INVESTIGATION OF ROBOT ASSISTED SENSORIMOTOR UPPER LIMB REHABILITATION AFTER STROKE

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Investigation of Robot Assisted Sensorimotor Upper Limb Rehabilitation after Stroke

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Strokes lead to both motor and sensory impairments in the neural circuit. Traditional stroke rehabilitation mainly focuses on motor restoration, but sensory participations together with motor recovery are frequently overlooked and poorly understood. Tactile perception is highly involved in the motor relearning process after a stroke, whereas tactile impairments and their contributions to the rehabilitative effects have received limited attention. Robots have been adopted for motor rehabilitation with high intensities. Robots have also been integrated with neuromuscular electrical stimulation (NMES) for effective motor relearning in our previous works. The objectives of this study include investigations on 1) the rehabilitation effectiveness when robot-assisted upper limb rehabilitation was integrated with enriched tactile sensory inputs, 2) the rehabilitation effectiveness when robot-assisted upper limb rehabilitation was integrated with sensory inputs induced by NMES, and 3) the extent of tactile impairments in the upper limb during textile fabric stimulation in stroke survivors. The study was divided into the following three parts:

In the first part, we investigated the rehabilitation effects of the robot-assisted upper limb rehabilitation integrated with enriched tactile sensory inputs. Thirty-two participants suffering from chronic stroke received robot-assisted training either in the clinical service setting (n=16) with an enriched rehabilitation environment, or in the well-controlled research setting (n=16). The results indicated that the functional improvements following the robotic hand training were comparable for the two groups, whereas the integration of enriched tactile sensory inputs led to greater independence in daily living and a more effective release in muscle tones.

In the second part, we investigated the rehabilitation effects of the robot-assisted upper limb rehabilitation integrated with NMES. Thirty chronic stroke patients were randomly assigned to receive upper limb training with either an NMES robotic hand (n=15) or a pure robotic hand (n=15). The results indicated that more effective distal rehabilitation could be obtained by the NMES robot than the pure robot, especially in the areas of lowered muscle spasticity and enhanced voluntary motor recovery and muscle coordination.

In the third part, we investigated the extent of tactile impairments in the upper limb during textile fabric stimulation via electroencephalography (EEG) in stroke survivors. Twelve chronic stroke patients and fifteen healthy adults received 64-channel EEG detection with three different fabric stimuli on both sides of the volar forearms. The results supported the feasibility of using EEG to investigate tactile impairments following a stroke. The findings also suggested that the tactile impairments after stroke could be represented by a shifted power spectrum, increased power intensity, and remapped sensory cortical areas.

In conclusion, integrating the tactile sensory inputs into the robot-assisted training by providing enriched tactile sensory inputs and NMES could contribute to more functional recovery in the entire upper limb compared to robot-assisted training without tactile sensory integrations for chronic stroke. Moreover, EEG is capable of neurologically evaluating the extent of tactile impairments in stroke patients' upper limbs.

PUBLICATIONS ARISING FROM THE THESIS

Journal papers

1. Y.H. Huang, W.P. Lai, Q.Y. Qian, X.L. Hu, E.W. Tam, Y.P. Zheng. Translation of robot-assisted rehabilitation to clinical service: A comparison of the rehabilitation effectiveness of EMG-driven robot hand assisted upper limb training in practical clinical service and in clinical trial with laboratory configuration for chronic stroke. Biomedical Engineering Online, 2018, 17(1):91.

2. Q.Y. Qian, C.Y. Nam, Z.Q. Guo, Y.H. Huang, X.L. Hu, S.C. Ng, Y.P. Zheng, W.S. Poon. Distal versus proximal - an investigation on different supportive strategies by robots for upper limb rehabilitation after stroke: a randomized controlled trial. Journal of NeuroEngineering and Rehabilitation, 2019, 16(1):64-64.

3. Y.H. Huang, C.Y. Nam, W.M. Li, W. Rong, Y.N. Xie, Y.C. Liu, Q.Y. Qian, X.L. Hu. A comparison of the rehabilitation effectiveness of neuromuscular electrical stimulation robotic hand training and pure robotic hand training after stroke: a randomized controlled trial. Biomedical Signal Processing and Control, 2020, 56:101723.

4. J. Jiao, X.L. Hu, Y.H. Huang, J.Y. Hu, C.C. Hsing, Z.Q. Lai, C. Wong, H. Xin. Neuro-perceptive Discrimination on Fabric Tactile Stimulation by Electroencephalographic (EEG) Spectra. Biomedical Signal Processing and Control, 2019. Under Revision.

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LIST OF ABBREVIATIONS

ADLs	Activities of Daily Living
ARAT	Action Research Arm Test
CONSORT	Consolidated Standards of Reporting Trials
EEG	Electroencephalography
EMG	Electromyography
FIM	Functional independence measurement
FMA	Fugl-Meyer Assessment
FMA-UE	Fugl-Meyer Assessment for Upper Extremity
FMA-S/E	Fugl-Meyer Assessment for Shoulder-Elbow
FMA-W/H	Fugl-Meyer Assessment for Wrist-Hand
MAS	Modified Ashworth Scale
MI	Primary Motor Cortex
MMSE	Mini Mental State Exam
NMES	Neuromuscular Electrical Stimulation
PPC	Power Percentage Change
SI	Primary Somatosensory Cortex
SII	Secondary Somatosensory Cortex
UE	Upper Extremity

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CHAPTER 1

INTRODUCTION

1.1 Stroke

1.1.1 Overview

Stroke is the leading cause of death and permanent disability in adults. In 2010, stroke was ranked as the second cause of death [1] and the third cause of disability [2] that affect individuals worldwide. According to the Hong Kong Hospital Authority Statistical Report [3], there were more than 20,000 new stroke cases every year over the ten-year period from 2006 to 2016 with an accumulated number of 250,000 stroke patients. Globally, by 2014, individuals who survived a stroke episode numbered more than 33 million [4]. Moreover, these patients cost and estimated $73.7 billion in stroke-associated costings [5].

Stroke is a clinical syndrome causing sudden focal or global loss of cerebral function due to the interrupted or reduced blood flow in part of the brain. This is attributed either to abnormal vascular structures, or a rupture of the blood vessels or obstruction of the blood supply [6, 7]. Stroke is further classified into two main types according to its onset pathogenesis: ischemic stroke and hemorrhagic stroke. Ischemic stroke is the most common type and accounts for 80% of all the acute strokes [6], which are also regarded as a cerebral infarction that's caused by a narrowed brain artery and a significantly diminished blood flow. Haemorrhagic stroke is typified by the leaking or rupturing of the blood vessel. The two types of stroke culminate in a lack of oxygen and nutrients reaching the brain leading to permanent cell death and both occur quite rapidly.

