_{11,x}}}$$

For the thumb, as there is only one force measured, the calculation is as that of $\overrightarrow{F_{2,y}}$ (see Equation 3.1).

Next, by using the same set of equations and knowing the actual moment arm from the center of MCP joint and the center of PIP joint as well as $\overrightarrow{F_{1,y}}$ and $\overrightarrow{F_{2,y}}$, we are able to obtain the actual moments on the user's MCP and PIP joints, i.e. $\overrightarrow{M_{MCP,z}}$ and $\overrightarrow{M_{PIP,z}}$.

3.3. Results and Discussions

3.3.1. Stability Test

Each strain gauge was tested in terms of stability throughout prolonged period of about an hour. In general, the output of each strain gauge fluctuated ±0.8 mV around its average and the total baseline drift over one hour period is never more than 5 mV (see Figure 3.9). Thus essentially, the maximum measurement error due to the strain gauge is in the level of 10^{-2} Nm. With the average joint moment on MCP and PIP being around 1 Nm to 4 Nm (Li et al. 2000), maximum measurement error at the order of 10^{-2} Nm is considered acceptable.

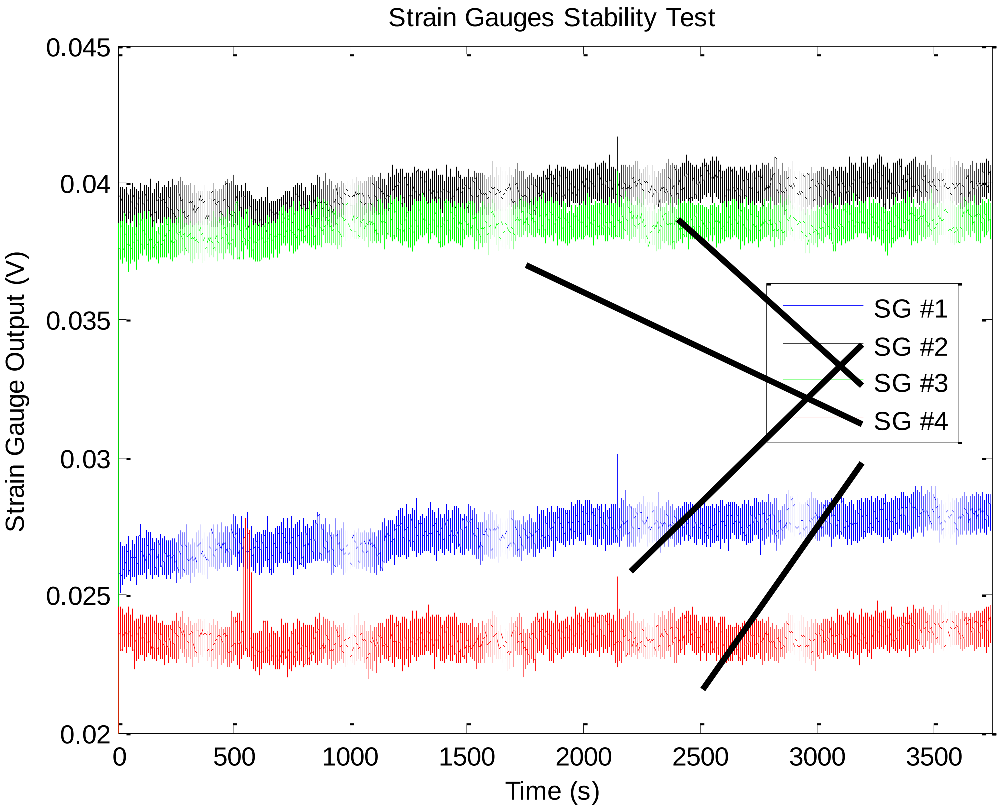


Figure 3.9. Stability test result for 4 strain gauges mounted on the middle phalanx bar (MPB).

3.3.2. Flexion-Extension Linearity Test

Next, as we aim to use the device to measure both flexion and extension forces of each digits, linearity of both flexion and extension forces measurement was tested. This was done by means of 10 repetitions of measuring 4 different loads in both flexion and extension directions. As shown in Figure 3.10 below, strain gauge outputs indicate high linearity with a typical R-squared value of around 0.99; ensuring that linear conversion is sufficient to obtain the moment value from the voltage measured.

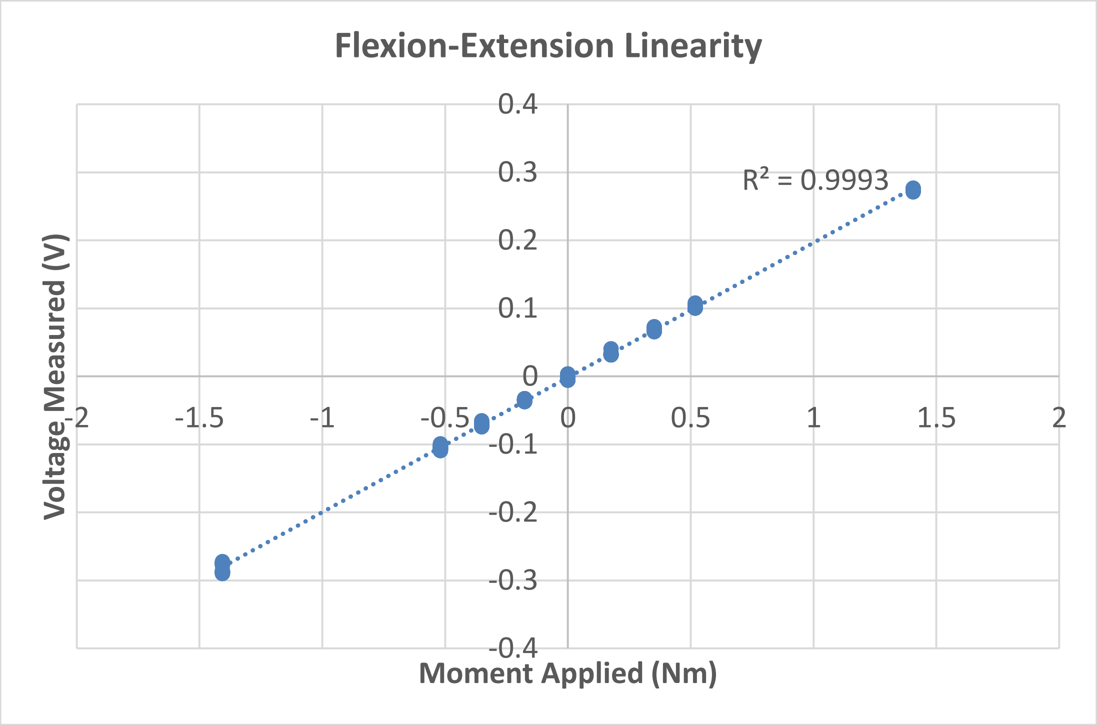


Figure 3.10. Flexion-extension linearity test results on one single strain gauge. Negative values indicate flexion while positive values indicate extension.

3.3.3. Repeatability Test

After ensuring the stability and linearity of the system, calibration of each individual strain gauge was conducted. This is then followed by tests on the repeatability of the measurement by means of taking 10 measurements of 8 different known loadings in random sequences. As can be seen in Table 3.2, the standard deviations of the measurements are always below 1% of the load, which would be acceptable for the intended applications of the device.

Table 3.2. Repeatability test results of one strain gauge measurement on the device.

Applied Moment (Nm)	Mean Measured Moment (Nm)	SD (Nm)	SD (% Moment)
0.0000	0.0000	0.0018	-
0.2009	0.2013	0.0013	0.67
0.3134	0.3137	0.0030	0.95
0.4018	0.4022	0.0029	0.73
0.4741	0.4748	0.0035	0.73
0.6027	0.6035	0.0023	0.37
0.6268	0.6273	0.0049	0.79
0.8036	0.8044	0.0042	0.52
1.4384	1.4399	0.0056	0.39

3.4. Summary

In this chapter, it has been demonstrated that we were able to develop a hand exoskeleton device capable of facilitating measurement of finger flexion and extension forces on the proximal phalanx of the thumb and on the proximal and middle phalanges of the other four fingers. On top of that, the measurement's stability, linearity, as well as repeatability using the device were tested and verified. The uses of the device as: (1) a measurement device for study of hand and fingers mechanics, and (2) rehabilitation device with individual finger assistance feature, will be discussed in Chapter 3 and 4, respectively.

Chapter 4

Study II: Hand and Fingers Characteristics after Stroke

This chapter describes the use of the modified hand exoskeleton robot, as described in the Chapter 3, to assess hand and fingers characteristics after stroke, especially in terms of muscle strength and finger individuality. Additionally, this chapter also suggests the possibility of using finger individuality as an index to assess hand function in general. The works described in this chapter has been published previously in HKIE Transaction Volume 22, Issue 2, 2015 (Special Issue on Robotics) (Susanto, Tong & Ho 2015).

4.1. Introduction

Motor impairment after stroke has been always associated with muscle spasticity, muscle weakness, and loss of dexterity. One kind of dexterity that is often significantly reduced post stroke is the finger individuality, which is still not well understood. Having developed the hand exoskeleton robot and modified it with additional sensors, we would like to explore the possibility of assessing muscle weakness and finger individuality after stroke using the device.

Additionally, assessment of hand function post stroke nowadays is normally done by means of clinical assessments, where an assessor asks the patient to do certain tasks and gives him a score based on his performance in completing the task as specified by the clinical assessment itself. Some of the most commonly used assessments are Fugl-Meyer Assessment (FMA), Action Research Arm Test (ARAT), and Wolf Motor Functions Test (WMFT) (Fugl-Meyer et al. 1975; Gladstone et al. 2002; Hsueh et al. 2002; van der Lee et al. 2002; Wolf et al. 2001). These tests, while have been tested for their inter-rater reliability, are still somewhat prone to a certain level of subjectivity. Robotic devices, while have been used a lot as for rehabilitation purposes, have seldom, if not never, been used to assess motor function despite their ability to provide accurate and repeatable measurements.

This study aims to use the developed device to further understand the fingers characteristics after stroke, especially in terms of one finger correlation with the others and how it affects the functionality of the whole upper limb. Comparisons will be done against neurologically-intact control subjects in terms of both finger joints moments and fingers individualities. The study also aims to correlate the finger individuality with difference clinical assessments to explore the possibility of using finger individuality index as an option to assess hand function in general.

4.2. Methodology

4.2.1. Subjects

For this study, six stroke survivors were to be recruited. The inclusion criteria for the stroke subjects were: 1) chronic stroke survivor (stroke onset > 6 months); 2) right hand dominant; 3) right side hemiplegic; 4) Fugl-Meyer assessment score for wrist and hand (FMA-WH) more than or equal to 5; and 5) able to follow instructions and understands the contents and purposes of the study, proven with Mini Mental State Examination (MMSE) score higher than 21. The subjects, however, must not fall into the following exclusion criteria: 1) recurrent stroke, 2) other neurological, neuromuscular, or orthopedic disease, or 3) shoulder or arm contracture/pain.

For comparison, six right-handed age-matched neurologically-intact control subjects (CS) were to be recruited.

4.2.2. Protocol

Prior to the study, four clinical assessments for upper limb motor functions, namely Fugl-Meyer assessment (FMA), Action Research Arm Test (ARAT), Motor Status Scale (MSS), and Wolf Motor Function Test (WMFT), were done on the stroke survivors by an assessor.

Throughout the study, the subject was seated on a height-adjustable chair, his right arm was supported by an arm-rest and was kept in position with his: 1) right shoulder positioned at 90 degrees abduction, neutral rotation, and no flexion/extension; 2) right elbow flexed at 90 degrees; and 3) right arm pronated at 90 degrees that the palm is facing medially.

The subject's fingers lengths were measured, as well as the lengths of different segments of each finger, i.e. wrist-MCP, MCP-PIP, PIP-DIP, and DIP-fingertip segments. Passive range of motion (ROM) of the MCPs and PIPs of each finger were also measured. Two repetitions of grip strength measurement were then performed on the subject's right hand by using the WCS-100 electronic hand dynamometer (Nantong Beisite Industry Trade Co., Ltd.).

Subsequently, skin preparation was done on five sites on the subject's right arm where electromyogram (EMG) electrodes were to be placed on. The five muscles of interest are abductor pollicis brevis (APB), extensor digitorum (ED), flexor digitorum superficialis (FDS), biceps brachii (BIC), and triceps brachii (TRI). EMG signals of these five muscles were to be recorded and analyzed. The skin preparation was done by cleaning the subject’s skin using Nuprep Skin Prep Gel (Weaver and Company, USA) and followed by another cleaning using alcohol.

The subject was then asked to perform two repetitions of isometric maximum voluntary contraction (MVC) of each of the five muscles of interest. The EMG data of the MVCs were to be used for EMG signal normalization.

This study made use of hand exoskeleton robot (Tong et al. 2010), which was modified to suit the requirements of this study (Susanto et al. 2012) as described in the previous chapter. The hand exoskeleton robot itself is especially adjustable in terms of finger segments lengths in order to facilitate the high variance of hand sizes of its users. After adjusted according to the initial measurements of the subject's fingers lengths performed earlier, the hand exoskeleton robot was put on the subject's right hand. With the hand exoskeleton robot on the subject's hand, the subject was asked to exert isometric maximum voluntary torques (MVTs) on different fingers and in different directions and different positions.

Essentially, in this part of the study, each subject was asked to perform hand opening, hand grasping, and individual finger flexion and extension on every fingers in a randomized order. Thus a complete set of the tasks would consist of 12 tasks: 1 flexion and 1 extension for each of the 5 fingers, as well as 1 whole hand grasping, 1 whole hand opening, in a randomized order. These tasks were done isometrically; hence obtaining the isometric MVT of each instructed finger and the isometric enslaving force of the non-instructed fingers.

In no particular order, two repetitions of the complete flexion tasks were to be performed at both 0% (fully extended) and 50% (middle) positions, and the same applied to the extension tasks at both 50% (middle) and 100% (fully flexed) positions. The positions 0%, 50%, and 100% are defined as the positions at which the subject's MCP joints are positioned at 0, 27.5, and 55 degrees flexion, respectively, and his PIP joints at 0, 32.5, and 65 degrees flexion, respectively. Throughout the study, EMG signals from five different muscles, namely abductor pollicis brevis (APB), extensor digitorum (ED), flexor digitorum superficialis (FDS), biceps brachii (BIC), and triceps brachii (TRI), were acquired and recorded; so were the moments on and the angles of each subject's MCP joints and PIP joints.

4.2.3. Outcome Measures

Three aspects of particular interest in this study are: (1) post-stroke weakness, (2) loss of finger dexterity, and (3) relationship between finger dexterity and hand functional ability. In order to analyze these three aspects, we applied different outcome measures.

The post-stroke weakness was evaluated by comparing the exerted joint moment during isometric MVT tasks. Combination of the joint moments measured in different fingers during a single task will be put into a formula that estimates the finger individuality (FI_i) as described below:

$$FI_i = \frac{F_{i,i}}{\sum_{j=1}^{5} F_{i,j}}$$

with $\overline{F_{i,j}}$ indicates the maximum flexion/extension force of finger j while finger i was instructed to perform an isometric MVT in the same flexion/extension direction and $\overline{F_{i,i}}$ indicates the maximum flexion/extension force of finger i while it was instructed to perform isometric flexion MVT. Meanwhile, i and j were the index of the five fingers, with 1 represents the thumb finger, 2 for the index finger, 3 for the middle finger, 4 for the ring finger, and 5 for the little finger. FI_i indicates the individuality level of the respective finger and ranges from 0 to 1, with 0 indicating that the instructed finger is completely unable to exert any force in the instructed direction and 1 indicating that the instructed finger is able to perform MVT in the instructed direction with the other 4 fingers not moving towards that direction at all. Hence, in this case an FI_i value of 0.2, for example, would indicate that the instructed finger exert the same amount of force as the average of the forces exerted by the other four fingers.

Averages of the $FI_i$of the five fingers (FII_{1to5}), as defined below, then served as a general index of the overall fingers individualities and were also used as the outcome measures to evaluate the change in finger dexterity after stroke.

$$FII_{1to5} = \sum_{i=1}^{5} \frac{FI_i}{5}$$

The same FII_{1to5} parameter was then plotted against different clinical scores, i.e. WMFT, ARAT, FMA, and MSS collected in the assessment prior to the study, and their correlation were calculated to estimate the relationship between finger dexterity and overall hand functional ability.