The International Classification of Function, Disability and Health (ICF) framework published by the World Health Organization (WHO) [8], places the effects of stroke on individual (Figure 1-1) into four principal categories, namely pathology (disease or diagnosis), impairment (symptoms and signs), limitations on activity (disability), and restrictions on participation (handicap). These effects are influenced by several factors, including where the obstruction is located, and the extent of brain tissue affected. Most survivors will experience some degree of difficulty related to movement, communication, emotional disturbance, and post-stroke fatigue. Movement-related difficulties are generally due to muscular weakness caused by stroke which, in more severe cases, may cause paralysis, leaving survivors unable to move certain parts of their bodies. Hemiparesis is the most common effect after stroke, which leads to sensorimotor deficits on both contralateral upper and lower limbs. These impairments not only reduce the patients' sense of touch, temperature, pain, and proprioception [9, 10], but also limit the upper limb function and lower limb ability to walk, balance, and stand [11]. Survivors of stroke may also find their movement ability affected by complications such as drop foot, muscle spasticity, and poor stamina. Communication problems including aphasia and dysarthria are also very common following a stroke, which could be observed in around one third of stroke survivors [12, 13]. The condition of dysarthria impairs the speech musculature and thus the ability to articulate properly, leaving speech slurred or even incomprehensible [13], while aphasia results from damage to portions of the brain responsible for the understanding and/or formulation of language, both written and spoken [12]. Together, these two disorders can cause frustration in stroke survivors who, even if they manage to make themselves understood to a limited extent, are unable to interact

meaningfully with others, with consequent damage to the formation and maintenance of relationships. Emotional disturbances in the form of anxiety, depression, or emotionalism occurred after stroke are also frequently observed [14]. Another feeling of frustration, in particular, requires stroke survivors' careful management because, if not properly dealt with, it can become an irritability which further damages relationships with their families and others, and may even become anger or aggression. Furthermore, post-stroke fatigue affects 40-74% of survivors [15] and, unlike normal fatigue, cannot always be reduced by rest and does not necessarily bear any relation to activity or exertion. Rather, it may be due to the extra expenditure of energy required of survivors to accomplish motor tasks and deal with emotional disorders. In other aspects, changes in behavior, and problems in thinking and memory loss have been widely noted in stroke survivors [16, 17]. The duration of the effects of stroke varies across the population: in some cases, such effects are minor and of short duration while in others, they can be serious and long term. It should be noted that as the left and right sides of the brain control the opposite sides of the body, when a stroke affects the right side of the brain, neurological complications will be seen on the left-hand side of the body, and vice versa. For instance, the most frequent manifestation following a stroke is hemiplegia with unilateral motor deficits. These effects relate to lesions occurring that impact the middle cerebral region's supply of arterial blood. It is also interesting to observe that while paralysis and memory loss afflict most survivors of stroke, those with brain lesions on the left are more likely to experience difficulties with speech or language and have a slow and cautious behavioral style, while those with brain lesions on the right are more likely to experience difficulties related to vision, and their behavior tends to be characterized by quickness and curiosity.

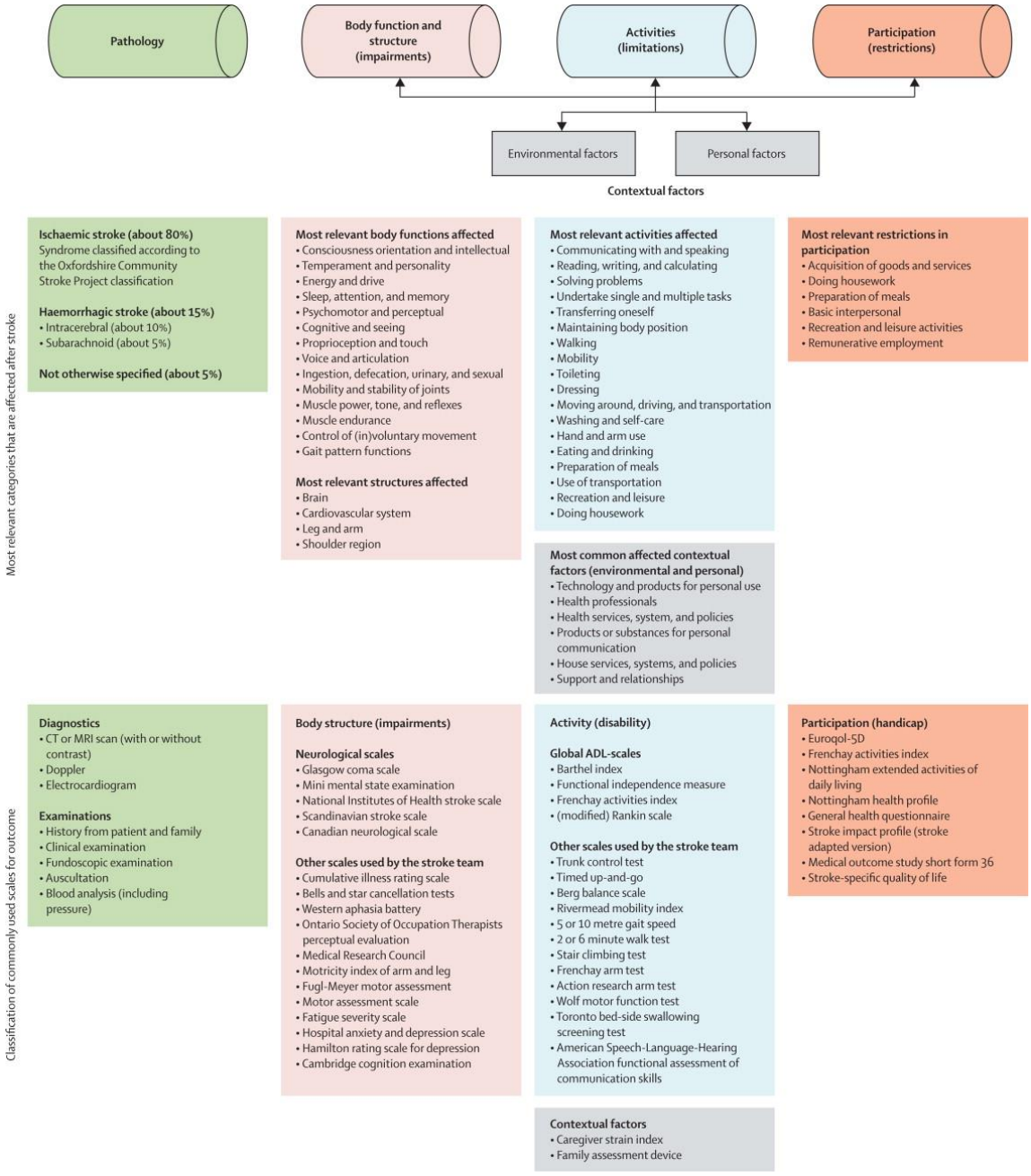


Figure 1-1. The international classification of function, disability, and health framework for the effect of stroke on an individual. Adapted from [18].

1.1.2 Post-Stroke Upper Limb Motor Impairment

Normally, 80% of stroke survivors regain their walking ability to a certain extent following lower limb motor rehabilitation in the early post-stroke period [18, 19]. On the contrary, very few stroke survivors (11.6%) regain their upper limb function returning them to normal levels after 6 months of stroke onset, and limited upper limb functional recovery could be obtained by another 38% of stroke survivors [20, 21]. The post-stroke upper limb motor impairments primarily include muscle weakness or contracture, spasticity, joint laxity, and impaired motor control [22]. Such damage challenges a patient's mobility and coordination of their impacted upper extremities, particularly distal regions such as the hands and fingers. This can lead to hindrance in performance of everyday tasks: including eating, dressing, reaching, gripping and holding objects [22-24]. To sum up, upper limb motor deficits after stroke significantly affect their abilities of performing activities of daily living (ALDs), and accompanied with lower self-independence and living quality [25].

1.1.3 Post-Stroke Upper Limb Sensory Impairment

Somatosensory deficits are another frequent impairment following a stroke. Two studies reported that up to 85% of stroke survivors undergo somatosensory deficits, which is usually experienced as a reduced sensation for touch, temperature, pain, and proprioception [9, 10]. Somatosensation can be classified into exteroception and proprioception [9]. The former refers to superficial tactile sensation induced by mechanoreceptors, thermoreceptors and nociceptors, while those deep sensory inputs from the receptors of muscles and joints refer to the latter [9, 26]. These sensory impairments usually result in stroke victims having difficulty in exploring and

manipulating their surroundings safely, and that will lower their autonomy, independence, sociability and quality of life, and even lead to learned non-use [10, 27-29]. Stroke patients who regain sufficient levels of motor skills, still require enough sensory abilities to secure them from dangers of not sensing [30]. The experiencing of discomfort and pain from somatosensory damage is also a recurrent symptom reported by stroke survivors in clinic [29]. Various studies have reported that partial sensory recovery can occur during the stroke rehabilitation subconsciously over time even without specific sensory rehabilitation [31-34]. Nevertheless, emerging evidence claimed that better improvements on both sensory and motor recovery could be achieved by specialized sensory interventions [29].