Additionally, as we were also interested in understanding the role that different combinations of fingers, e.g. the last four fingers except the thumb, the first three fingers only (thumb, index finger and middle finger), or the first two fingers (thumb and index finger), played in overall hand functions, we slightly modified and generalized the formulas of FI_i and $FII_{m\ to\ n}$ to suit the needs and again correlated them to the different clinical scores. Those parameters were then redefined as follows:

$$FII_{m\ to\ n} = \sum_{i=m}^{n} \frac{FI_i}{n-m+1}$$

$$FI_i = \frac{\overline{F_{i,i}}}{\sum_{j=m}^{n} \overline{F_{i,j}}}$$

The redefinition of FI_i generalized it as such that it only reflected the individuality of the respective finger with respect to the combination of fingers of interest. Similarly, the redefined $FII_{m\ to\ n}$ only gave overview of the individuality of the respective fingers combination. Hence, in this study, in addition to the FII_{1to5}, we then also examined the correlation between the individuality of the four fingers except the thumb (FII_{2to5}), that of the first three fingers (FII_{1to3}), as well as that of the first two fingers (FII_{1to2}) and the clinical scores. The R-squared values of those correlations were then used as the outcome measure for the relationship between finger dexterity and hand functional ability.

4.2.4. Data Analysis

Independent t-test with significance level of 0.05 was used to examine the existence of any significant difference between the two groups in terms of joint moment. Similarly, the same technique was also applied to analyze FI_i, and $FII_{m\ to\ n}$.

4.3. Results

Six right-handed right hemiplegic stroke survivors, of which five are males and one is female (age range = 28-69 years old, mean = 55.8 years old), were recruited for this study. Their demographics data as well as their clinical assessment scores are presented in Table 4.1. For the control group, another five males and one female, with age ranging from 29 to 71 years old (mean = 55.3 years old) were recruited. Their grip force was 328.19 N in average with a standard deviation of 81.06, as shown in Table 4.2 below.

Table 4.1. Clinical characteristics of the 6 stroke survivors recruited for this study.

Stroke Subjects							
Subject	**Age**	**Fugl-Meyer Assessment Scores**		**ARAT**	**MSS**	**Wolf**	**Grip Force (N)**
		Shoulder / Elbow	**Wrist / Hand**				
ES1 (Male)	65	36	20	38	36.6	3.6	222.46
ES2 (Male)	63	23	13	34	36.2	3.5	105.84
ES3 (Male)	69	20	5	15	20	2.3	55.37
ES4 (Male)	43	20	7	22	24.2	2.1	103.88
ES5 (Female)	67	21	9	25	33.4	3.13	78.89
ES6 (Male)	28	19	10	20	28	2.6	74.48
Mean	**55.8**	**23.17**	**10.67**	**25.67**	**29.73**	**3.36**	**106.82**
SD	*16.6*	*6.43*	*5.32*	*8.73*	*6.79*	*1.32*	59.76

Table 4.2. Demographic data of subjects in the control group.

Control Group		
Subject	**Age**	**Grip Force (N)**
CS1 (Male)	70	229.32
CS2 (Male)	36	436.10
CS3 (Male)	71	344.96
CS4 (Male)	29	392.29
CS5 (Female)	66	244.51
CS6 (Male)	60	321.93
Mean	**55.3**	**328.19**
SD	*18.4*	81.06

As shown in Figure 4.1 and Table 4.3 the mean maximum MCP and PIP joint moments during isometric flexion MCP for healthy subjects were about 1.78 Nm and 0.93 Nm, respectively. As for the stroke survivors, in average, their joint moments were slightly more than one-third of those of the healthy subjects.

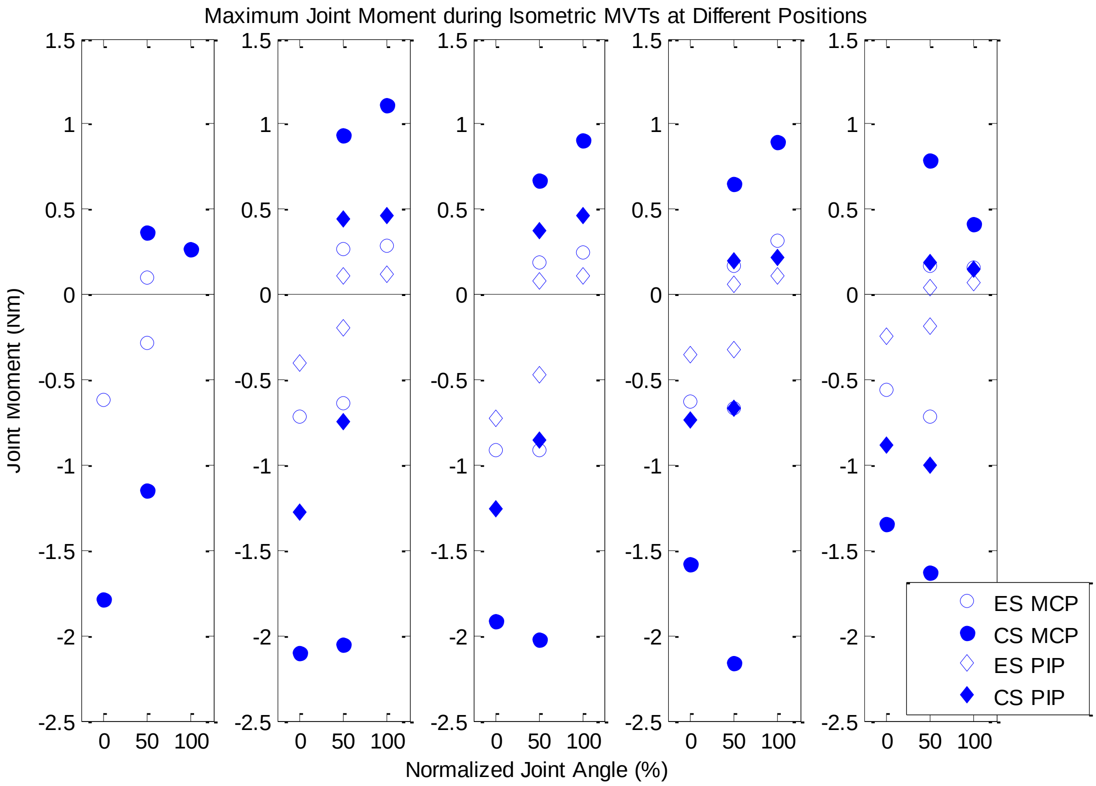


Figure 4.1. Mean maximum MCP and PIP joint moments during isometric MVTs of finger flexions and extensions in different positions (ES - stroke subjects; CS - healthy subjects; MCP - maximum MCP joint moment; PIP - maximum PIP joint moment). Positive value indicates finger extension, while negative value indicates finger flexion.

With regard to extension MVTs, as can be seen in Figure 4.2, in general finger extension was relatively weaker and more difficult to perform without involving the other fingers, even for healthy subjects. The chronic stroke subjects had higher level of flexor muscle tone that often kept their hand in a flexed posture. This is all depicted clearly in Figure 4.2 (c) and (d), where some of the values were negative, indicating flexion performed, despite the instruction being to extend their finger(s).

Table 4.3. Detailed values of maximum MCP and PIP joint moments during isometric MVTs of finger flexions and extensions in different positions.

	MCP Joint Moment			PIP Joint Moment		
	ES (Nm)	**CS (Nm)**	**ES:CS Ratio**	**ES (Nm)**	**CS (Nm)**	**ES:CS Ratio**
Thumb						
Flexion 0	-0.62	-1.79	0.35		N/A	
Flexion 50	-0.28	-1.15	0.25			
Extension 50	0.10	0.37	0.27			
Extension 100	0.27	0.27	0.99			
Index						
Flexion 0	-0.72	-2.11	0.34	-0.40	-1.28	0.31
Flexion 50	-0.64	-2.05	0.31	-0.19	-0.75	0.26
Extension 50	0.26	0.93	0.28	0.11	0.44	0.24
Extension 100	0.28	1.11	0.25	0.12	0.47	0.25
Middle						
Flexion 0	-0.91	-1.92	0.48	-0.73	-1.26	0.58
Flexion 50	-0.91	-2.02	0.45	-0.47	-0.86	0.55
Extension 50	0.19	0.67	0.28	0.08	0.37	0.22
Extension 100	0.25	0.90	0.28	0.11	0.47	0.23
Ring						
Flexion 0	-0.62	-1.58	0.39	-0.36	-0.74	0.48
Flexion 50	-0.67	-2.17	0.31	-0.32	-0.67	0.49
Extension 50	0.17	0.65	0.27	0.06	0.20	0.29
Extension 100	0.31	0.90	0.35	0.11	0.22	0.49
Little						
Flexion 0	-0.56	-1.35	0.41	-0.25	-0.88	0.28
Flexion 50	-0.72	-1.63	0.44	-0.18	-1.00	0.18
Extension 50	0.17	0.78	0.21	0.04	0.19	0.23
Extension 100	0.15	0.42	0.37	0.07	0.15	0.48
Mean						
Flexion	**0.66**	**1.78**	**0.37**	**0.36**	**0.93**	**0.39**
Extension	**0.22**	**0.70**	**0.36**	**0.09**	**0.31**	**0.30**
Overall	**0.44**	**1.24**	**0.36**	**0.23**	**0.62**	**0.35**

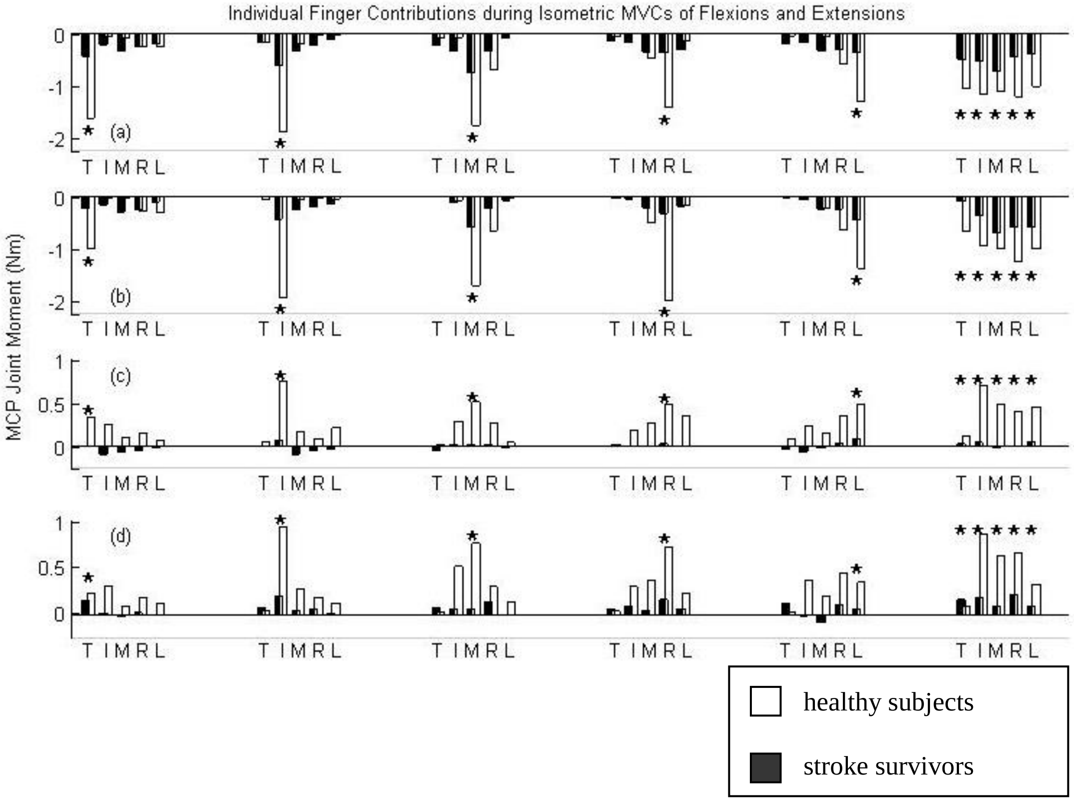


Figure 4.2. Individual finger contributions during isometric MVTs of (a) finger flexions at 0% joint angle; (b) finger flexions at 50% joint angle; (c) finger extensions at 50% joint angle; and (d) finger extensions at 100% joint angle. (T - thumb; I - index finger; M - middle finger; R - ring finger; L - little finger; marked with '*' are the instructed fingers).

As shown in Table 4.4 below, for healthy subjects in general, the index finger was outstandingly independent when compared to the other four fingers. While the other four fingers had FI of around 0.5 - 0.6, the FI of index finger reached 0.713. On the other hand, for stroke subjects, the FI values of the 4 fingers except thumb were found to be significantly lower at just about 44% - 54% of those of the healthy subjects; while for the thumb, the stroke subjects' FI was also lower at about 65% of that of the healthy subjects, despite no significant difference found.

Table 4.4. Finger individuality summary for all subjects from both healthy and stroke groups. The mean values were averaged from all tasks, both flexion and extension MVTs, and both at fully extended/flexed or middle starting positions.

Subjects	FI_i					$FII_{1,5}$
	Thumb (FI_1)	**Index** (FI_2)	**Middle** (FI_3)	**Ring** (FI_4)	**Little** (FI_5)	
Healthy Subjects						
CS1 (Male)	0.411	0.513	0.604	0.541	0.495	0.513
CS2 (Male)	0.579	0.823	0.730	0.809	0.727	0.734
CS3 (Male)	0.758	0.721	0.489	0.440	0.395	0.561
CS4 (Male)	0.458	0.869	0.692	0.676	0.746	0.688
CS5 (Female)	0.360	0.624	0.380	0.473	0.265	0.420
CS6 (Male)	0.524	0.727	0.507	0.502	0.555	0.563
Mean	**0.515**	**0.713**	**0.567**	**0.574**	**0.531**	**0.580**
SD	**0.142**	**0.130**	**0.133**	**0.141**	**0.187**	**0.115**
Stroke Subjects						
ES1 (Male)	0.636	0.540	0.500	0.368	0.569	0.523
ES2 (Male)	0.304	0.519	0.573	0.350	0.194	0.388
ES3 (Male)	0.142	0.131	0.144	0.204	0.229	0.170
ES4 (Male)	0.307	0.234	0.114	0.126	0.117	0.180
ES5 (Female)	0.549	0.538	0.370	0.360	0.366	0.437
ES6 (Male)	0.060	0.302	0.120	0.112	0.219	0.162
Mean	**0.333**	**0.377**	**0.304**	**0.253**	**0.282**	**0.310**
SD	**0.224**	**0.178**	**0.206**	**0.120**	**0.162**	**0.159**
% of FI (Stroke/Healthy)	**64.7**	**52.9**	**53.6**	**44.1**	**53.1**	**53.4**
p-value	**0.124**	**0.004***	**0.025***	**0.002***	**0.034***	**0.007***

Table 4.5 below showed a relatively high correlation between FII_{1to5} and different standard clinical scores such as FMA-SE, FMA-WH, ARAT, MSS, and WMFT. The correlation increased when FII taking into account only the four fingers except the thumb (FII_{2to5}). Unsurprisingly, FII_{1to2} and FII_{1to3} were found to be lower than FII_{1to5} and FII_{2to5}.

Table 4.5. Pearson product-moment correlation coefficient (Pearson's $\boldsymbol{r}$) between finger individuality indices (FIIs) and different clinical scores.

	Pearson's $\boldsymbol{r}$			
	$\boldsymbol{FII_{1to5}}$	$\boldsymbol{FII_{2to5}}$	$\boldsymbol{FII_{1to3}}$	$\boldsymbol{FII_{1to2}}$
ARAT	0.866	0.859	0.829	0.875
WMFT	0.915	0.950	0.879	0.855
FMA-SE	0.767	0.750	0.701	0.714
FMA-WH	0.789	0.795	0.717	0.768
MSS	0.885	0.900	0.867	0.901
Mean	**0.844**	**0.851**	**0.799**	**0.823**
SD	**0.063**	**0.080**	**0.084**	**0.079**

The FIIs were further broken down according to the direction of MVT, i.e. flexion and extension, and the starting position, i.e. fully extended/flexed and middle. While difference in starting position does not seem to greatly affect the calculation, it was pretty apparent that flexion FIIs correlated better to those clinical scores than extension FIIs did (see Table 4.6).

Table 4.6. Pearson product-moment correlation coefficient (Pearson's $\boldsymbol{r}$) between flexion and extension finger individuality indices (FIIs) and different clinical scores with the FIIs calculated separately in terms of starting position (i.e. fully extended/flexed and middle).