1.1.4 Relationships between Post-Stroke Sensory Impairment and Motor Impairment

Present day clinical guidelines on rehabilitation following a stroke episode give credence to recovery of motor performance and neglect sensory damage and the required restoration, this is despite both motor and sensory abilities paralleling each other and are dependent on each other. It is widely accepted that sensory deficiency limits the restoration of motor functions, because fine motor control depends on undamaged somatosensation from inward-bound (or afferent) inputs [9]. Therefore, the process of how sensory deficits affect motor function could be summarized as: (1) stroke patients with sensory deficit receive insufficient and impaired sensory information, (2) with impaired somatosensory information, capability of motor functions that involve sensory participations are disturbed, and (3) the functional restoration of the impaired upper limb is limited or even diminished [22, 35].

A study of longitudinal design determined that survivors of stroke significantly manifested higher levels of severe motor deficiency when they also suffered from sensory

deficit [36]. Several studies established an association between sensory deficits and reduced functional movement and lower ADLs in the subacute period following a stroke [37-39]. Neurophysiological studies performed presently indicated the importance of internal and external somatosensation for motor function [40]. This was attributed to the considerable changes that can occur in normal motor control as a consequence of pathological abnormalities of sensorimotor processing [41]. Several research studies into neurophysiological mapping explained the involvement of the motor cortex (MI) in somatosensation processing—so it does not only exist as a motor part [42-44]. This was attributed to its anatomy and its functional associations with both primary (SI) and secondary (SII) somatosensory cortices [45]. Further data was obtained by Gallien et al. [46] demonstrating how stroke survivors who lack sensory activation showed lower results following rehabilitation. Moreover, Huang et al. [47] proposed that increasing MI and SI stimulation through somatosensory activation can result in better neurological scores for both chronic and acute stroke patients. In conclusion, lack of sensory activation can have significant adverse impacts on motor rehabilitation and ADL function, and this is regularly underrated and neglected in today's stroke rehabilitation procedures.

1.1.5 Assessments for Post-Stroke Recovery in the Upper Extremities

To understand the nature and extent of upper extremities after stroke, valid and reliable evaluation methods on both motor and sensory function for upper limbs are required.

1.1.5.1 Assessments for Motor Recovery in the Upper Extremities

Evaluation of the motor recovery of upper body extremities is carried out clinically as follows:

1) Fugl-Meyer Assessment for Upper Extremity (FMA-UE)

Clinical assessment of motor performance following a stroke is frequently conducted using the Fugl-Meyer Assessment (FMA) scale, which is deemed extremely precise, repeatable and responsive [48]. The full score (66) for FMA tends to be achieved by the upper extremities using the motor scale part. Achieving such a score indicated complete motor and sensory recovery of the upper extremities. This scale can be split into two: 42/66 for FMA-shoulder/elbow (FMA-S/E) and 24/66 for FMA-wrist/hand (FMA-W/H), and that allows to examine the level of performance of upper extremities in the proximal and distal parts.

2) Action Research Arm Test (ARAT)

Action Research Arm Test (ARAT) is used to quantify the movement dexterity of the finger and the upper extremities' performance. Four function elements of gross movement, grasp, grip, and pinch constitute ARAT, which is further split into 19 items [49]. The range of measure for each item is from 0 to 3, which is equivalent to no movement, part of function and normal function, respectively. Thus, the lower the score the worse the damage is.

3) Modifies Ashworth Scale (MAS)

During recovery, a stroke can result in spastic paralysis. The Modified Ashworth Scale (MAS) works quickly and effortlessly to assess the efficacy of treatment. This is

conducted through resistance quantification when stretching soft tissue passively. It generates a scoring system that is ranked; the greater the score then the greater the post-stroke spasticity [50].

4) Functional Independence Measurement (FIM)

Another measurement, the Functional Independence Measure (FIM) serves to determine a patient's performance following a stroke, whilst also monitoring changes in this performance from the initial point of stroke rehabilitation to discharge and throughout follow-up [51]. Its benefits lie in the continuity of data and the collation of comparable data. It is made up of 18 items with scores ranging from 0 to 7. The higher the score for an item then the greater the independence of the patient for that item.

1.1.5.2 Assessments for Sensory Recovery in the Upper Extremities

Clinical examinations for sensory deficits are challenging when contrasted with clinical assessment of motor performance and this is because the methodologies used are not very reliable or reproduceable and they are poorly standardized [9, 52]. To follow are a number of somatosensory methods employed frequently:

(1) Semmes-Weinstein monofilament test (SWM)

One model examines a patient's reaction to a touch sensation of the monofilaments. This is termed the Semmes-Weinstein monofilament (SWM) test and it is quantified numerically. It was formed for the identification of patients that had a higher chance of neuropathic ulceration. It is a clinical assessment to assess damages to the peripheral nerve and also compression syndromes that occur prior to and/or following recovery [53, 54].

(2) Two-point discrimination test

Another test two-point discrimination test examines a patient's ability to indicate two points that are close to each other on a tiny skin region and the degree to which this can be done [55, 56]. It allows tactile agnosia measurement, and it also enables diagnosing those who can't identify the two points even though their cutaneous sensation and proprioception remain unaffected. It is likely to indicate damage to the brain but can also be performed together with the testing of light touch or pain though examination of dermatomes.

(3) Rivermead assessment of somatosensory performance (RASP)

Another quantitative tool is the Rivermead assessment of somatosensory performance (RASP) that has 0 to 60 interval scale [57]. This examines surface localization and pressure, proprioception, temperature, discrimination of sharp-blunt, bilateral sensory excitation and two-point discrimination. Ten regions around the body are tested using RASP—all being bilateral regions including the hand (both palm and dorsal), face (cheeks) and the plantar and dorsal regions of the foot.

(4) Quantitative sensory testing (QST)

A consistent, all-inclusive tool is termed the quantitative sensory testing (QST) tool which is used to "characterize the somatosensory phenotype of patients with neuropathic pain" [58]. It uses interval scales that are quantitative. The protocol of QST produces rational values, and supplies a more detailed assessment for the various somatosensory modalities. 13 tests are covered in the tool and these test pain level, thermal identification, assessment of mechanical level of detection for both vibration and touch, allodynia, mechanical

sensing of pain using both a blunt and pinprick instrument and also testing of central systems like pain summation following repeated pinprick activation (wind-up pain).

1.2 Upper Limb Sensorimotor Rehabilitation After Stroke

1.2.1 Efficient Training Standards for Upper Limb Sensorimotor Recovery

Founded on the results of many systematic reviews together with many clinical controlled trials of a randomized nature and together with neurological reporting, various guidelines for efficacious recovery programs for the upper extremities have been defined for enhancement of motor rehabilitation and functional independence in tasks that are performed every day.

(1) Early recuperation together with intentional effort:

Emerging evidence revealed that effective rehabilitation after stroke should be initiated instantly after a stroke [59]. A tight association between effective recovery and self-inspiration and voluntarily taking part was found [18]. Similarly, voluntary efforts from the residual neuromuscular pathway was confirmed as a means of improving function when compared with continuous passive training [60, 61]. Moreover, improvement of motor reactions and neural plasticity can be attained by early physical training together with intentional effort, thereby achieving the maximized motor outcomes [62, 63].