	Pearson's $\boldsymbol{r}$							
	Fully extended/flexed				**Middle**			
	FII_{1to5}	FII_{2to5}	FII_{1to3}	FII_{1to2}	FII_{1to5}	FII_{2to5}	FII_{1to3}	FII_{1to2}
Instructed direction: Extension								
ARAT	0.730	0.637	0.686	0.678	0.697	0.722	0.714	0.751
WMFT	0.614	0.771	0.611	0.501	0.819	0.859	0.838	0.860
FMA -SE	0.652	0.569	0.474	0.326	0.631	0.590	0.588	0.641
FMA -WH	0.546	0.504	0.445	0.508	0.649	0.648	0.618	0.666
MSS	0.638	0.693	0.682	0.735	0.813	0.858	0.831	0.846
Mean	**0.636**	**0.635**	**0.580**	**0.550**	**0.722**	**0.735**	**0.718**	**0.753**
SD	**0.066**	**0.104**	**0.114**	**0.162**	**0.089**	**0.122**	**0.116**	**0.100**
Instructed direction: Flexion								
ARAT	0.932	0.906	0.891	0.867	0.938	0.938	0.891	0.891
WMFT	0.964	0.988	0.861	0.809	0.963	0.945	0.947	0.891
FMA -SE	0.846	0.749	0.939	0.965	0.803	0.883	0.724	0.805
FMA -WH	0.902	0.844	0.918	0.900	0.859	0.926	0.772	0.786
MSS	0.907	0.910	0.813	0.746	0.901	0.869	0.901	0.837
Mean	**0.910**	**0.879**	**0.884**	**0.857**	**0.893**	**0.912**	**0.847**	**0.842**
SD	**0.044**	**0.089**	**0.050**	**0.084**	**0.064**	**0.034**	**0.094**	**0.048**

4.4. Summary

In this chapter, we demonstrated the use of the hand exoskeleton robot as a measurement device to study hand and fingers characteristics after stroke. Based on the results here, the discussion on how hand and fingers change following stroke would be presented in Chapter 6. With regard to finger individuality index, since it has been shown here that flexion FII had better correlation with other clinical scores when compared to extension FII, the extension FII would not be used in the next chapters. As no difference between $FII_{1to5}$and FII_{2to5} was observed, only flexion FII_{2to5} would be used in the next chapters. This was also meant to make the study more comparable with other studies on finger individuality that normally only take into account the four fingers other than the thumb (Li et al. 2001; Li 2002; Li et al. 2000).

Chapter 5

Study III: Robot-Assisted Finger Training in Chronic Stroke Survivors

This chapter discusses the use of the modified hand exoskeleton robot as a hand and fingers rehabilitation device for chronic survivors. It describes the study design, the control algorithm design, and the results of the pilot RCT with 19 chronic stroke survivors. The works described in this chapter has been published previously in Journal of NeuroEngineering and Rehabilitation in 2015 (Susanto, Tong, Ockenfeld, et al. 2015).

5.1. Introduction

Among others, individuals with stroke experience loss of those hand functions and dexterity, muscle weakness, abnormal synergies pattern, spasticity and a reduced range of motion in several joints in their paretic arm (Brunnström 1970); and regaining some dexterity in paretic arm proved to be very challenging with only around 38% of stroke patients could do so even six months after stroke (Kwakkel et al. 2003; Kwakkel et al. 2008; Nakayama et al. 1994). Hand functions recovery, in particular, is very limited with no consistent pattern of improvement shown in different studies reviewed by Langhorne et al (Langhorne et al. 2009; Langhorne et al. 2011). Given the central role that hand movements normally play, such as grasping, holding and manipulating objects, and their impacts to the quality of life of stroke survivors, it is of high importance to restore those functions.

Several therapy approaches for stroke rehabilitation have been developed over the last decades to reduce the motor impairments of the upper extremity (Langhorne et al. 2009; Langhorne et al. 2011). However, rehabilitation of hand and finger functions for patients 6 months after stroke has been difficult, time consuming and rarely practicable (Langhorne et al. 2009; Langhorne et al. 2011). Robotic devices have shown to be a promising complement to conventional therapy by facilitating repetitive movement training with high intensity and precision (Lum et al. 2012; Lo et al. 2010; French et al. 2010). They can be programmed and customized to suit the patient's individual needs, while simultaneously measure and record the movements and give feedback on the individual performance. However, in spite of the fact rehabilitation robots and studies related to its efficacy are numerous, not many are focusing on hand movements and not to mention finger movement, as have been previously described in Chapter 2 and 3.

This study aims to investigate the feasibility and possible efficacy of this robot-assisted fingers training for chronic stroke survivors, not only in the fingers themselves, but also on the more proximal joints and on the upper limb as a whole.

Furthermore, we will also evaluate the long-term effect of this 20-session training program on the paretic upper limb over a six-month follow-up.

5.2. Methodology

5.2.1. Device and Control Algorithm

The modified hand exoskeleton robot as described in previous chapter was again used in this study. The control platform was incorporated into the LabVIEW program developed. In the study, the hand exoskeleton robot provides assistance to the user's paretic hand to do three kinds of gestures: hand grasping and opening (all fingers are instructed to flex and extend), three-finger pinching and opening (only the thumb, the index finger, and the middle finger are instructed to flex and extend), and two-finger pinching and opening (only the thumb and the index finger are instructed to flex and extend). For the last two gestures, the non-instructed fingers (i.e. the ring and little fingers in three-finger pinch, and the middle, ring, and little fingers in two-finger pinch) were kept in flexed position by the linear actuators.

In order for the hand exoskeleton robot to initiate its assistance, the MCP joint moments of the instructed fingers have to be above the threshold level, and those of the non-instructed fingers have to be below the threshold level. Based on the finding by Li et al that average enslaving force, i.e. the force produced by a non-instructed finger while another finger is instructed to perform maximum voluntary torque

(MVT), in stroke survivors is around 25% (Li et al. 2003), the threshold level for each finger is set to be 20% of the maximum MCP joint moments measured while the user is performing isometric of flexion and extension MVT on the respective individual finger.

In addition to that, depending on the intended use of the device, the linear actuators can actually be detached from the digits, effectively removing the assistance of the robot and allowing these digits be moved passively with only minimum friction from the sliding potentiometer and the mechanical components. In this study, this feature is used for the non-assisted training of the control group.

5.2.2. Software Architecture

The LabVIEW program described in Section 3.2.5 was again used with some modifications. The data acquisition loop was slightly modified and a control algorithm loop was added to the program. The data acquisition loop was modified such that it also calculates whether or not the robot assistance shall be initiated and determines which command is to be sent to the MCU, based on the control algorithm described in the previous section. The control algorithm loop is structurally and functionally very similar to the serial TX loop, it is used to send a command to the MCU; the difference being that this loop is exclusively used to send commands generated by the based on the control algorithm to the MCU. This design is implemented intentionally to still allow manual override of command via the serial TX loop.

5.2.3. Subjects

Individuals with stroke can take part in the study if they satisfy the following inclusion criteria: (1) have primary stroke 6 to 24 months prior to the beginning of the intervention, (2) have moderate stroke condition, indicated by 50 > Fugl-Meyer Assessment (FMA) score > 18, (3) have the ability to understand simple commands, represented by Mini Mental State Examination (MMSE) score > 21, and (4) have the ability to differentiate sensation on one finger from that on the other fingers. Stroke survivors are excluded from the study should they have: (1) recurrent stroke, (2) other neurological, neuromuscular, or orthopedic disease, or (3) shoulder or arm contracture/pain.

5.2.4. Randomization

Participants were randomized evenly into 2 groups: (1) the robot-assisted (robot) group and (2) the non-assisted (control) group. The randomization was done by simple random number generator.

5.2.5. Protocol

In the Human Locomotion Laboratory of The Hong Kong Polytechnic University, participants underwent a total of 20 sessions robot-assisted finger training using the hand exoskeleton robot describer earlier (Tong et al. 2010; Susanto et al. 2012; Hu et al. 2013), with each session lasting for about 60 minutes. The training intensity is set at 3 to 5 times a week and all the 20 sessions were to be completed within 4-5 consecutive weeks. Approval on the human subjects ethics review has been obtained from the Departmental Research Committee of The Hong Kong Polytechnic University prior to the study.

In every session, the participant was first seated comfortably on a chair and his blood pressure was measured. This was then followed by a 10-minute stretching that was done passively. It is meant to relax the muscle tones and starts from the distal part, i.e. hand and each finger, and gradually moving up to the more proximal joints up to the shoulder. In between the stretching and the training part, some preparations for the training itself took place. Skin preparation was done on 7 sites (6 muscle groups of interest and 1 bony prominence) on the paretic arm on which EMG electrodes were to be placed. The six muscle groups of interest are: (1) abductor pollicis brevis (APB), (2) first dorsal interosseous (FDI), (3) flexor digitorum superficialis (FDS), (4) extensor digitorum (ED), (5) biceps brachii (BIC), and (6) triceps brachii (TRI), while the reference electrode was placed on the lateral epicondyle of the humerus.

Following the electrodes placement is the EMG activity measurements during each of the six muscles' isometric maximum voluntary contraction (MVC). Each patient was asked to perform MVC on each of the muscle, with each measurements lasting for about 5 seconds and around 3 seconds relaxing period before and after the MVC. The measurement was done twice for each muscles of interest. The data obtained from this MVC measurement were to be used as the normalization reference for all the EMG data obtained later in the session.

The hand exoskeleton robot was then put on the subject's paretic hand. The subject's forearm was placed on an arm rest with his elbow positioned at 90 degrees flexion. The subject was subsequently asked to perform individual finger flexion and extension isometric MVT in a randomized order. The extension and flexion joint moments for both MCP and PIP joints of each finger were measured by the strain gauges installed on the hand exoskeleton robot. This measurement also served as the calibration process for the control algorithm, which has been described previously.

The training section with the hand exoskeleton robot comprised three parts: hand grasp, three-finger pinch, and two-finger pinch. In all three parts, the subjects were to do the same task, the only difference is, as the names suggest, the gesture of the hand the subject were going to use in order to complete the task. The task was to move an object, i.e. a kitchen sponge, on a horizontal plane which is the table in front of the subject. Four points are marked on the table, in the shape of a rhombus with a horizontal diagonal of 500mm and a vertical diagonal of 300mm. The sequence of the movement is fixed as follows: started from the paretic side, to the non-paretic side, forward, backward, and then back to the paretic side. This movement is done continuously for about 4 minutes for hand grasp, 8 minutes for three-finger pinch, and another 8 minutes for two-finger pinch. One minute, two minutes, and another two minutes breaks are allowed after each part of the training, respectively.

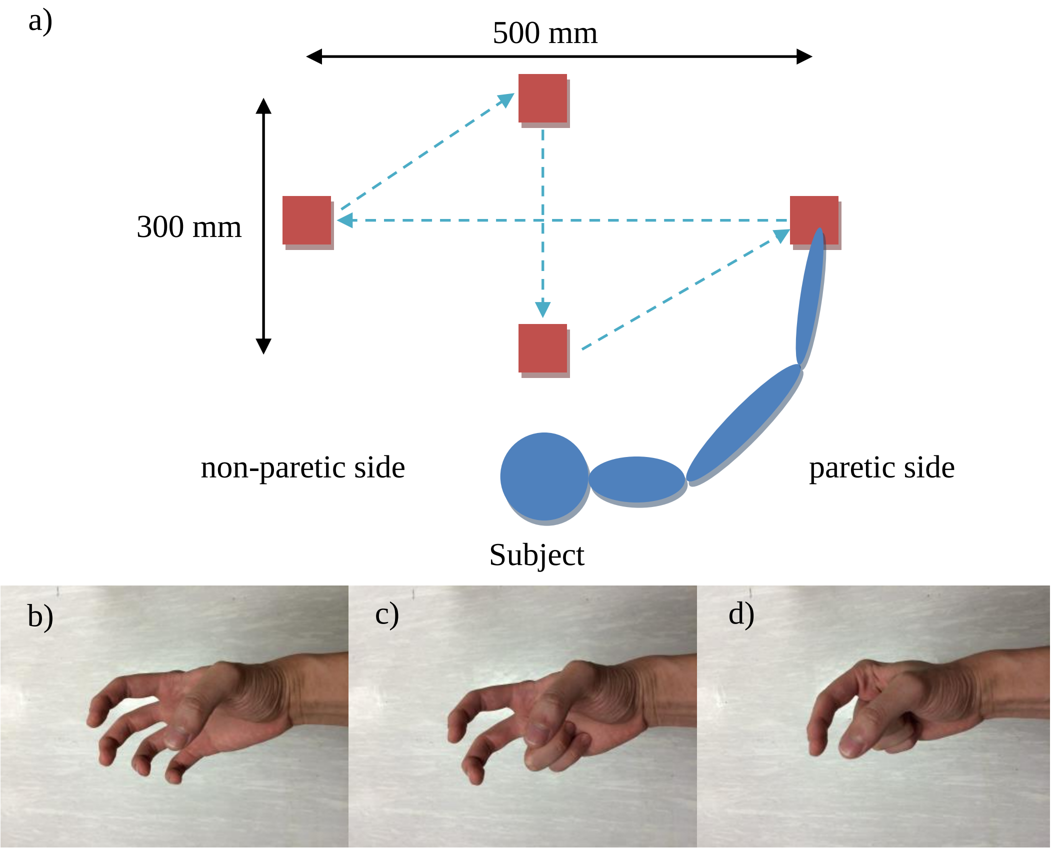


Figure 5.1. Illustrations of the training tasks. a) a diagram describing the setting of the training table and the direction of the movements that the subject was supposed to follow; b) an illustration of hand grasping; c) an illustration of 3-finger pinching; and d) an illustration of 2-finger pinching.

For the robot group, the movements of the subject's hand were to be assisted by the linear actuator based on the control algorithm. On the other hand, for the control group, the movements were done actively by the subject himself with the linear actuators of the device being detached from the digits.

In the evaluation section, the subject was to do different functional tasks without wearing the hand exoskeleton robot. Each task was to be done three times. The first task is to move an object horizontally from the ipsilateral side to the contralateral side then back to the ipsilateral side. The target points are the two markers along the horizontal diagonal of the rhombus used during the training. Second, the patient was asked to move a sponge vertically upwards and downwards and place the sponge onto a 170 mm tall two-level shelf. For the third to fifth tasks, the patient were asked to take and lift, respectively, a pen, a paper, and a 1 Hong Kong dollar coin (with a diameter of around 25.5 mm), from the table, hold them in the air for about 5 seconds and release it back on the table. Throughout the session, verbal instructions and postural control were continuously given to the subject to minimize compensation.

EMG data, joint moment data, as well as joint angles data were monitored and recorded throughout the whole evaluation and training parts. EMG data for FDI muscle, however, were only monitored and recorded during the evaluation section because in the training section, the subjects were to wear the hand exoskeleton robot and placement of EMG electrodes on FDI muscles while wearing the hand exoskeleton robot may cause discomfort for the subject. Thus, EMG electrodes on FDI muscle were actually placed after the training section and before the evaluation section.

5.2.6. Outcome Measures

Three clinical assessments, i.e. Action Research Arm Test (ARAT), Wolf Motor Function Test (WMFT), and Fugl Meyer Assessment (FMA), were adopted to evaluate the voluntary motor functions of the subject's paretic upper limb. This set of clinical assessments were done twice before the beginning of the intervention: one within 2 weeks from the starting date (Pre1), and another one within 1 week from the starting date (Pre2); and twice after the intervention is completed: once within 3 days after the last day of intervention (Post), and once more as 6-months follow-up (6Mo). The whole series of clinical assessments, i.e. Pre1, Pre2, Post, and 6Mo, for one subject were done by one same assessor out of the 4 assessors involved in this study. The assessors were of no knowledge about the subjects grouping.

The Action Research Arm Test (ARAT) is an upper extremity recovery assessment tool which covers not only proximal control of the arm, but also its dexterity (Hsueh et al. 2002). The assessment can be divided into 4 subsets: grasp, grip, pinch, and gross movement and has an overall maximum score of 57. Nevertheless, due to the uni-dimensional nature of the test, subset scores should never be used independently (Koh et al. 2006).

Wolf Motor Function Test (WMFT) aims to quantify UE functional ability in stroke patients based on the performance and the time required to complete single (or multiple) joint motions and functional tasks (Wolf et al. 2001). The WMFT consists of 17 items in total: 6 joint segment movements, 9 functional tasks, and 2 strength measurements. All tasks are to be performed as quickly as possible with a maximum allowed time of 120 seconds (Wolf et al. 2001). Only the 6 joint segment movements and 9 functional tasks are scored and timed (maximum total score = 75), strength is measured in terms of kilograms. With the study putting more emphasize on hand functions and dexterity, the subscore of WMFT with only its 9 functional tasks included (WMFT-FT) was analyzed as well.

The Fugl-Meyer Assessment (FMA) was an impairment index specifically designed to assess the motor function, balance, sensations, and joint functions in hemiplegic stroke survivors based on their performance (Fugl-Meyer et al. 1975; Gladstone et al. 2002). In this study, only the motor function part of the upper extremity Fugl-Meyer assessment, i.e. FMA-UE (motor function), which has a total score of 66, was used. To specifically evaluate the improvement on the larger and more proximal joints, i.e. shoulder and elbow, the shoulder and elbow subset score of the FMA (FMA-SE) was also analyzed independently.

All of the above clinical scores will be considered as the primary outcome measures of this study, with more emphasis put on ARAT and WMFT (including WMFT-FT) as the study places a heavier focus on hand function and dexterity.