(2) Rigorous practice with accurate repeats:

The formulated guidelines did not indicate any particular intensity level for use with post-stroke recovery patients. However, several systematic reviews determined that when practice was repeated for damaged extremities and when this was performed at high-

intensity, this would greatly benefit efficient motor recovery following a stroke [62, 64]. Moreover, research on cortical mapping that is focused in Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) [65] together with neurological examinations like transcranial magnetic stimulations (TMS) [66] indicated that training processes stimulated changes in cortical motor pathways.

(3) Synchronized motor control of multiple joints using task-oriented training:

Synchronized actions as part of specific training actions can aid in rapid recovery of motor independence with respect to performance of daily tasks [67]. Various systematic reviews supported this concept and indicated how efficient enhancements in motor movement could translate to related limb performance, when multiple joint movements were performed in a synchronized fashion [68]. This would be performed in task-driven training and is indicated more for distal joints like fingers and wrists [69]. Furthermore, greater levels of compatibility were indicated between synchronized control of motor movement and recuperation when using the Brunnstrom staging strategy [70] with a particular focus on transferring muscle synergies in the various portions of the upper extremities following a stroke episode.

4) Sensory integrated motor rehabilitation

It is well known that somatosensory sensation is of particular importance during the restoration process of motor recovery [9, 22, 35] (as elaborated in Chapter 1.1.4). Several studies have reported that better rehabilitation outcomes can be obtained by stroke patients with better sensory function, while sensory impairments have been successfully correlated with poor functional mobility and inhibited ADLs [36-39]. Meanwhile, using sensory

inputs within motor recovery has been suggested to potentially promote better functional restoration [46, 47].

1.2.2 Conventional Therapeutic Treatments

Once a stroke survivor has been stabilized, stroke recovery is initiated followed by conventional therapeutic treatments. This is usually with one to two days following the stroke. Nevertheless, it is unrealistic for acute stroke patients to remain long in hospital [71]. Even in developed nations, due to limits in resources form a lack of labor and money, intensive therapeutic treatments are usually excluded. Several forms of conventional recovery have been recommended to aid stroke patients to recover their fundamental sensorimotor performance. Of those, there are two most frequently used in the clinic, which includes constraint-induced movement treatment (CIMT) [72] and the Bobath approach [73].

(1) Constraint-Induced Movement Therapy (CIMT)

Constraint-induced movement therapy (CIMT) is physical therapeutic treatment that has been highly successful in recovery of upper limbs that are highly impacted and has also been shown to be capable of overcoming the learned non-use concept after stroke [72, 74]. CIMT is composed of three primary parts including: (1) Intensive, repetitive, structured training of the highly impacted arm; (2) Immobilization of the least impacted arm; (3) Implementation of a set of behavioral methods that transfers the benefits from the clinic to reality (thus, turning it into functional results) [72]. The clinically outcomes on the efficacy of this technique indicated that intensity of CIMT was greatly associated with outcomes and this is costly with respect to resources [75]. Moreover, patients diagnosed

with moderate or severe stroke are not identified as ideal patients for CIMT based on the research [76].

(2) Bobath approach

The Bobath approach is also known as neurodevelopmental treatment (NDT), is a manually-delivered therapy and it is frequently used in recovery training following a stroke [77]. This technique aims to enhance motor learning to ensure efficacious motor control in different settings, thereby enhancing participation and performance. This treatment is a combination of physiotherapy, occupational therapy as well as treatment for speech and language. It focuses on facilitating stroke survivors' abilities of exploring their world and its surroundings, partaking and relaying their requirements to the highest levels in all parts of their life, and not just during recovery training [73].

1.2.3 Device-Assisted Therapeutic Interventions

A number of devices and techniques to assist rehabilitation have been designed to help physical therapists manage the labor-intensive long-term rehabilitation process [78-80], with rehabilitation robots and neuromuscular electrical stimulation the most widely used in post-stroke rehabilitation.

1.2.3.1 Rehabilitation Robots

Rehabilitation robots were designed to provide highly intensive and repetitive physical training, and have the advantage of being more cost-effective than professional manpower. The robotic system can be divided into three types, based on training mode: passive, active, and interactive [81]. Passive-mode robots provide full assistance to patients through

continuous passive motion (CPM), and require no active effort from patients. However, due to the lack of human active engagement and sufficient sensorimotor stimulation, improvement in patients trained by passive robots remains small and cannot be maintained for a long time [82]. Active-mode robots provide only limited assistance, based on the stroke survivors' motion intention, and the provision of too little assistance can lead to frustration and low motivation, whereas interactive-mode robots provide adaptable assistance depending on the performance of the stroke patients. A number of robots have been developed for upper limb rehabilitation, with specific training purposes and to serve particular joints; the training effects of such robots have been investigated and proved to be effective [78, 79, 83]. Of these, voluntary intention robot-assisted training was reported to achieve better motor recovery when compared with CPM intervention [84, 85]. Electromyography (EMG) is the most frequently selected voluntary input to control a robotic system. The effectiveness of robotic systems was also compared with conventional physical treatment [86], with results indicating that comparable motor achievements could be obtained by robots and traditional physical therapy.

However, several limitations could also be observed during robotic training. On the one hand, rehabilitation robots cannot directly activate the targeted muscle groups, and thus cannot effectively limit compensatory motions [87, 88]. On the other hand, rehabilitation robots usually do not offer sensory stimulation during training, although sensory inputs may contribute to a more effective strategy for stroke rehabilitation. It is also noted that the current upper limb rehabilitation robots are tailored for the proximal joints like elbow and shoulder, whereas there are comparatively few robots for distal joints like wrist and hand.

1.2.3.2 Neuromuscular Electrical Stimulation (NMES)

Neuromuscular Electrical Stimulation (NMES) could activate the targeted muscles through cyclic electrical currents, and generate sensory feedback [89]. NMES has been frequently employed in post-stroke rehabilitation for promoting the muscle strength of the affected upper limbs, motor control, and range of motion [11, 90, 91]. NMES are commonly utilized in several ways to elicit muscle contractions: (1) it can be simply applied as a passive technique; (2) it can be combined with muscle activities and triggered by EMG; and (3) it can be controlled by the position of the limb [92]. The major advantage of NMES is that it not only provides repetitive sensorimotor experiences and effectively limits compensatory motions, but can also enhance muscular power and, ultimately, improve motor function for stroke patients [93, 94]. However, training programs that only depend on NMES can be suboptimal as a result of the difficulty involved in controlling movement trajectories, and early onset fatigue [95, 96].

1.2.3.3 EMG-driven NMES Robotic System

To take advantage of the benefits of both rehabilitation robots and NMES, EMG-driven NMES robotic systems have been proposed, and the training effects of the combined systems have been evaluated as effective [87, 97-100]. Comparisons between the effectiveness of NMES robotic devices and other training programs have been addressed by several studies. For instance, Qian et al. [99] pointed out that NMES robot-assisted upper limb rehabilitation program obtained more functional recovery than conventional physical therapy for stroke patients. Other research has directly compared the training effects of NMES robotic devices and robotic devices used alone and all studies have demonstrated that better outcomes could be achieved by robotic systems with NMES than

by pure robots [87, 97, 101]. As with the robotic systems, the investigations of NMES robots mainly focus on the elbow and wrist joints, while relatively few NMES robots facilitating hand and finger functions exist. In our previous works, an EMG-driven NMES robotic hand was developed and proved to be effective for post-stroke upper limb rehabilitation [98, 102]. The devices allow hand movements to be precisely controlled, delivering sensory inputs and activating the target muscles directly to enable finger extension/flexion selectively.

1.3 Objectives of the Study

1.3.1 Research Gaps

In current clinical practice, rehabilitation robots have been successfully and widely used to provide effective sensorimotor rehabilitation with high intensity and repetition. However, during robot-assisted upper limb rehabilitation after a stroke, several research gaps exist, as outlined below.

(1) Lack of effective hand rehabilitation

Robotic devices currently available for upper limb rehabilitation mainly focus on the elbow and wrist joints [97, 99-101], with very little intervention in the hand and fingers [103]. Nevertheless, deficit of hand function is the most common upper limb disability, and regaining hand function is much more difficult than the motor recovery of elbow and shoulder joints. One reason for this is that early rehabilitation usually starts from proximal joints and pays less attention to the recovery of distal joints. Another reason is that the proximal compensatory movements take over the movements of the distal parts during

functional recovery, thus leaving the distal parts impaired. Therefore, developing effective rehabilitation devices that could truly benefit hand functions is especially important for stroke patients.

(2) Overlooking sensory perception and its contribution to motor recovery

At present, traditional stroke rehabilitation mainly focuses on motor restoration; however, sensory deficit is widely underestimated and overlooked, even when the recovery of sensory and motor function is closely linked. Recently, emerging evidence claimed that better improvements to both sensory and motor recovery could be achieved by specialized sensory interventions [29]. However, the contributions of tactile sensory inputs to rehabilitative effects have seldom been quantitively investigated. Action should be taken to integrate sensory stimulation into motor rehabilitation and facilitate more effective post-stroke sensorimotor rehabilitation.

(3) Poorly evaluated sensory deficits from a neurological perspective

To properly understand the character and extent of sensory deficits after stroke, reliable and valid sensory evaluation methods are required. However, the evaluation methods used in current clinical practice are rather superficial and subjective [9, 52, 104]. Certain standard assessments can only provide limited variations of sensation and cannot be used for those patients with severe cognitive deficits [9]. Most importantly, current clinical assessments lack knowledge of neural response to fine tactile perception. Therefore, sensory deficits are poorly evaluated and understood from a neurological perspective.

1.3.2 Research Objectives

In this study, we investigated the training effectiveness of robotic hand training after integrating tactile sensory stimulations via enriched tactile sensory inputs and NMES for chronic stroke patients. Meanwhile, a new approach, using different textiles to evaluate the extent of tactile impairments after stroke via electroencephalography (EEG), was proposed.

The objectives of this study include:

(1) To investigate the rehabilitation effectiveness when robot-assisted upper limb rehabilitation was integrated with enriched tactile sensory inputs.

(2) To investigate the rehabilitation effectiveness when robot-assisted upper limb rehabilitation was integrated with sensory inputs induced by NMES.

(3) To investigate the extent of tactile impairments in the upper limb during textile fabric stimulation in stroke survivors.

CHAPTER 2

A COMPARISON OF REHABILITATION EFFECTIVENESS OF EMG-DRIVEN ROBOTIC HAND TRAINING IN CLINICAL SERVICE WITH ENRICHED SENSORY INPUTS AND IN CLINICAL TRIAL AFTER STROKE

2.1 Introduction

A stroke is one of the biggest causes of long-term disability in adults [105]. It was reported that around 300,000 people in Hong Kong and over 7 million people in Mainland China were suffered and survived a stroke by 2014. On average, in Mainland China, there was 2 million new cases each year with a yearly increase of 8% from 2009 to 2014 [3, 106]. Around 80% of stroke survivors have major upper extremity impairment and disabilities that impact their activities of daily living (ADLs) [107, 108]. Only 25% of stroke survivors regain limited motor recovery in their paretic arms, even after going through post-stroke rehabilitation [19]. Physical treatment may lead to a better recovery of arm function if carried out in the subacute period (in the six months following the stroke) than in the chronic stage (after the initial six month period) [109]. It is commonplace in contemporary clinical practice for the professional manpower of stroke rehabilitation to be more active during the in-patient period (at subacute stage) as opposed to focusing on long-term treatments for chronic stroke. Nonetheless, various recent studies have shown that intensive training can lead to vast improvements in motor abilities even in the chronic

period following a stroke [71, 110]. It is crucial to address, however, the undeniable concern that rehabilitation manpower is not adequate enough, and this is even the case in developed countries that have quick-growing numbers of stroke patients. For this reason, it is crucial to identify effective methods of managing long-term rehabilitation for patients' post-stroke.

Rehabilitation robots have long played an important role in helping human therapists to provide the intensive physical training, since they can be more repetitive and less costly than using human beings for the job [111]. A number of robotic devices have been designed for upper limb training following a stroke, with the robots' effectiveness being assessed through clinical trials [78, 79, 83]. Some trials have tested robot-assisted rehabilitation, in which the robot is controlled by voluntary user inputs, and such trials have found such robots could promote better functional recovery than those that use continuous passive motions (meaning there is no voluntary input from the user and thus that the robot controls the paralyzed limb [84]. Song et al [85] created a voluntary intention driven robot, in which the use of electromyography (EMG) of the residual upper limb muscle was used to indicate the voluntary motor inputs of stroke patients. The randomized clinical trial that tested this robot showed that those suffering with chronic stroke acquired significantly more motor improvements using the EMG-driven robot than when using passive motion assistance on its own [112]. Furthermore, research in the form of a large randomized multi-center trial was also carried out by Lo et al [86]. The latter made comparisons between the MIT-Manus robotic system for upper limb training and traditional, physical therapies. According to the findings, the robot was able to achieve the same objectives in terms of motor improvements as traditional therapy [86]. The

findings therefore indicate that, in cases where human therapy is not suitable or sufficient, robot-assisted post-stroke training may be a viable, cost-effective alternative for rehabilitation of stroke patients.

Nonetheless, nearly every positive report was found by carrying out research-driven trials, with evidence from real clinical service configurations lacking. Therefore, the assumption is that the positive reports in the trials will undoubtedly apply to the real services after commercialization. In fact, it appears that the viability and efficacy of robot-assisted upper limb training in clinical practice have been thrown into doubt in cases where ensuring trial-quality management in a real, long-term setting has been challenging [113-117]. On the other hand, the enriched sensory inputs during the training in the clinical service may contribute to a more remarkable motor improvements for stroke patients. Because the sensory inputs play a crucial role during the process of motor restoration, and integrating sensory inputs into the motor rehabilitation has been proposed to potentially promote better functional recovery [46, 47]. However, the actual training effectiveness of sensorimotor integrated training have been seldom investigated. Hence, some differentiations in the efficacy of rehabilitation found between well-controlled research studies and more flexible services need to be further investigated. A number of aspects can render the making of comparisons between the effectiveness of robot-assisted rehabilitation services and clinical trials more difficult. Firstly, in a real service setting, rehabilitation schedules tend to be fairly flexible in terms of client payments. However, the training schedules in trial studies tends to be more constrained, and such schedules come at no cost to the patients. Sometimes, patients may even be paid to take park. Secondly, there is a high level of participant (client) variability in real clinical service, as

opposed to trials, in which inclusion criteria are often adhered to, meaning that it is incredibly hard to replicate the trials and implement them in service management in exactly the same manner (especially in the private sectors). There is also issues of financial sustainability to consider. What's more, in clinical trials, participants are not typically permitted to be subjected to any other treatments that could interfere with the given therapy. Nonetheless, it is not possible in a real service setting to prevent a patient from being given other treatments if they deem them to be beneficial. In our prior research, we proposed an EMG-driven robotic hand, and a single group clinical trial has examined its efficacy [118]. An EMG-driven robotic hand has been available to individuals since 2011 in a self-funded private university clinic. Therefore, the objective of the current work is to compare the training effects of an EMG-driven robotic hand in a clinical setting in a private clinic with enriched sensory inputs and in a clinical trial in a laboratory setting. Meanwhile, it is important to ensure minimum disturbance to the routine clinical management and service being given to the current patients.