As the secondary outcome measure, finger individuality index (FII) will be derived from the finger force data during individual finger MVC as an indicator of how the hand function changes throughout the 20-session training. FII is simply defined as:

$$FII = \sum_{i=2}^{5} \frac{FI_i}{4}$$

$$FI_i = \frac{\overline{F_{i,i}}}{\sum_{j=2}^{5} \overline{F_{i,j}}}, \quad for\ 2 \leq i \leq 5$$

With $\overline{F_{i,j}}$ indicates the maximum flexion force of finger j while finger i is doing an isometric MVT in the same flexion direction and $\overline{F_{i,i}}$ indicates the maximum flexion force of finger i while doing isometric flexion MVT. Meanwhile, i and j indicate the index of the fingers, with 1 represents the thumb,2 for the index finger, 3 for the middle finger, 4 for the ring finger, and 5 for the little finger.

FI ranges from 0 to 1, with 0 indicating that the instructed finger is completely unable to exert any flexion force and 1 indicating that the instructed finger is able to perform flexion MVT with the other 3 fingers not flexing at all. FII averages the FI of the 4 fingers and serves as a general index of their individualities as a whole.

5.2.7. Data Analysis

Analysis focuses on the primary outcome measures within and between groups. Our hypothesis is that the stroke survivors in the robot group will (1) have a better functional improvement at the end of the intervention and (2) be able to better maintain their functional ability after the intervention.

Non-parametric Wilcoxon's Signed-Rank test was done on for Pre1 and Pre2 scores on each group to make sure there is no significant change going on prior to the study; and to confirm that the two groups are indeed comparable, Mann-Whitney U-test was done for Pre2 assessments between groups. With those confirmed, for subsequent analysis of functional improvements, only Pre2 data were used as the baseline since it represents the latest functional condition of the patient before intervention.

Wilcoxon's Signed-Rank test was again performed to test changes in functional ability within each group at different time points. Mann-Whitney U-test, on the other hand, was used to perform inter-group analysis in terms of the functional improvement after the intervention (Pre2-Post) and the maintainability of the training effect 6 months after the intervention (Pre2–6Mo). A confidence interval of 95% was used throughout the analysis to determine significance and intention to treat principle was applied.

Additionally, mean change of FMA, ARAT, and WMFT scores were compared against the minimal clinically important difference (MCID) or minimal detectable change (MDC) value estimated by Page et al., van der Lee et al., and Lin et al., respectively (Page et al. 2012; van der Lee et al. 2002; Lin et al. 2009). Proportions of participants who exceeded the respective MCID/MDC values were also computed.

The same combinations of non-parametric tests were also used to perform intra- and inter-group analysis of FII.

5.3. Results

From January until September 2013, a total of 37 individuals with stroke responded to our media release and underwent a screening, eighteen of which were considered not suitable (see Figure 5.2 for more details). A total of 19 stroke survivors met the requirements to participate in the study and were randomly and evenly distributed into 2 groups; the robot-assisted (robot) group and the non-assisted (control) group. These nineteen stroke survivors (14 males and 5 females, aged 53.2 ± 9.9 years old) signed the consent form and participated in the study. Eighteen of the participating stroke survivors completed the 20-session training as well as the follow-up assessment, while the other one completed the training but did not take the follow-up assessment due to relocation to another city (see Figure 5.2). Additionally, Table 5.1 below, which shows the demographic data of the participants, indicates the two groups were not significantly different in terms of age, sex, handedness, affected side, stroke type, and mean months from onset to the first training session.

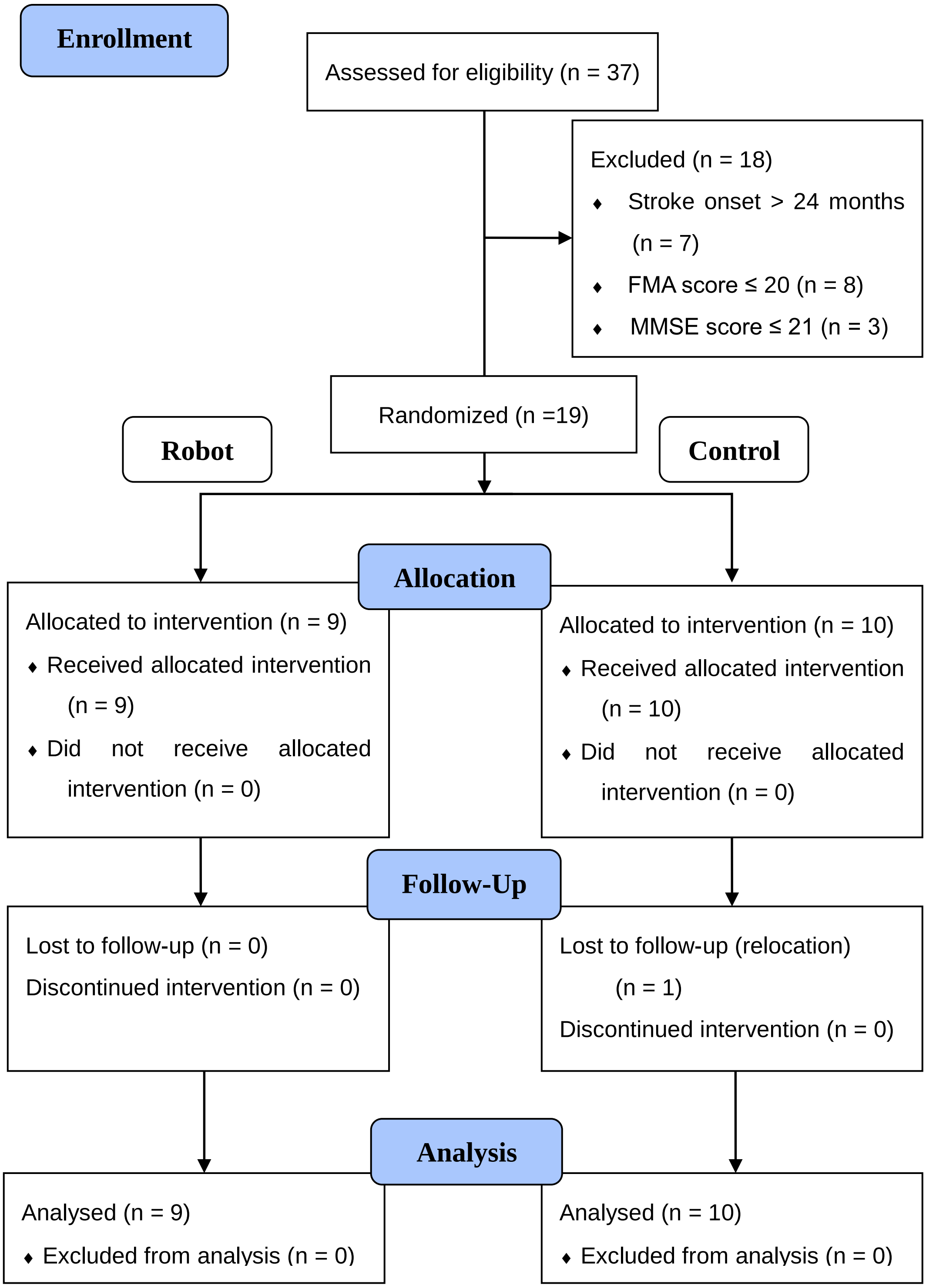


Figure 5.2. CONSORT flow diagram of the participants

Table 5.1. Demographic data of the participants.

Characteristic	Robot (n=9)	Control (n=10)
Mean age [SD]	50.7[9.0]	55.1[10.6]
Sex, male (%)	7(78)	7(70)
Handedness, right (%)	9(100)	10(100)
Affected side, right (%)	3(33)	4(40)
Stroke type, hemorrhagic (%)	3(33)	5(50)
Mean months from onset to first training session [SD]	16.4[5.8]	16.1[5.1]

Table 5.2 and Table 5.3 summarized the intra-group statistical analysis of the primary outcome measures. No significant difference was found between Pre1 and Pre2 measurements of the clinical assessments, indicating stable baseline values prior to the intervention. The robot group showed superiority over the control group with significant functional improvements after intervention (Pre2 vs. Post) present in all clinical scores of the robot group except FMA. This trend continued even until the 6-month follow-up as the robot group maintained significant improvement of ARAT ($p = 0.044$) and FMA-SE ($p = 0.020$), while the control group showed no significant improvement after 6 months.

Table 5.2. Comparisons of clinical assessment scores within the robot group.

Outcome Measures	**Mean±SD**				**p-value**	
	Pre1	**Pre2**	**Post**	**6Mo**	**Pre2 vs. Post**	**Pre2 vs. 6Mo**
Robot						
ARAT	16.56±10.86	17.33±10.62	31.33±8.01	28.33±11.97	0.008*	0.044*
WMFT Score	34.56±8.37	35.33±8.54	44.89±10.77	42.56±9.03	0.007*	0.109
WMFT Time	53.78±18.00	51.44±20.67	36.54±18.61	34.04±15.76	0.011*	0.066
WMFT-FT Score	10.22±6.27	11.22±7.44	20.11±7.99	17.67±7.89	0.007*	0.123
WMFT-FT Time	89.51±24.46	86.16±31.14	55.78±27.47	56.58±28.23	0.008*	0.066
FMA	31.67±12.19	31.89±11.98	37.00±12.48	38.00±13.53	0.065	0.123
FMA-SE	18.44±7.40	17.89±7.43	21.33±6.82	21.56±7.95	0.012*	0.020*
FMA-WH	10.56±5.12	11.11±5.30	12.56±4.52	13.78±5.16	0.438	0.210

Abbreviations: ARAT, Action Research Arm Test; WMFT, Wolf Motor Function Test; WMFT-FT, the functional movement tasks of Wolf Motor Function Test; FMA, Fugl-Meyer Assessment; FMA-SE, the shoulder and elbow parts of Fugl-Meyer Assessment; FMA-WH, the wrist and hand parts of Fugl-Meyer Assessment.

* indicates significant difference.

Table 5.3. Comparisons of clinical assessment scores within the control group.

Outcome Measures	Mean±SD				p-value	
	Pre1	Pre2	Post	6Mo	Pre2 vs. Post	Pre2 vs. 6Mo
Control						
ARAT	18.60±9.88	20.80±8.30	28.50±5.95	27.40±8.78	0.014*	0.083
WMFT Score	35.10±5.43	35.40±4.00	40.40±6.50	38.30±6.86	0.027*	0.107
WMFT Time	49.60±15.83	47.15±18.42	43.52±12.55	44.47±13.91	0.333	0.445
WMFT-FT Score	12.70±4.00	14.40±3.47	16.80±4.77	15.60±5.28	0.085	0.550
WMFT-FT Time	76.54±29.21	71.44±26.90	67.22±20.58	70.00±26.53	0.333	0.959
FMA	33.30±6.78	34.60±8.16	40.30±7.54	37.30±9.72	0.008*	0.083
FMA-SE	20.50±4.22	20.50±5.37	23.80±5.33	21.90±6.02	0.012*	0.230
FMA-WH	10.30±3.20	11.30±3.29	13.30±2.49	12.10±3.70	0.018*	0.255

Abbreviations: ARAT, Action Research Arm Test; WMFT, Wolf Motor Function Test; WMFT-FT, the functional movement tasks of Wolf Motor Function Test; FMA, Fugl-Meyer Assessment; FMA-SE, the shoulder and elbow parts of Fugl-Meyer Assessment; FMA-WH, the wrist and hand parts of Fugl-Meyer Assessment.

* indicates significant difference.

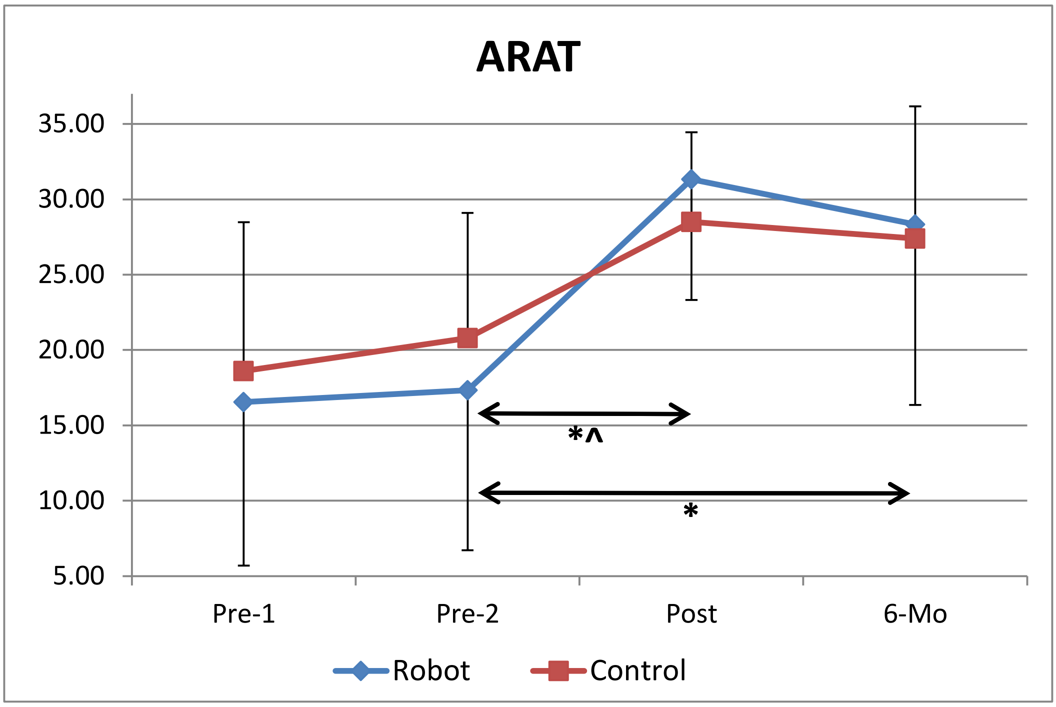


Figure 5.3. Comparison of ARAT score between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

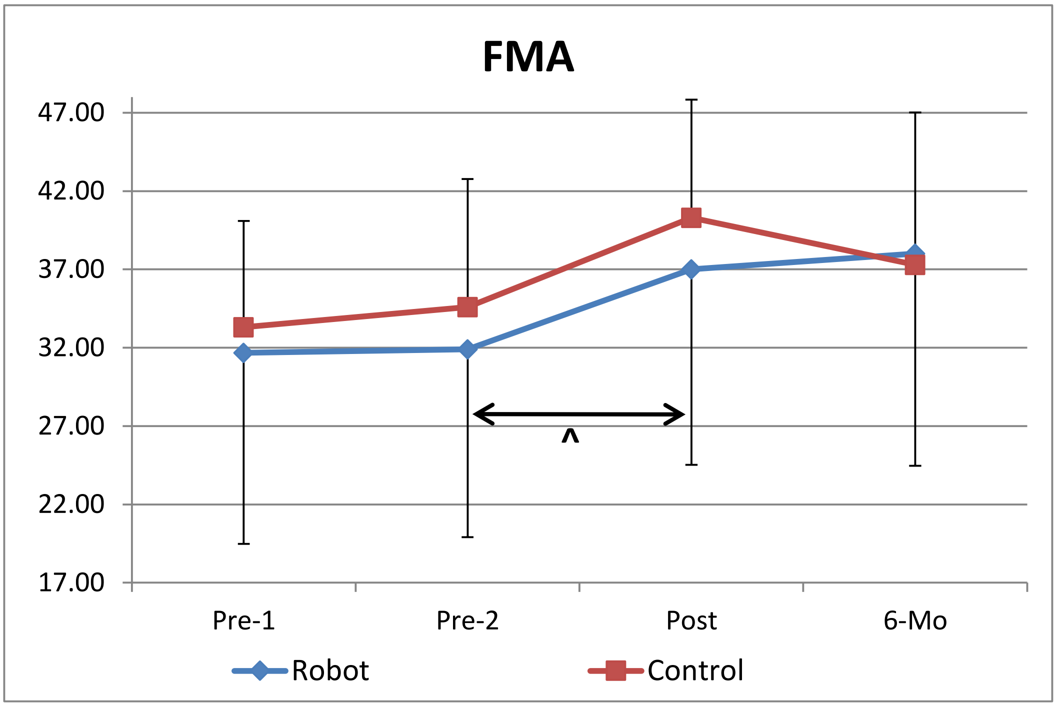


Figure 5.4. Comparison of FMA score between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