2.2 Methodology

2.2.1 EMG-Driven Robotic Hand

Figure 2-1 presents the system of EMG-driven robotic hand that is proposed in the presented research, and it can help with finger extension and flexion in those who have suffered a stroke. There were five linear actuators in the robotic hand (Firgelli L12, Firgelli Technologies Inc.), which mechanically helped the five fingers [118]. The proximal and distal section of all four fingers individually were rotated around virtual

centers within the metacarpophalangeal (MCP) and proximal interphalangeal (PIP). The thumb was rotated around the virtual center of its MCP joint. There were two degrees of freedom to every finger in the finger assembly (DOF), with the range of motion (ROM) being 55˚ for MCP joints and 65˚ for PIP joints. The two joints had angular rotation speeds of 22˚/s at the MCP joint and 26˚/s at the PIP joints, throughout the opening and closing of the hand.

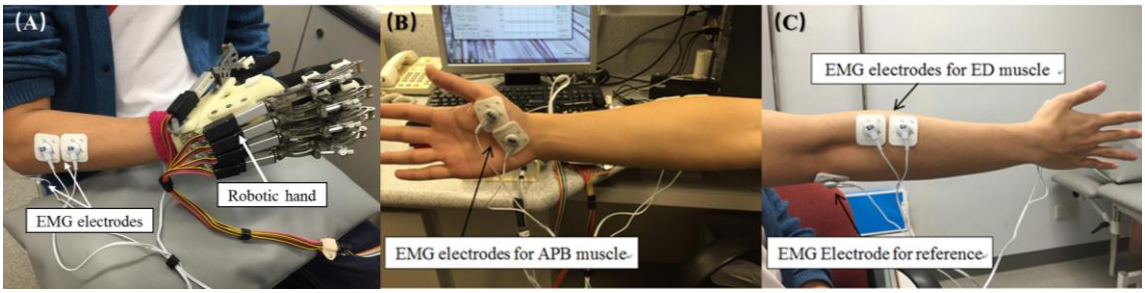


Figure 2-1. The electromyography (EMG)-driven robotic hand system: (A) The wearable system consisting of a mechanical exoskeleton of the robotic hand and EMG electrodes; (B,C) the illustration of the configuration of the EMG electrodes attached to the extensor digitorum (ED) muscle and abductor pollicis brevis (APB) muscles. The reference electrode was attached on the olecranon. Adapted from [119].

In order to allow for phasic and sequential limb tasks (such as hand closing and opening) to be carried out, it was crucial to employ the abductor pollicis brevis (APB) and extensor digitorum (ED) muscles as voluntary neuromuscular drives. The driving muscle for finger movements was determined to be the APB during the “hand closing”, which is because the EMG signals of the APB in the paralyzed limb following a stroke experience lesser impacts of spasticity and tend to be much easier to control when compared with the flexor

digitorum (FD) muscle [120]. The present research used EMG-triggered control. Throughout the training, there was an established threshold level at each movement stage that was three times the standard deviation (SD) above the EMG baseline in the resting state. When the EMG activation level of the APB muscle met the pre-determined threshold during hand-opening, (3 SD above the baseline), the robotic hand in the present research closed at a constant speed (22˚/s for MCP and 26˚/s for PIP joints), and mechanically conducted finger flexion. During hand-opening, when the ED muscle's EMG activation level met the pre-determined threshold (3 SD above the baseline), the robotic hand opened at a constant speed (22˚/s and 26˚/s at the MCP and PIP joints, respectively). Following the initiation of the system, there is no voluntary efforts needed from the user, since the robot will work automatically throughout the whole process of hand opening and closing in the proposed ROM.

To begin with, the EMG signals provided by the driving muscles (obtained via EMG electrodes) were amplified by 1000 times (preamplifier: INA 333; Texas Instruments Inc., Dallas, TX), and subsequently sampled at 1000 Hz through the application of an acquisition card (DAQ, 6218 NI DAQ card; National Instruments Corp). A band-pass filter was then used to filter them, which ranged from 10-500 Hz. Following digitization, EMG signals generated by the APB and ED muscles were corrected and low-pass filtered applied (fourth-order, zero-phase forward and reverse Butterworth filter; cut-off frequency, 10 Hz) in order to gain an envelope of EMG signals (i.e., the EMG activation level) consistent with real-time control.

2.2.2 Clinic versus Laboratory

This study used a non-randomized, controlled trial that assesses two different settings, namely the clinical service setting under a business environment and the laboratory setting (Table 2-1). The clinical service setting was hosted at the University's Jockey Club Rehabilitation Engineering Clinic (JCREClinic), which offers a range of holistic clinical services, such as orthoses, prostheses, and robotic rehabilitation treatments to local residents. The interior configuration of the JCREClinic can be seen in Figure 2-2. It has a main entrance, reception desk, corridor, waiting area for guests and several treatment rooms. All treatments and appointments offered by the JCREClinic are provided on both a schedule and walk-in basis. Appointments can be made by telephone, email or WhatsApp message. In terms of robotic hand training, the following process is carried out: Firstly, a patient has to make their appointment, after which they will be asked to come for a consultation with the physical therapist in charge of the training. During the consultation, the physical therapist will review the patient's medical and rehabilitation history, assess the level of mobility in their upper limbs by assigned clinical scores, (this will be presented later in more detail). Subsequently, the physical therapist will assist the patient with carrying out various robotic hand training tasks, such as gauging the fit, size, and testing the target muscles that will be used for controlling the potential robotic device. It is here that the physiotherapist will discuss the possible effects of rehabilitation with the client based on the prior trial findings [118]. Upon acceptance of the robotic hand upper limb system by the clients, they will be required to attend a 20-session training schedule (90 mins/session) that is set up by the clinic based on the availability of both the physiotherapist and the client. The recommended training frequency is 3-5 sessions per

week. There is a maximum of 4 sessions per week for the management service. Nonetheless, given other commitments, the patient may wish to re-arrange the schedule to a later date. There is a service charge of 400 Hong Kong Dollars per session, and patients have the right to withdraw from the program at any point without consequence.

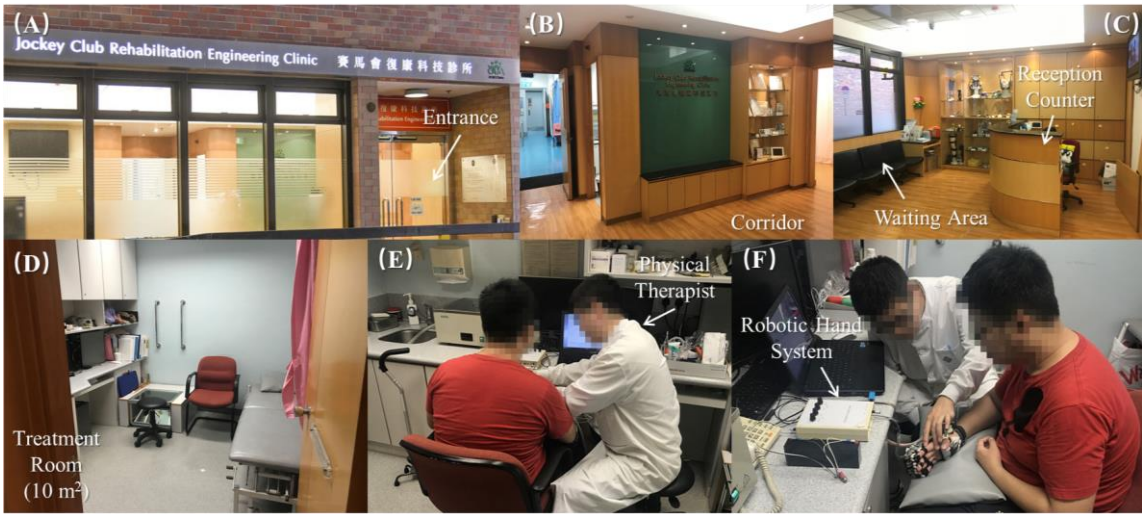


Figure 2-2. The interior configuration and training setup of the robotic hand training in Jockey Club Rehabilitation Engineering Clinic: (A) Entrance, (B) corridor, (C) waiting area for guests and reception counter, (D) treatment room with estimated area presented by square meter, and (E, F) the training setup of the robotic hand rehabilitation system assisted by a physical therapist. Adapted from [119]