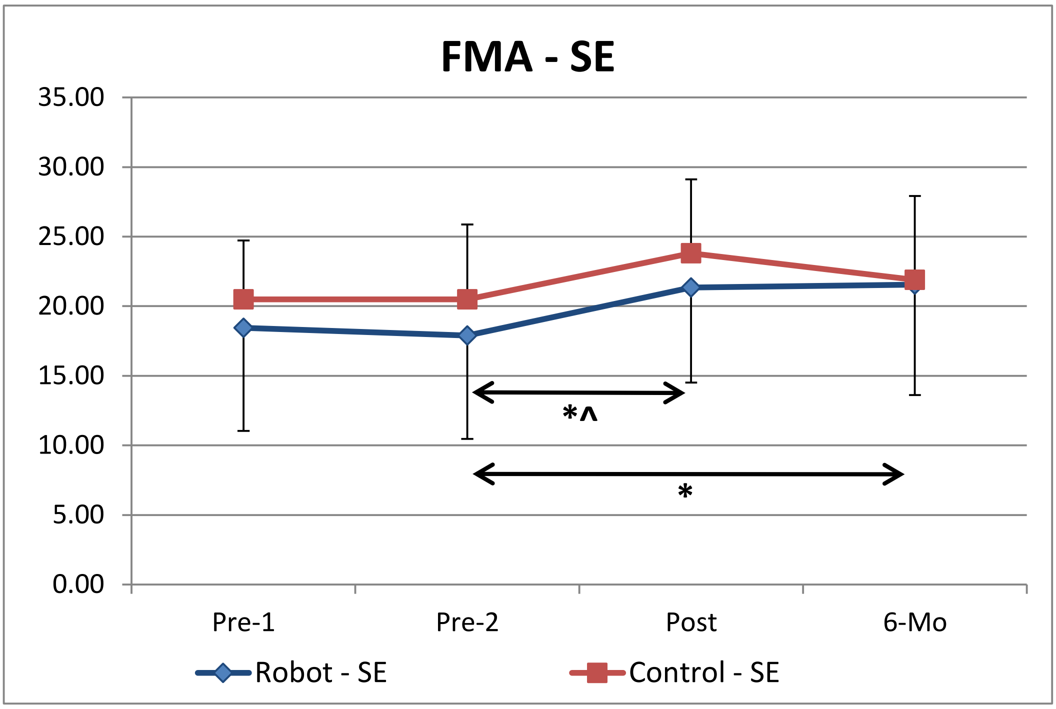


Figure 5.5. Comparison of FMA-SE score between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

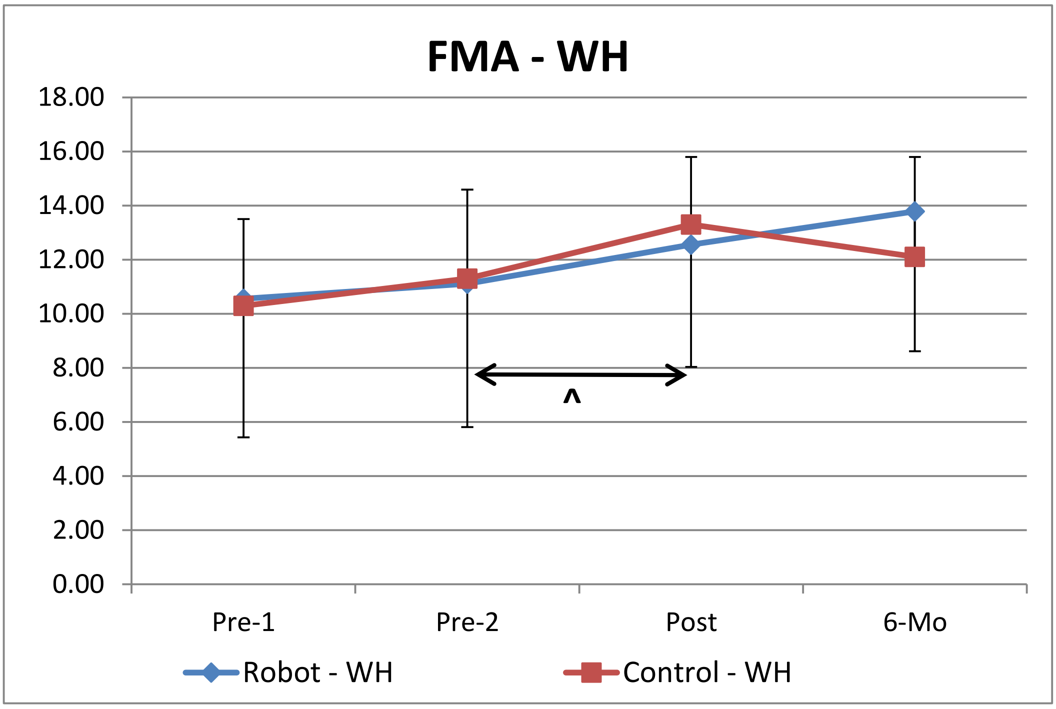


Figure 5.6. Comparison of FMA-WH score between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

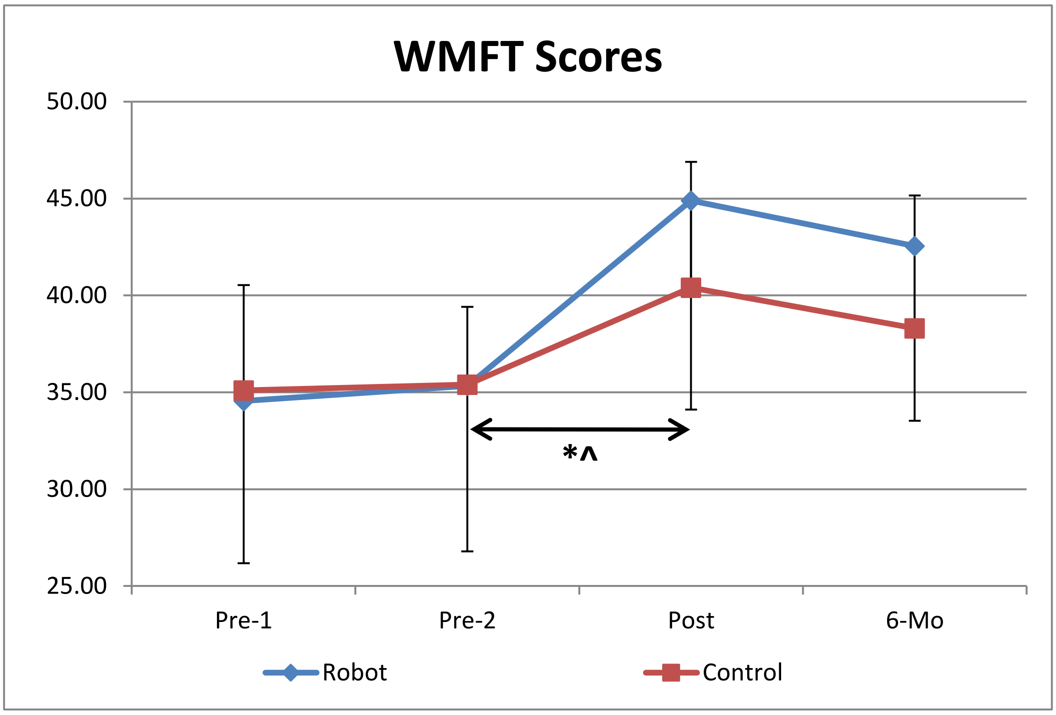


Figure 5.7. Comparison of WMFT score between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

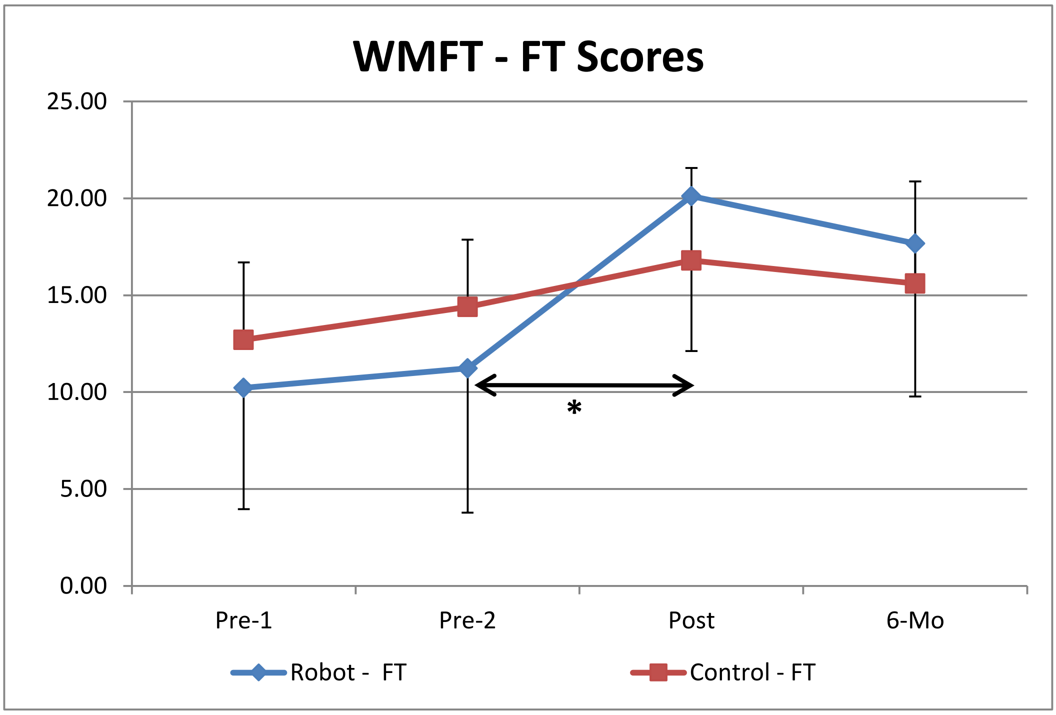


Figure 5.8. Comparison of WMFT-FT score between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

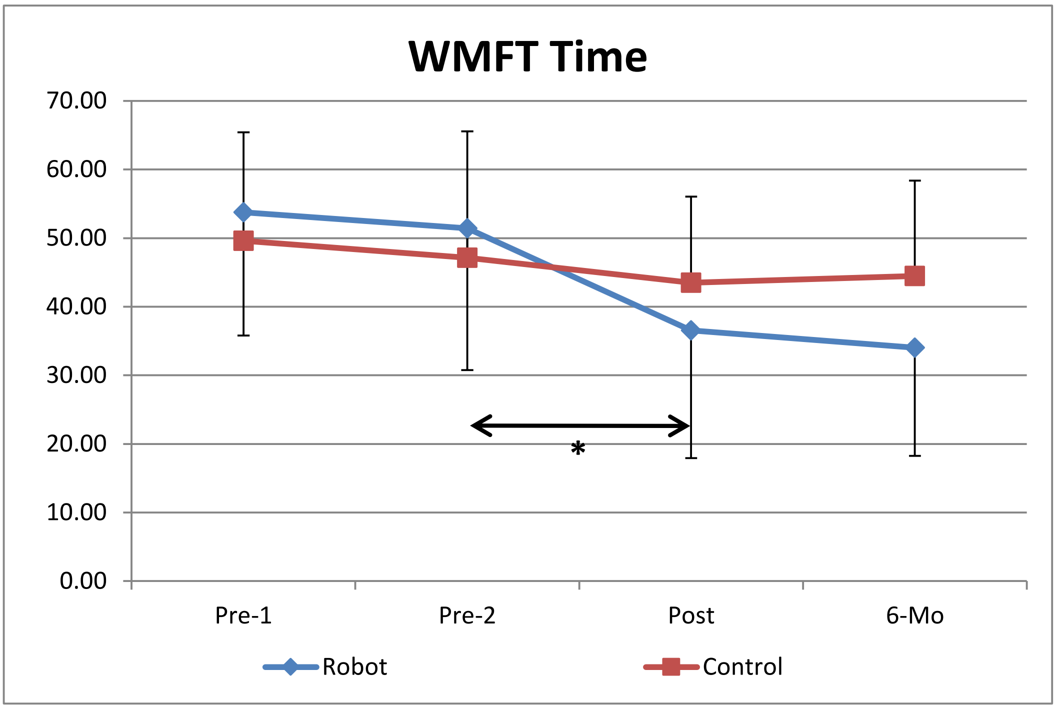


Figure 5.9. Comparison of WMFT average time between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

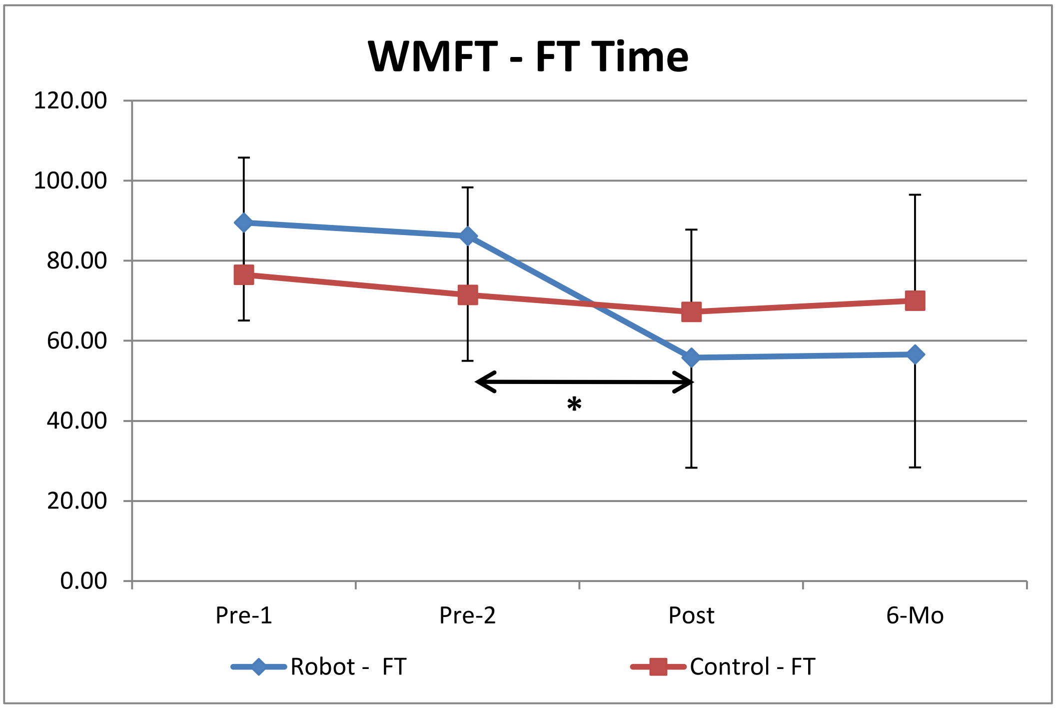


Figure 5.10. Comparison of WMFT-FT average time between the two groups at different time points. * and ^ indicate significant improvement in robot and control group, respectively.

Comparisons between groups have shown that functional improvement (Pre2 - Post) of WMFT-FT score and time were significantly better (both $p = 0.017$) in the robot group than in the control group (see Table 5.4). Meanwhile, no significant difference inter-group was found 6 months after the intervention (Pre2 – 6Mo).

When compared to their respective MCID/MDC values, as can be seen in Table 5.5, the average change in FMA, ARAT, and WMFT scores of the robot group were all higher than the MCID/MDC values both post-training and at 6-month follow-up; while for the control group, in line with the intra-group analysis, only FMA and ARAT showed higher improvement than their MCID/MDC values post training, and only ARAT maintained this 6 months post training. Similarly, there were more participants in the robot group exceeds the MCID/MDC values than there were in the control group, in all clinical scores and for both post-intervention and follow-up assessments.

Table 5.4. Inter-group comparisons of post-intervention effects.

Outcome Measures	**Mean Change ±SD**		**p-value**
Improvement	**Robot**	**Control**	
Pre2-Post			
ARAT	14.00±5.75	7.70±6.91	0.053
WMFT Score	9.56±7.54	5.00±6.46	0.113
WMFT Time	-14.91±12.06	-3.63±10.96	0.079
WMFT-FT Score	8.89±8.67	2.40±4.12	0.017*
WMFT-FT Time	-30.38±23.74	-4.22±21.01	0.017*
FMA	5.11±6.55	5.70±4.35	0.968
FMA-SE	3.44±2.01	3.30±2.65	0.905
FMA-WH	1.44±4.14	2.00±1.67	0.484
Pre2-6Mo			
ARAT	11.00±13.91	6.60±11.09	0.497
WMFT Score	7.22±12.50	2.90±5.07	0.720
WMFT Time	-17.40±24.10	-2.68±8.80	0.156
WMFT-FT Score	6.44±11.26	1.20±3.71	0.356
WMFT-FT Time	-29.58±39.92	-1.44±12.42	0.095
FMA	6.11±10.90	2.70±4.42	0.604
FMA-SE	3.67±5.35	1.40±2.87	0.356
FMA-WH	2.67±4.97	0.80±1.99	0.565

Abbreviations: ARAT, Action Research Arm Test; WMFT, Wolf Motor Function Test; WMFT-FT, the functional movement tasks of Wolf Motor Function Test; FMA, Fugl-Meyer Assessment; FMA-SE, the shoulder and elbow parts of Fugl-Meyer Assessment; FMA-WH, the wrist and hand parts of Fugl-Meyer Assessment.

* indicates significant difference.

Table 5.5. Comparison of intervention effects against MCID/MDC.