Table 2-1. Comparisons between the clinic and laboratory. Adapted from [119]

	Clinic	Laboratory
Interior Configuration		
Entrance	√	√
Reception Counter	√	×
Corridor	√	×
Waiting area	√	×
Treatment room/area	√	√
Appointment		
Walk-in appointment	√	×
Scheduled appointment	√	√
Schedule		
Mutual agreement	√	√
Fixed training intensity	×	√
Accept reschedule	√	×
Contact Person		
Reception assistant	√	×
Research staff	×	√
Trainer		
Physical therapist	√	×
Research staff	×	√
Enriched sensory inputs	√	×
Fee	√	×
Withdrawal	√	√

The EMG-driven robot hand and upper limb training in the laboratory condition was carried out in Hong Kong Polytechnic University's neurorehabilitation lab (Figure 2-3). The lab consists a physical training area, a cognitive training area, and an office area. The training relevant to the robotic hand took place in the physical training area. The EMG-driven robot hand treatment was free of charge to those who took part in the laboratory study.

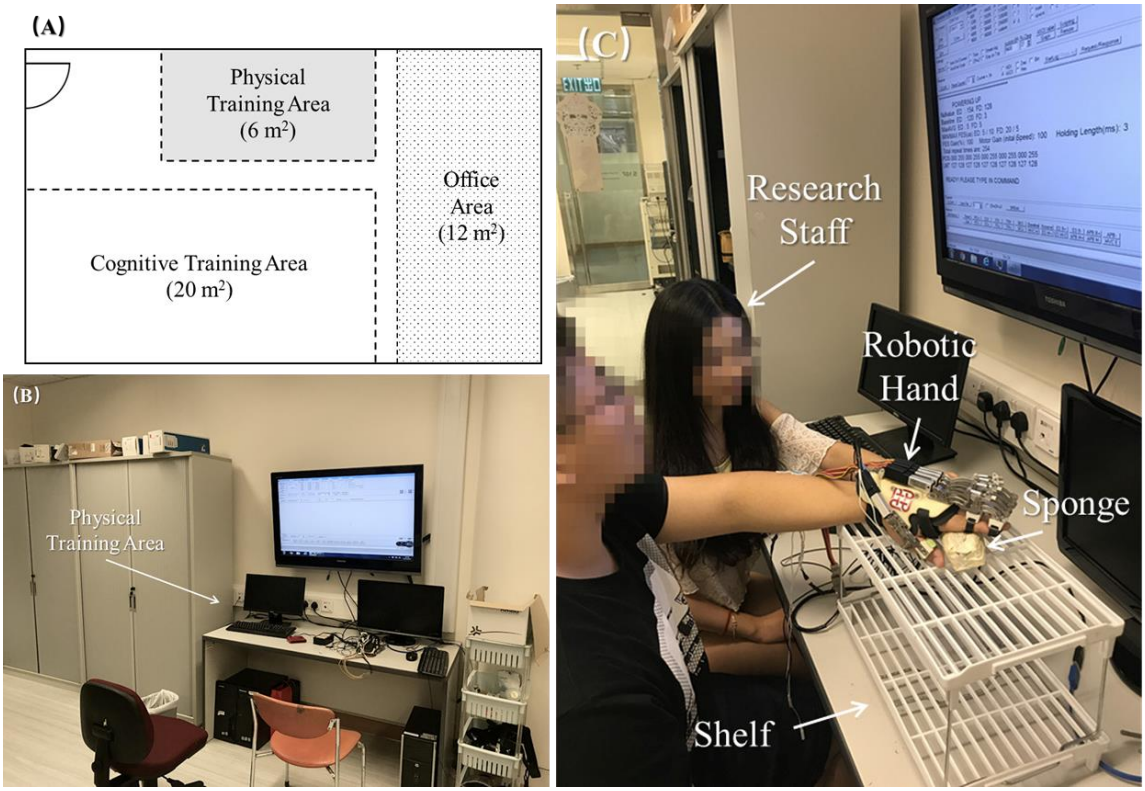


Figure 2-3. The interior configuration and training setup of the robotic hand training in a neurorehabilitation laboratory: (A) Lab planar graph with estimated area presented by square meter, (B) physical training area, and (C) the training setup of the robotic hand rehabilitation system assisted by a research staff. Adapted from [119].

2.2.3 Participants Recruitment

The Human Subjects Ethics Sub-Committee at Hong Kong Polytechnic University provided approval for this research. The participants taking part under the laboratory condition were labelled the "lab group", and those in the clinical trial condition as the "clinic group". Different methods were used to recruit participants in the two different groups, with lab groups participants being selected from local areas according to a number of inclusion criteria as follows [118]: (1) There had to be a period of at least six months since the stroke occurred in the patients; (2) the patient had to be able to extent both MCP

and PIP to 180° passively; (3) the patient had to be able to demonstrate spasticity of 3 or less on the Modified Ashworth Scale (MAS) [50] during extension of wrist and finger joints; (4) the patient had to have a detectable voluntary EMG signal (such as the signal amplitude that is in excess of 3 standard deviation (SD) more than the mean of the baseline) from the target muscles in the paretic side; and (5) There was a sufficient ability of the participant to follow the experimental instructions in line with the Mini-Mental State Examination (MMSE＞21) [121]. What's more, lab group participants were forbidden from receiving any other upper limb physical treatments when receiving robotic hand training, and failure to adhere to this would result in removal from the study. Prior to treatment, all recruited participants provided written consent.

In the clinic group, participants were chosen from a pool of clients that were scheduled to receive robotic hand therapy in the JCREClinic. All such clients were screened, with potential participants being the patients who showed upper limb motor deficits in line with the same inclusion criteria given for the lab group. After this, those who were most interested in taking part and who agreed to abstain from any other treatment throughout the training period were selected for participation. Consolidated Standards of Reporting Trials flowchart of the training program can be seen in Figure 2-4.

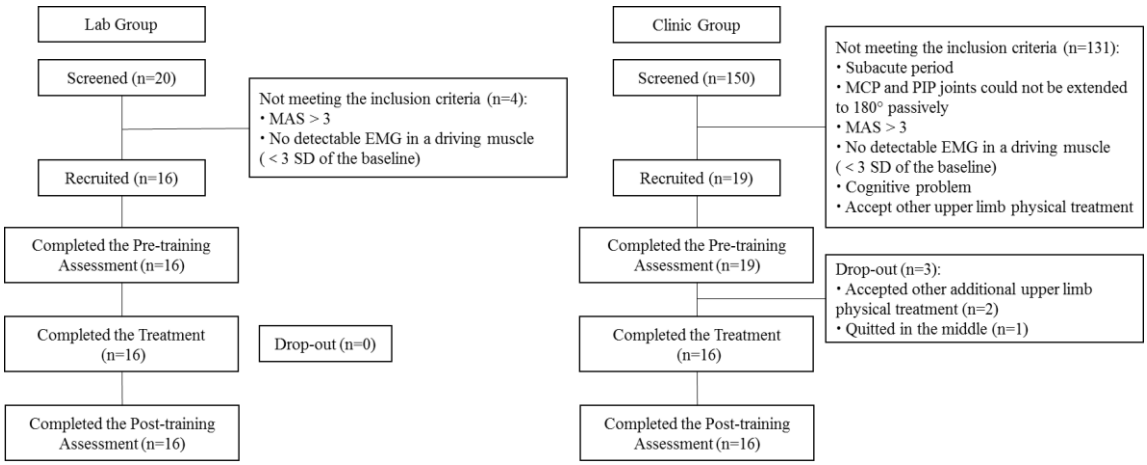


Figure 2-4. The consolidated standards of reporting trials flowchart of the controlled clinical trial in chronic stroke patients. Adapted from [119].