Outcome Measures	MCID/ MDC	Pre2-Post		Pre2-6Mo	
		Robot	Control	Robot	Control
Mean Change					
ARAT	5.70	14.00*	7.70*	11.00*	6.60*
WMFT Score	5.55	9.56*	5.00	7.22*	2.90
WMFT Time	-4.36	-14.91*	-3.63	-17.40*	-2.68
FMA	4.25	5.11*	5.70*	6.11*	2.70
Proportion Exceeding MCID/MDC					
ARAT	5.70	9/9(100%)	6/10(60%)	6/9(67%)	5/10(50%)
WMFT Score	5.55	8/9(89%)	4/10(40%)	4/9(44%)	2/10(20%)
WMFT Time	-4.36	8/9(89%)	6/10(60%)	6/9(67%)	5/10(50%)
FMA	4.25	5/9(56%)	5/10(50%)	5/9(56%)	4/10(40%)

Abbreviations: ARAT, Action Research Arm Test; WMFT, Wolf Motor Function Test; FMA, Fugl-Meyer Assessment; MCID, Minimal Clinically Important Difference; MDC, Minimal Detectable Change.
*indicates average improvement higher than MCID/MDC.

FII was monitored throughout the training. It can be seen from Figure 5.11 that there was an increasing trend for both groups until the 10th session; but beyond that, the control group seemed to be leveling off while the robot group continued to increase. Nevertheless, non-parametric test between the FII in the first session and that in the last session showed no significant improvement in both the robot group ($p = 0.096$) and the control group ($p = 0.527$). Neither was a significant difference found when performing inter-group comparison of the FII improvement ($p = 0.400$).

As additional information, both groups experienced significant increase in total flexion-extension repetitions made (accumulated from all grasping, three-finger pinching, and two-finger pinching). The robot group improved significantly from performing 80.56 ± 23.23 repetitions initially to 109.11 ± 9.41 repetitions in the last session ($p = 0.004$), while the control group went from 62.13 ± 17.96 repetitions in the first training session to 83.63 ± 22.12 repetitions by the last session ($p = 0.002$). Inter-group comparison, however, showed that the robot group significantly performed more repetitions by the last session ($p = 0.006$) although no significant difference was found in terms of repetition made between the two groups the first session ($p = 0.090$).

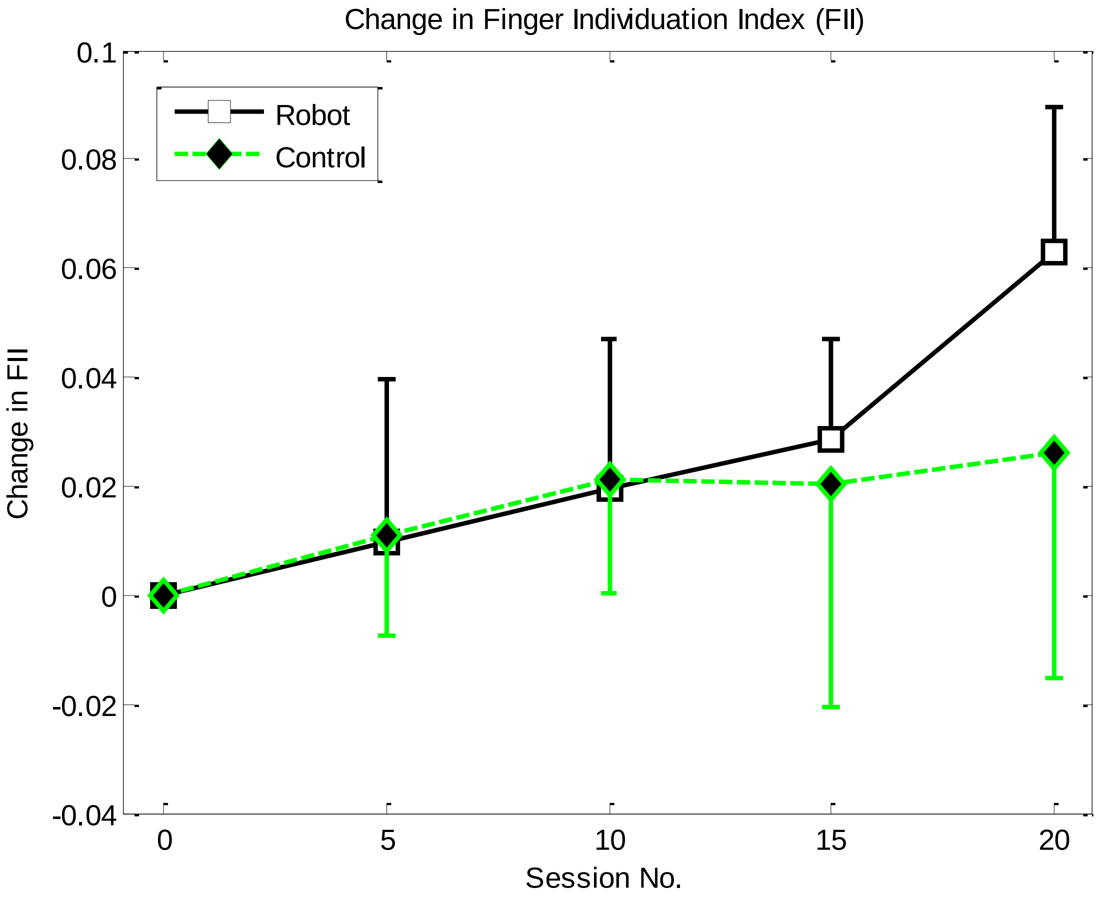


Figure 5.11. The change in FII throughout the 20-session training. Improvement in FII is more obvious in the robot group (black solid line) than in the control group (green dashed line).

5.4. Summary

This chapter showed the implementation of fingers training using the hand exoskeleton robot developed. The results showed the ability of the studied technique to provide significant improvement for individuals with stroke both during the training period and six months after the completion of the training. The following Chapter 6 will discuss in more details about this.

Chapter 6

Discussion

This chapter discusses the results obtained from the studies described in Chapter 4 and Chapter 5. From the results of the study described in Chapter 4, the weakness after stroke, the finger individuality after stroke and the possibility of using finger individuality index as an option to provide continuous monitoring of finger individuality, and possibly hand function in general. From the results described in Chapter 5, this chapter discusses the feasibility, the potential efficacy, and the possible recovery mechanism of the robot-assisted finger training. On top of that, the potential role of such robot-assisted training in clinical settings, also in relation to CIMT, is also discussed here.

6.1. Hand and Fingers Characteristics after Stroke

6.1.1. Weakness

For the joint moments, as can be seen in Figure 4.1, for healthy subjects, the average maximum MCP and PIP joint moment while the subject doing isometric MVC on individual finger flexion is about 1.78 Nm and 0.93 Nm, respectively. These values are actually different from what was reported by Li et al. which were around 3 Nm and 1.5 Nm for MCP and PIP respectively when the force was exerted at the distal interphalangeal joint (DIP) (Li et al. 2000). However, the differences can be attributed to the facts that: 1) The healthy subjects in this study were of older age with an average of 55.3 years old while in their study, the subjects were male university students of 28.9 years old in average who are presumably stronger in nature; and 2) in this study, the forces were exerted at the middle of the proximal phalanx and at the middle of the middle phalanx, while in their study, the force was exerted at the DIP, causing a longer moment arm that subsequently increased the measured moment.

As for the stroke survivors, in average, their joint moments were about one-third of those of the healthy subjects (see Table 4.3). This is in a good agreement with the fact that their average grip strength measured in the beginning of the study, which is also about one-third of that of the healthy subjects (see Table 4.1 and Table 4.2). This weakness in stroke subjects, which is evident in this study, has been shown to be partially resulted from the inability of the stroke survivors to recruit adequate skeletal motor units to generate the desired movement due to disruption in the neural pathways (Gracies 2005a; Gracies 2005b). Apart from that, there are also some other factors such as disuse-induced paretic muscle atrophy (Ng & Shepherd 2000), and loss and/or decreased firing rates of agonist motor units (McComas et al. 1973;

Rosenfalck & Andreassen 1980), that have been claimed to play significant roles in post-stroke muscle weakness.

6.1.2. Loss of Finger Individuality

The FII_{1to5} for each finger of each stroke subject and control subject can be seen in Table 4.4. The values were the average of the FIs of each finger during different isometric MVTs at different positions (i.e. finger flexions at 0% and 50% joint angles, and finger extensions at 50% and 100% joint angles); hence, representing the overall individuality of all five fingers in both flexion and extension directions.

With significant difference found between the two groups in terms of the FIs of all fingers except thumb as well as in terms of the FII_{1to5}, loss of individuality post stroke seems evident in this study. One possible mechanism controlling the loss of finger individuality could be just like the hypothesis proposed by Dewald et al with regard to the development of abnormal synergy post stroke where increased influence from the ipsilateral reticulospinal pathways with its multisegmental collateralization may induce co-activation of different muscles; making activation of individual muscle becomes more difficult (Ellis et al. 2007; Dewald et al. 1995; Matsuyama et al. 2004).

The hypothesis was based on: (1) studies on motor control in monkeys, which are thought to be also applicable to human being, suggesting that muscles on the distal part of the limbs are controlled by corticospinal pathways and, to a certain possibility, rubro-spinal pathways (Landgren et al. 1962; Clough et al. 1968; Brouwer & Ashby 1990; Kuypers & Martin 1982; Lemon 2008); and (2) previous findings that lesions in stroke subjects varied from cortical motor areas to subcortical region, which often subsequently damage the corticospinal pathways (Grefkes & Fink 2011; Dewald et al. 1995) and subsequently cause a reorganization in the central nervous system due to loss of corticospinal input that is replaced by greater influence from the bulbospinal input (Dewald et al. 1999). With those results, it was hypothesized that the ventromedial spinal descending pathways that are unlikely to be damage after stroke, specifically vestibulospinal and reticulospinal pathways, could potentially modify the activity in the muscles. In this case, the extensive branching nature of the vestibulo- and/or reticulospinal pathways could anatomically explain the abnormal muscle co-activation developed post-stroke, which subsequently results in loss of dexterity. As convincing as it is, evidence supporting this hypothesis remains very limited and the definite physiological mechanism remains unknown.

6.1.3. Finger Individuality and Hand Functional Ability

Additionally, although further investigation and proof are needed, according to this pilot study with only six subjects, the FII is actually closely related to other scoring systems used widely in clinical settings, such as the wrist and hand part of upper-limb Fugl-Meyer Assessment (FMA-WH), Action Research Arm Test (ARAT), Motor Status Scale (MSS), and Wolf Motor Function Test (WMFT) scores. Taking the mean of the FIIvalues of the five fingers of each stroke subject, and compare it with the respective subject's FMA-WH, ARAT, MSS, and Wolf test scores, it is shown in Table 4.5 that there is a reasonably strong correlation between FII and each of those four, indicated by the considerably high Pearson’s r values.

The fact that flexion FIIs correlated better to clinical scores, compared to extension FIIs, suggests that individual extension may not be as essential as individual flexion in daily activities. This is easily understandable as our activities of daily living seldom require selective fingers extension. We do need selective finger flexion at times but collective extension of all five fingers does not usually hinder us from performing activities of daily living. Such a high level of dexterity is only necessary while performing very specific tasks, such as playing musical instruments like piano or guitar.

We believe it is no coincidence that in many of the hand gestures that require extension of certain fingers and flexion of the others, we would use the thumb in a way that it would prevent the supposedly flexed fingers from extending. When we try to indicate the number one, by extending our index finger, our thumb would be positioned on the dorsal side of the middle, ring, and little fingers, in order to assist in the prevention of their extension; and it is also the same with other gestures like the number two and the number three gestures.

This could also possibly serve as a counter-argument to Raghavan et al who suggest that finger individuality does not correlate well to clinical scores assessing hand functions possibly because the separation in the corticospinal projections might be based on function rather than finger topography (Raghavan et al. 2006). The different findings of the two studies might be down to how the finger individuality is defined. In their study, it appears that the digit independency index used was calculated from overall finger movement in both flexion and extension directions. Having mentioned that, and having explaining the significance of a finger's flexion individuality over its extension individuality during daily activities, we have reasons to believe that should they be able to separate the digit's flexion independency from its extension independency, the results might be different.

Thus, potentially, this FII may even be able to be used clinically and provide a continuous monitoring system and complement to the clinical scoring systems that are widely used nowadays. For this, though, further study with larger number of subjects is necessary.

6.2. Robot-Assisted Fingers Training in Chronic Stroke Survivors

6.2.1. Feasibility

While this was not particularly design as a feasibility study, there are several indications that were able to give us some ideas about the feasibility of this rehabilitation technique to be applied in clinical settings. First of all, the fact that all 19 subjects participated in this study completed the 20-session training indicates that all these participants with varying levels of disability (FMA score ranging from 21 to 49 pre-training) were able to handle the intensity and requirements of the training and did not experience any adverse effect. Additionally, only one of them did not complete the 6-month follow-up and it was due to relocation to another city. This zero percent training drop-out rate in this study made it clearer that the training here does not put excessive burden to the participants. On top of that, while several reports of discomforts due to inaccurate alignment and positioning of the hand exoskeleton robot had been made to the experimenter, no report of serious pain and/or injury was made.

6.2.2. Potential Efficacy and its Possible Underlying Mechanisms

With robot-assisted therapy being able to facilitate repetitive motions with higher intensity and precision, we had it applied to finger dexterity rehabilitation. The results, as shown in Chapter 5, demonstrated improvements in all outcome measures by the end of the 20-session training have indicated the superiority of the robot group over the control group, who only showed significant improvements in ARAT and FMA scores. Furthermore, the clinical scores of about 44% to 67% of the participants in robot group improved better than their respective MCID/MDC values even after 6 months, compared to 20% to 50% of the participants in the control group.

There are two factors that may contribute to the superiority of the robot group. First is the encouraged and repetitive use of the paretic hand during the training in the early chronic phase (6 to 24 months post stroke onset) that seems to minimize of the behaviorally reinforced learned non-use, which is also one of the proposed contributing factors to the efficacy of CIMT (Taub et al. 2002; McIntyre et al. 2012). Furthermore, despite the non-existent of direct evidence, considering the use-dependent nature of brain plasticity (Draganski & Kherif 2013; Draganski et al.

2014), we believe that expansion of paretic arm representation area in the primary motor cortex (M1) might have also accompanied the aforementioned factor. The control group, who shared the same factor, also seems to benefit from it; indicated by the significant improvement of FMA and ARAT scores post training as well as the significantly more repetitions performed by both groups in the last training session compared to the first session.

The second factor, which also seems to be the difference maker as it is unique only to the robot group, is the control algorithm. As described in chapter 5.2.1, the control algorithm requires the user to activate only the instructed fingers and relax the rest, uninstructed, fingers. This might have provided the robot group with the necessary biofeedback to promote motor learning and muscle coordination.

Another finding shown is the possible beneficial effects of this training on the proximal joints, i.e. shoulder and elbow, despite the focus of the training being on hand and fingers functions. Significant improvements of FMA-SE score were found in both groups post training. It appears that the involvement of those more proximal joints in the course of completing the tasks might have beneficial effects. This is also in agreement with the finding of Oujamaa et al. regarding the importance and benefit of involving exercise of more distal joints of the paretic arm in upper limb rehabilitation (Oujamaa et al. 2009). In conjunction with the absence of proximal to distal motor deficit gradient (Beebe & Lang 2008), this finding further support the notion of holistic upper limb rehabilitation as opposed to single joint rehabilitation.

When comparing the tasks performed by the robot group to those performed by the control group, one may understandably anticipate better improvement in the control group due to reduced intensity in the robot group caused by the device assistance. This, however, was proven not evident by our results which indicated the superiority of the robot group. One possible explanation for that is that the subjects in the robot group may have compensated the reduced intensity by performing more repetitions of the tasks and using less non-paretic arm support throughout the course of the training. The significantly higher number of repetitions performed by the robot group in the last session certainly supports this argument. This increased actual use of their paretic arm and its induced motor function improvements may also lead to subsequent increased use of the paretic arm in their daily life.

Nevertheless, despite all these promising results in the post-training assessment, the long-term efficacy of this training is still in question as, although ARAT and FMA-SE scores of the robot group still showed significant improvement after 6 months, the inter-group analysis at the 6-month follow-up time point showed no significant difference between the two groups’ clinical scores improvement. This might be attributed to the large variations among the subjects; proving significant difference after 6 months may need a larger sample size.

Similarly, it is also questionable that the improvement in the robot group's FMA-WH score was not statistically significant despite the training targeting the hand and fingers. Significant improvement post training, though, was found in ARAT, which also put a lot of emphasis on hand function assessment. Looking deeper into the scoring system of and the actual tasks tested in FMA-WH and ARAT, we found 2 factors that might cause the difference: (1) the resolution of the scoring and (2) the way the 2 assessments interpret improvement.

In terms of scoring system, FMA-WH, and FMA in general, applies 3-point scoring system, in which for each task, the subject can score 0, 1, or 2. On the other hand, for ARAT, the subject can score 0, 1, 2, or 3 points for each task; making it slightly more sensitive to change, when compared to FMA. For the second factor, we shall first take a look at the categorization of each score in the 2 assessments.

Typical categorization of FMA-WH score is shown below (Fugl-Meyer et al. 1975; Gladstone et al. 2002):

(0) cannot be performed

(1) can hold paper but not against tug

(2) can hold paper against a tug

(example taken from the FMA assessment part (C) – Grasp task (B))

While for ARAT, the categorization is defined as (Hsueh et al. 2002):

(0) cannot perform any part of the test

(1) can partially perform the test

(2) can complete the test but took abnormally long or had great difficulty

(3) performs test normally

From those definitions, we can understand that the 2 assessments interpret full functionality in a somewhat different way. In order to improve from 1 point to 2 (full) points in FMA-WH, one needs to increase his muscle strength to be able to hold the object against tug. On the other hand, improvement from 1 point to 2 points or 2 points to 3 points on ARAT suggests that one can perform the task with less difficulty and in less period of time than he used to be able to.

Considering these factors, the non-significant difference of FMA-WH and the significant difference of ARAT post-training may suggest that the subjects in the robot group actually improved in terms of coordination and speed, but not necessarily in terms of strength. This is further supported by the significant improvement in WMFT time and the non-significant difference in grip strength post-training.

Taking a look at the FII data, while there is no significant improvement difference between the 2 groups post training, it is apparent that the improvement in the control group seems to reach a plateau after the 10th session, while the robot group continued to improve even until the last 5 sessions. This may suggest that extension of the training may further benefit the stroke survivors as the improvement in FII is still ongoing. This is further supported by Oujamaa et al that proposed a minimum of 30 hours rehabilitation training for chronic stroke rehabilitation (Oujamaa et al. 2009).

Finally, just for references, we also tried to compare our results to other similar clinical studies using other hand rehabilitation devices. One thing to note is that the comparison is between the results of different clinical studies, rather than the results that different devices provide. The main reason for that is because other than the device used being different, there are many other factors that came into play as well. For example: the period from stroke onset for each subject (i.e. chronic or subacute stroke survivors), the number of sessions, the length of each session, the tasks performed, etc. Having mentioned that, compared to study from Takahashi et al using HWARD (with average FMA improvement of 7.00 and average ARAT improvement of 4.00) and study from Stein et al using Amadeo (with average FMA change of 5.08), the robot group's mean FMA improvement of 5.11 and mean ARAT improvement of 14.00 post training shows that this pilot RCT of finger training using the hand exoskeleton robot provides comparable, if not better, results than other clinical studies with other devices. More comparisons with studies using other devices were not possible to be done due to difference in the outcome measures implemented.

6.2.3. Role in Current Rehabilitation Setting in Relation to Constraint-Induced Movement Therapy (CIMT)

CIMT, at the moment, is considered one of the most promising techniques in the field of upper limb stroke rehabilitation; another being the robot-assisted rehabilitation (Langhorne et al. 2009; Langhorne et al. 2011). A combination of CIMT and robot-assisted rehabilitation is a hot topic in the field nowadays. Considering those, we deem it necessary to discuss about the role of this robot-assisted fingers training in current rehabilitation settings and its relation to the CIMT.

Despite numerous studies showing the efficacy of CIMT, there are controversies over the use of selected population in those studies (Langhorne et al. 2009). CIMT is a very intense and stringent training in nature; hence allowing only stroke survivors with higher level of residual functions to begin with to join the training (Langhorne et al. 2009; Langhorne et al. 2011). With regard to this, while we do not deny the efficacy of the CIMT for those who are capable of managing it, we are of the opinion that there should be a balance between training efficacy and its applicability to greater population of individuals with stroke.

While it may not be able to deliver as astounding results as CIMT does, robot-assisted rehabilitation does have the ability to cater rehabilitation for stroke survivors with higher level of disability when compared to CIMT, allowing more individuals with stroke to participate. Having reviewed 16 randomized controlled trial (RCT) on CIMT, McIntyre et al revealed that the participants of those studies had pooled pre-intervention WMFT, ARAT, and FMA scores of 44.85, 32.23, and 42.27, respectively (McIntyre et al. 2012). In our study, meanwhile, 8 out of 9 participants in the robot group scored below the pooled score in WMFT and ARAT pre-intervention test, and 7 out of 9 participants scored below the pooled score in FMA. The minimum pre-intervention score for WMFT, ARAT, and FMA respectively are 24, 8, and 21. These numbers can even be lower as the system can potentially facilitate stroke survivors with higher level of impairment provided that they have a certain level of finger individuality. The threshold of the control algorithm can also be adjusted to facilitate even more severe stroke survivors, although it remains to be explored if that would affect the efficacy of the training itself.

Still related to the previous point, a somewhat similar but different benefit of this robot-assisted fingers training is that, with its lower baseline requirements, it is able to accommodate earlier rehabilitation for the participants. Numerous studies have proven that earlier stroke rehabilitation is much more preferable when possible (Musicco et al. 2003; Bernhardt et al. 2008; Cumming et al. 2011; Sorbello et al. 2009). Furthermore, with claim being made by Wolf et al that despite its better post-training effects, no significant difference were found when early CIMT was compared to one-year delayed CIMT with regard to the participants' functional ability 24 months after randomization (Wolf et al. 2010). Having mentioned that, the possibility of combining this robot-assisted fingers training with CIMT is intriguing to us. Its ability to improve the participants' functional ability and its wide applicability for stroke survivors with various level of impairment could make it an excellent solution for those individuals with stroke who cannot handle CIMT right away. Our results, which show that after 20 sessions of robot-assisted fingers training, about 67% of the participants in the robot group were able to increase their WMFT score past the pooled WMFT score mean of 44.85 (McIntyre et al. 2012), also further support this notion. In the future, these stroke survivors can probably start their rehabilitation with robot-assisted training first, before finally joining CIMT once their functional ability can meet CIMT's criteria.

Subsequently, we also think believe that there is a need to establish a standard that can help to systematically decide if a stroke survivors can participate in CIMT or if he should undergo robot-assisted rehabilitation instead. Here, we have proven that this robot-assisted fingers training was manageable by stroke survivors with a WMFT score as low as 24. As for CIMT, it has been suggested that depression and pinching ability, instead of clinical scores, are the main predictor of its efficacy (Fabbrini et al. 2014). In terms of CIMT, McIntyre et al has reported that the pooled WMFT prescore means for the studies they reviewed were 44.85 (McIntyre et al. 2012); there is no information, however, regarding the minimum WMFT prescore that can benefit from the CIMT. Nevertheless, considering that: (1) the pooled WMFT prescore were 44.85, (2) CIMT requires tasks to be solely done by the paretic arm as the non-paretic arm is being constraint, and (3) only a WMFT task score of 3 or above indicate that the stroke survivor being assessed were able to complete the task without any assistance from the non-paretic arm, we can estimate that a WMFT score of at least 35 to 40 is necessary in order for an individual with stroke to be able to manage CIMT. When the boundary is established, we will be able to systematically direct a stroke survivor to a rehabilitation technique that would suit his needs better; and to a certain extent, this boundary will also open up the possibility to apply a sequential robot-assisted therapy and CIMT rehabilitation, resembling the one proposed by Hsieh et al. (Hsieh et al. 2014), in clinical settings.

6.2.4. Limitations

Lastly, there are several limitations of this study that are deserved to be addressed. First and foremost being the fact that this study is merely a pilot study with limited sample size, which is insufficient to fully prove the efficacy of the technique but is adequate to estimate the sample size necessary for a future full-scale study. Our estimation (with 80% power level) indicates the need of recruiting around 60 subjects per group to prove the significance. And secondly, not monitoring the changes in brain by any means, we were unable to point out the exact mechanisms of the recovery that took place during the training.

Chapter 7

Conclusions and Recommendations for Future Work

7.1. Key Findings and Conclusions

Hand exoskeleton robot was developed and equipped with joint moment sensing feature, enabling measurements of MCP and PIP joint moments of every individual finger. The device's measurement was evaluated for its stability, linearity and repeatability. The device was then used to evaluate hand and fingers characteristics after stroke. Comparisons with neurologically-intact control subjects suggested that stroke induced muscle weakness and loss of finger individuality. Our results suggested that, when compared to those on the control subjects, individual finger MVTs on stroke survivors were weaker and accompanied by higher enslaving forces from the non-instructed fingers.

Our results also suggested that the ability of every finger to perform isolated flexion correlated well with clinical scores such as ARAT, WMFT, FMA, and MSS. The extension independency of the fingers, however, did not show significant correlations to the clinical scores. Following this finding, a finger individuality index (FII) was designed and proposed to facilitate a continuous monitoring of finger function.

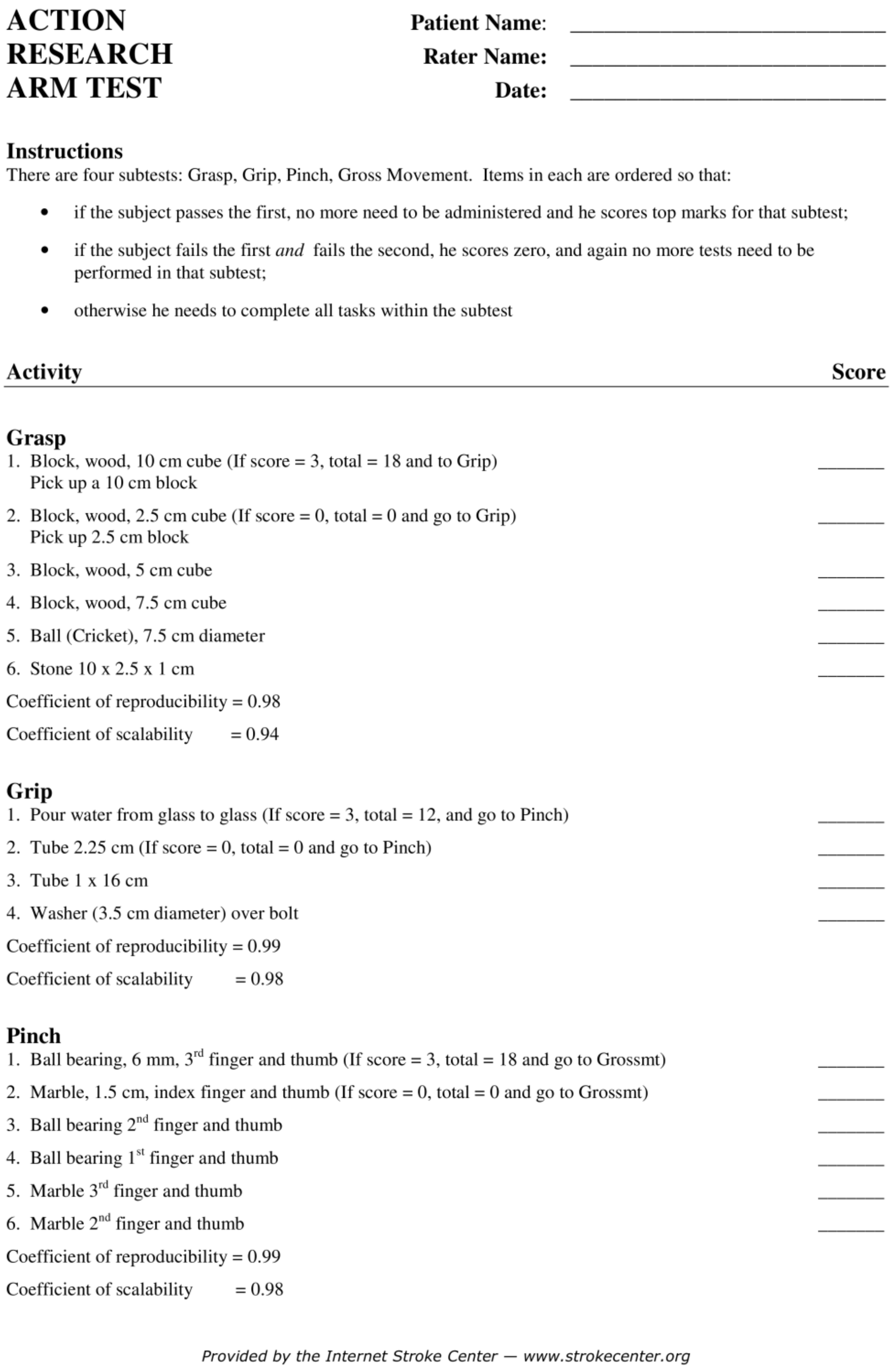
Subsequently, a robot-assisted fingers training was designed and proposed for chronic stroke survivors. The control algorithm for the training was designed based on the findings in the preliminary studies and some literatures. The system developed was modified accordingly to facilitate the training. Finally, a pilot randomized-controlled trial (RCT) with 19 stroke subjects was completed. The results showed feasibility and potential efficacy of the technique. The robot group improved significantly in the clinical scores (i.e. ARAT, WMFT, WMFT-FT, and FMA-SE) immediately post training and maintained such significant improvements in terms of ARAT and FMA-SE even 6 months post completion of the training. The control group improved in ARAT, WMFT, FMA, and FMA-SE scores post training, but failed to maintain any of the improvements 6 months later. In terms of FII, while the control group began to level off after the 10th session, the robot group continued to improve even until the 20th session; suggesting that more improvement could be obtained with more training sessions or hours. Possible mechanisms and the suggested role of this technique were also discussed in this thesis.

7.2. Recommendations for Future Works

For future studies, full-scale randomized-controlled trial with larger sample size should be conducted to verify the efficacy of the training protocol. It is also suggested that, in the full-scale RCT, brain scans should be done before and after the intervention to be able to monitor the changes in the brain and understand the possible mechanisms of the recovery. Ultimately, a combination of robot-assisted training with CIMT is also an interesting idea to explore.

Further improvements on the system can also be done. In fact, we have developed a new control system for this hand exoskeleton robot using Arduino Mega 2560 (Arduino LLC, USA) and Adafruit Motor Shield V2 (Adafruit Industries, USA), which allows us to have the following additional advantages: adjustable motor speed and integrated position feedback. The adjustable motor speed is achieved by means of pulse-width modulation (PWM) supported by the Arduino Mega 2560 board and will provide more flexibility for the training. The integrated position feedback is intended to ensure the whole range of motion is covered. In the system previously used in the study, the motor would stop moving after a certain period of time (e.g. 3 seconds); in some cases, such as in patients with high muscle tone, the motor would not be able to cover the whole ROM within the specified time frame. The integrated position feedback enables the system to stop only when the target position is reached, hence ensuring the whole ROM (either the device's ROM or the subject's passive ROM, whichever is less) to be covered. This new system will be tested and is intended to be used for our future studies.

Appendix A – Action Research Arm Test (ARAT) Form



ACTION
RESEARCH
ARM TEST

Patient Name: ______________________________
Rater Name: ______________________________
Date: ______________________________

Instructions

There are four subtests: Grasp, Grip, Pinch, Gross Movement. Items in each are ordered so that:

- if the subject passes the first, no more need to be administered and he scores top marks for that subtest;
- if the subject fails the first *and* fails the second, he scores zero, and again no more tests need to be performed in that subtest;
- otherwise he needs to complete all tasks within the subtest

Activity	**Score**
Grasp	
1. Block, wood, 10 cm cube (If score = 3, total = 18 and to Grip) Pick up a 10 cm block	_______
2. Block, wood, 2.5 cm cube (If score = 0, total = 0 and go to Grip) Pick up 2.5 cm block	_______
3. Block, wood, 5 cm cube	_______
4. Block, wood, 7.5 cm cube	_______
5. Ball (Cricket), 7.5 cm diameter	_______
6. Stone 10 x 2.5 x 1 cm	_______
Coefficient of reproducibility = 0.98	
Coefficient of scalability = 0.94	
Grip	
1. Pour water from glass to glass (If score = 3, total = 12, and go to Pinch)	_______
2. Tube 2.25 cm (If score = 0, total = 0 and go to Pinch)	_______
3. Tube 1 x 16 cm	_______
4. Washer (3.5 cm diameter) over bolt	_______
Coefficient of reproducibility = 0.99	
Coefficient of scalability = 0.98	
Pinch	
1. Ball bearing, 6 mm, 3rd finger and thumb (If score = 3, total = 18 and go to Grossmt)	_______
2. Marble, 1.5 cm, index finger and thumb (If score = 0, total = 0 and go to Grossmt)	_______
3. Ball bearing 2nd finger and thumb	_______
4. Ball bearing 1st finger and thumb	_______
5. Marble 3rd finger and thumb	_______
6. Marble 2nd finger and thumb	_______
Coefficient of reproducibility = 0.99	
Coefficient of scalability = 0.98	

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Grossmt (Gross Movement)

1. Place hand behind head (If score = 3, total = 9 and finish) _______
2. (If score = 0, total = 0 and finish _______
3. Place hand on top of head _______
4. Hand to mouth _______

Coefficient of reproducibility = 0.98

Coefficient of scalability = 0.97

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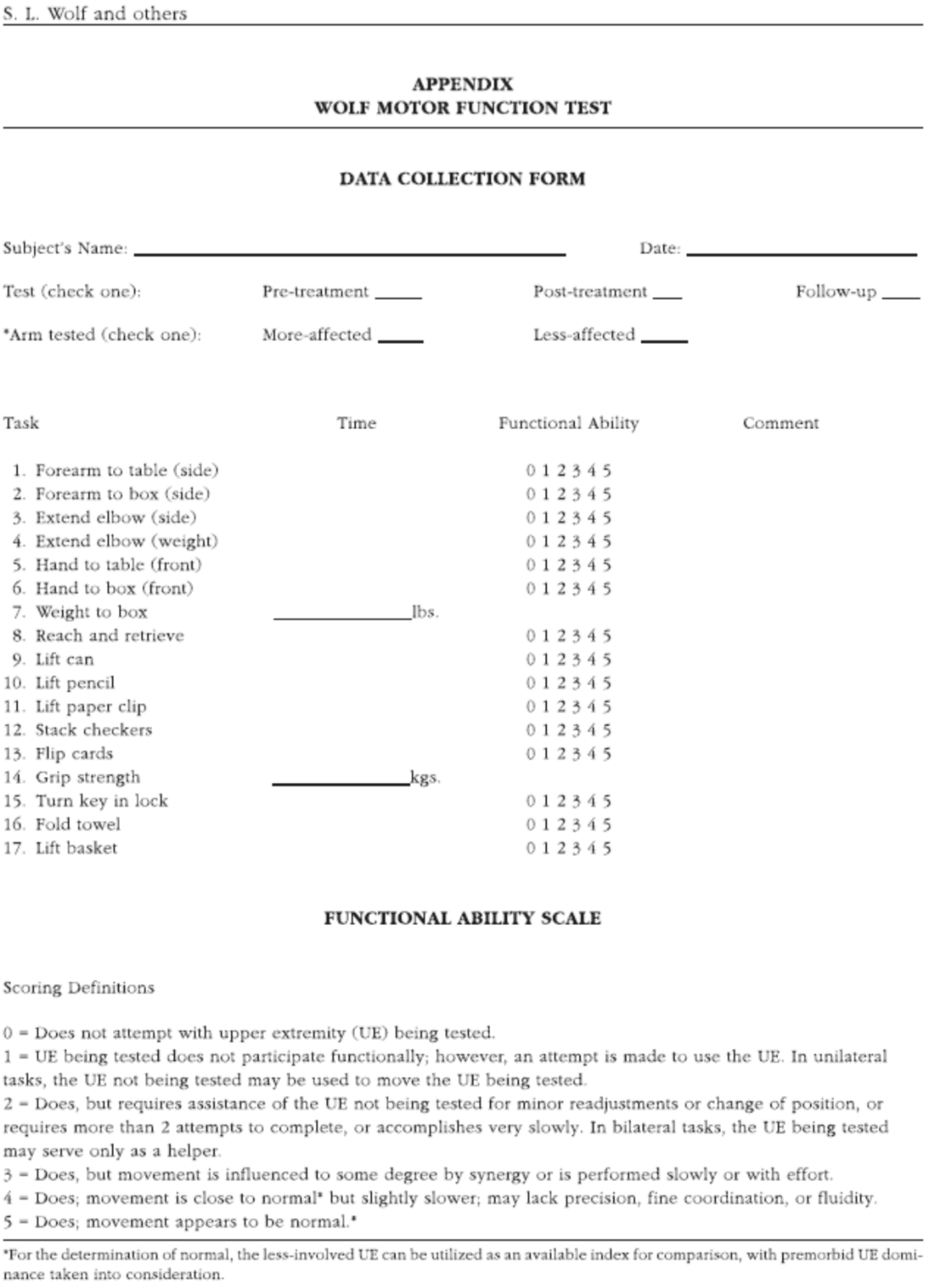
Appendix B – Wolf Motor Function Test (WMFT) Form



S. L. Wolf and others

APPENDIX
WOLF MOTOR FUNCTION TEST

DATA COLLECTION FORM

Subject's Name: ______________________ Date: ______________

Test (check one): Pre-treatment _____ Post-treatment ___ Follow-up ____

*Arm tested (check one): More-affected _____ Less-affected _____

Task	Time	Functional Ability	Comment
1. Forearm to table (side)		0 1 2 3 4 5	
2. Forearm to box (side)		0 1 2 3 4 5	
3. Extend elbow (side)		0 1 2 3 4 5	
4. Extend elbow (weight)		0 1 2 3 4 5	
5. Hand to table (front)		0 1 2 3 4 5	
6. Hand to box (front)		0 1 2 3 4 5	
7. Weight to box	____________lbs.		
8. Reach and retrieve		0 1 2 3 4 5	
9. Lift can		0 1 2 3 4 5	
10. Lift pencil		0 1 2 3 4 5	
11. Lift paper clip		0 1 2 3 4 5	
12. Stack checkers		0 1 2 3 4 5	
13. Flip cards		0 1 2 3 4 5	
14. Grip strength	____________kgs.		
15. Turn key in lock		0 1 2 3 4 5	
16. Fold towel		0 1 2 3 4 5	
17. Lift basket		0 1 2 3 4 5	

FUNCTIONAL ABILITY SCALE

Scoring Definitions

0 = Does not attempt with upper extremity (UE) being tested.
1 = UE being tested does not participate functionally; however, an attempt is made to use the UE. In unilateral tasks, the UE not being tested may be used to move the UE being tested.
2 = Does, but requires assistance of the UE not being tested for minor readjustments or change of position, or requires more than 2 attempts to complete, or accomplishes very slowly. In bilateral tasks, the UE being tested may serve only as a helper.
3 = Does, but movement is influenced to some degree by synergy or is performed slowly or with effort.
4 = Does; movement is close to normal* but slightly slower; may lack precision, fine coordination, or fluidity.
5 = Does; movement appears to be normal.*

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*For the determination of normal, the less-involved UE can be utilized as an available index for comparison, with premorbid UE dominance taken into consideration.

Appendix C – Fugl-Meyer Assessment Upper Extremity (FMA) Form

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FUGL-MEYER ASSESSMENT
UPPER EXTREMITY (FMA-UE)
Assessment of sensorimotor function

ID:
Date:
Examiner:

Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S: The post-stroke hemiplegic patient. A method for evaluation of physical performance. Scand J Rehabil Med 1975, 7:13-31.

A. UPPER EXTREMITY, sitting position

I. Reflex activity	**none**	**can be elicited**
Flexors: biceps and finger flexors	0	2
Extensors: triceps	0	2
Subtotal I (max 4)		

II. Volitional movement within synergies, without gravitational help			**none**	**partial**	**full**
Flexor synergy: Hand from contralateral knee to ipsilateral ear. From extensor synergy (shoulder adduction/ internal rotation, elbow extension, forearm pronation) to flexor synergy (shoulder abduction/ external rotation, elbow flexion, forearm supination).	Shoulder	retraction	0	1	2
		elevation	0	1	2
		abduction (90°)	0	1	2
		external rotation	0	1	2
	Elbow	flexion	0	1	2
	Forearm	supination	0	1	2
Extensor synergy: Hand from ipsilateral ear to the contralateral knee	Shoulder	adduction/internal rotation	0	1	2
	Elbow	extension	0	1	2
	Forearm	pronation	0	1	2
		Subtotal II (max 18)			

III. Volitional movement mixing synergies, without compensation		**none**	**partial**	**full**
Hand to lumbar spine	cannot be performed, hand in front of SIAS	0		
	hand behind of SIAS (without compensation)		1	
	hand to lumbar spine (without compensation)			2
Shoulder flexion 0°-90°	immediate abduction or elbow flexion	0		
elbow at 0°	abduction or elbow flexion during movement		1	
pronation-supination 0°	complete flexion 90°, maintains 0° in elbow			2
Pronation-supination	no pronation/supination, starting position impossible	0		
elbow at 90°	limited pronation/supination, maintains position		1	
shoulder at 0°	complete pronation/supination, maintains position			2
	Subtotal III (max 6)			

IV. Volitional movement with little or no synergy		**none**	**partial**	**full**
Shoulder abduction 0 - 90°	immediate supination or elbow flexion	0		
elbow at 0°	supination or elbow flexion during movement		1	
forearm pronated	abduction 90°, maintains extension and pronation			2
Shoulder flexion 90°- 180°	immediate abduction or elbow flexion	0		
elbow at 0°	abduction or elbow flexion during movement		1	
pronation-supination 0°	complete flexion, maintains 0° in elbow			2
Pronation/supination	no pronation/supination, starting position impossible	0		
elbow at 0°	limited pronation/supination, maintains extension		1	
shoulder at 30°-90° flexion	full pronation/supination, maintains elbow extension			2
	Subtotal IV (max 6)			

V. Normal reflex activity evaluated only if full score of 6 points achieved on part IV				
biceps, triceps,	0 points on part IV or 2 of 3 reflexes markedly hyperactive	0		
finger flexors	1 reflex markedly hyperactive or at least 2 reflexes lively		1	
	maximum of 1 reflex lively, none hyperactive			2
	Subtotal V (max 2)			
	Total A (max 36)			

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B. WRIST support may be provided at the elbow to take or hold the position, no support at wrist, check the passive range of motion prior testing		none	partial	full
Stability at 15° dorsiflexion elbow at 90°, forearm pronated shoulder at 0°	less than 15° active dorsiflexion dorsiflexion 15°, no resistance is taken maintains position against resistance	0	1	2
Repeated dorsifexion / volar flexion elbow at 90°, forearm pronated shoulder at 0°, slight finger flexion	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Stability at 15° dorsiflexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	less than 15° active dorsiflexion dorsiflexion 15°, no resistance is taken maintains position against resistance	0	1	2
Repeated dorsifexion / volar flexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Circumduction	cannot perform volitionally jerky movement or incomplete complete and smooth circumduction	0	1	2
	Total B (max 10)			

C. HAND support may be provided at the elbow to keep 90° flexion, no support at the wrist, compare with unaffected hand, the objects are interposed, active grasp		none	partial	full
Mass flexion from full active or passive extension		0	1	2
Mass extension from full active or passive flexion		0	1	2
GRASP				
A – flexion in PIP and DIP (digits II-V) **extension in MCP II-V**	cannot be performed can hold position but weak maintains position against resistance	0	1	2
B – thumb adduction 1-st CMC, MCP, IP at 0°, scrap of paper between thumb and 2-nd MCP joint	cannot be performed can hold paper but not against tug can hold paper against a tug	0	1	2
C - opposition pulpa of the thumb against the pulpa of 2-nd finger, pencil, tug upward	cannot be performed can hold pencil but not against tug can hold pencil against a tug	0	1	2
D – cylinder grip cylinder shaped object (small can) tug upward, opposition in digits I and II	cannot be performed can hold cylinder but not against tug can hold cylinder against a tug	0	1	2
E – spherical grip fingers in abduction/flexion, thumb opposed, tennis ball	cannot be performed can hold ball but not against tug can hold ball against a tug	0	1	2
	Total C (max 14)			

D. COORDINATION/SPEED after one trial with both arms, blind-folded, tip of the index finger from knee to nose, 5 times as fast as possible		marked	slight	none
Tremor		0	1	2
Dysmetria	pronounced or unsystematic slight and systematic no dysmetria	0	1	2
		> 5s	**2 - 5s**	**< 1s**
Time	more than 5 seconds slower than unaffected side 2-5 seconds slower than unaffected side maximum difference of1 second between sides	0	1	2
	Total D (max 6)			

TOTAL A-D (max 66)	

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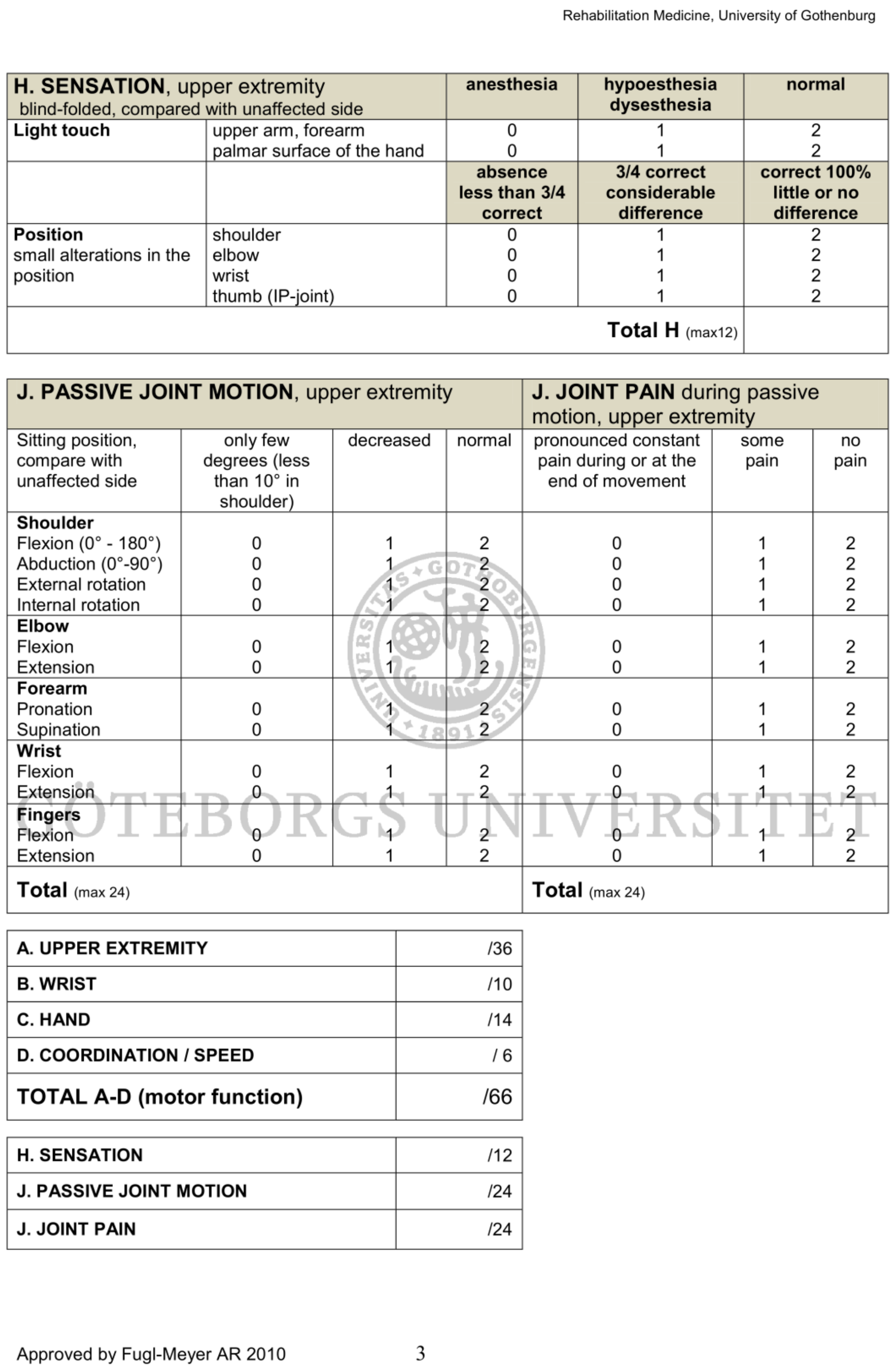

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H. SENSATION, upper extremity blind-folded, compared with unaffected side		**anesthesia**	**hypoesthesia dysesthesia**	**normal**
Light touch	upper arm, forearm	0	1	2
	palmar surface of the hand	0	1	2
		absence less than 3/4 correct	**3/4 correct considerable difference**	**correct 100% little or no difference**
Position small alterations in the position	shoulder	0	1	2
	elbow	0	1	2
	wrist	0	1	2
	thumb (IP-joint)	0	1	2
			Total H (max12)	

J. PASSIVE JOINT MOTION, upper extremity				**J. JOINT PAIN** during passive motion, upper extremity		
Sitting position, compare with unaffected side	only few degrees (less than 10° in shoulder)	decreased	normal	pronounced constant pain during or at the end of movement	some pain	no pain
Shoulder						
Flexion (0° - 180°)	0	1	2	0	1	2
Abduction (0°-90°)	0	1	2	0	1	2
External rotation	0	1	2	0	1	2
Internal rotation	0	1	2	0	1	2
Elbow						
Flexion	0	1	2	0	1	2
Extension	0	1	2	0	1	2
Forearm						
Pronation	0	1	2	0	1	2
Supination	0	1	2	0	1	2
Wrist						
Flexion	0	1	2	0	1	2
Extension	0	1	2	0	1	2
Fingers						
Flexion	0	1	2	0	1	2
Extension	0	1	2	0	1	2
Total (max 24)				**Total** (max 24)		

A. UPPER EXTREMITY	/36
B. WRIST	/10
C. HAND	/14
D. COORDINATION / SPEED	/ 6
TOTAL A-D (motor function)	/66

H. SENSATION	/12
J. PASSIVE JOINT MOTION	/24
J. JOINT PAIN	/24

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