2.2.4 Training Protocols

All participants attended the 20 sessions of robotic hand upper limb training, and during each session, the participants were asked to carry out repetitive upper limb tasks, such as hand grasping and release actions, as well as lateral and vertical task training. In the former lateral task, partakers had to pick up and hold a target object from the table on the paretic side of the participant. They were then asked to move the object 50 cm horizontally, let it go, pick it up again, and place it back in its original place. For the latter vertical task, participants were requested to pick up the object from a low shelf, raise it 17 cm vertically, put it on the midline of the upper layer of the shelf, pick it up again, and put it back in its original place. In our prior research, the processes are clearly outlined [118].

The major differences in the training programs in the clinic and the lab groups were the training intensity and weekly frequency, as well as variations in sensory inputs and the interaction between participants and treatment provider. The program for the clinic group was carried out in a treatment room of the JCREClinic by a physiotherapist on a one-to-

one basis, with sessions lasting 90 minutes in total. For those in the clinic group, a negotiable frequency of sessions was established with a maximum of 4 sessions per week. Nonetheless, there was a final averaged training frequency for the clinic group of 2.25 weekly sessions, and the range in sessions was 1-3 per week. This was because of re-arrangements issues previously discussed. The training pace for those in the clinic group was fairly flexible, with partakers permitted to take a five-minute break whenever required to eliminate fatigue. Patients could have verbal communications with the physiotherapist and vice versa during the break. The findings showed that, in a 90-minute training session, those in the clinical service would gradually increase the overall training duration from under forty-five minutes to over one hour (on average) over the course of the program. In addition, the enriched sensory inputs were provided via various target objects during the grasping motions, which includes sponge, alloy tube, tennis ball and toy carrot.

However, in the lab group, a project research assistant invited participants to take part in the robotic hand training in the laboratory over five weeks, for 4 sessions per week. Every twenty minutes of training was followed by a ten-minute break to limit muscle fatigue. An accumulated practice time of 60 minutes per session was thus achieved, similar to that of our previous trial [118]. In addition, only the sponge could be used by the participants in the lab setting,

2.2.5 Outcome Evaluations

To assess improvements of motor functions in the upper limbs, various clinical assessments were assigned by an individual reviewer who was blinded to the study. In this research, the assessments used were the Fugl-Meyer Assessment [48] (FMA, generating a full score of 66 for the upper limb assessment, which was subsequently divided into shoulder/elbow (S/E, 42/66) and wrist/hand (W/H, 24/66)), the Modified Ashworth Scale (MAS) [50] to assess finger, wrist and elbow flexors, the Action Research Arm Test (ARAT) [49], and Functional Independence Measure (FIM) [51]. The FMA can be used to assess motor functions in voluntary limb movements. What's more, any resistance in passive muscle stretching can be evaluated by the MAS, which indicates the muscular spasticity, predominantly in the flexors. Upper limb voluntary movements are measured using the ARAT, with finger actions being the main point of focus. The FIM indicates the basic quality of ADLs for those who have suffered a stroke.

2.2.6 Statistics

The variations of demographic characteristics for the participants between the two groups were assessed using the independent t-test or the Fisher exact test. Comparisons were made between the baselines of the two groups' clinical scores, and these comparisons were made using an independent t-test that had an insignificant statistical difference ($p>0.05$) on the primary clinical assessments (i.e., pre-assessments on FMA). After this, a one-way analysis of covariance (ANCOVA) was applied to assess the extent of group differences in post-training clinical assessments by using the pre-assessment as a covariate. A paired t-test was carried out after this to explore intragroup differences at different time

points prior to and following the training. Moreover, the variations of each clinical assessment following the programs were compared using independent t-tests. In the present research, the levels of statistical significance were found to be 0.05, 0.01, 0.001.

2.3 Results

Twenty patients in the lab group were screened, which lead to the selection of 16 participants. In the clinic group, 19 out of 150 patients fitting the inclusion criteria and subsequently being selected for participations. Three participants of clinic group withdrew from the study, two of them were due to undertaking other upper limb rehabilitation program throughout this training, and one person opted to withdraw for personal reasons in the middle of the study. Thus, 32 participants took part in the EMG-driven robotic hand assisted upper limb training altogether, albeit in a clinical trial study (n = 16) or in a clinical service (n = 16). Table 2-2 shows the demographic data relating to the recruited participants. There appeared to be no statistical difference between the groups as far as age, gender, side of stroke, type of stroke, career, and age of onset were concerned. Twenty-eight participants had left their jobs, and four participants in the clinic group indicated that they were still employed when the research was taking place. A greater number of sessions took place each week ($p<0.001$) for the lab group than the clinic group.

Table 2-2. Demographic characteristics of the participants. Adapted from [119].

Characteristics	Clinic group (n=16)	lab group (n=16)	P value
Age[a] in years (mean±SD)	53.50±13.08	53.06±10.27	0.917
Gender[b] (male/female)	8/8	12/4	0.273
Stroke side[b] (right/left)	9/7	10/6	1.000
Type of stroke[b] (ischemic/hemorrhagic)	10/6	10/6	1.000
Employment[b] (working/not working)	4/12	0/16	0.101
Times since stroke[a] in years (mean±SD)	3.16±1.85	5.53±4.30	0.052
Training sessions per week[a] (mean±SD)	2.25±0.58	4.00±0.00	0.000***

Difference with statistical significance is marked with '*' (P<0.05, independent t-test). Significant levels are indicated as, 1 asterisk for <0.05, 2 asterisks for ⩽0.01, and 3 asterisks for ⩽0.001.

[a] Test for independent samples.

[b] Fisher's exact test.

The comparison between the clinical scores of both groups prior to training can be seen in Table 2-3. In the MAS elbow and ARAT, significant inter-group differences to the pre-clinical assessment were found (p<0.05). No significant difference was seen for the pre-clinical assessment between both groups for the MAS finger, MAS wrist, FMA, and FIM (P>0.05).

Table 2-3. The pre-clinical assessments of each group. Adapted from [119].

Clinical Score	Clinic Group	Lab Group	P values **(Cohen's d)**
FMA $_{\text{Full score}}$	13.75±11.44	17.50±15.26	0.438 (0.28)
FMA $_{\text{Shoulder/Elbow}}$	10.31±8.14	12.44±10.48	0.527 (0.23)
FMA $_{\text{Wrist/Hand}}$	3.44±4.18	5.06±5.50	0.354 (0.33)
ARAT	3.81±8.30	11.69±12.18	0.041* (0.76)
FIM	56.63±9.25	58.50±14.09	0.660 (0.16)
MAS $_{\text{Finger}}$	1.70±0.76	1.34±1.08	0.279 (0.39)
MAS $_{\text{Wrist}}$	1.65±0.95	1.10±0.66	0.066 (0.67)
MAS $_{\text{Elbow}}$	1.91±0.74	1.21±1.10	0.044* (0.75)

The mean and standard deviations (SD) for each measurement of the pre-clinical assessments, and the probabilities with the estimated effect sizes of the statistical analyses. Intergroup differences with statistical significance are marked with '*' ($P<0.05$, independent t-tests).

Abbreviations: FMA, Fugl-Meyer Assessment; ARAT, Action Research Arm Test; FIM, Functional Independence Measurement; MAS, Modified Ashworth Scale.

The clinical scores of both groups for the FMA, ARAT, FIM and MAS prior to the initial training session and following the final training session are presented in Figure 2-5. Table 2-4 summarizes the values of both groups' clinical assessments. Vast rises were evident in the clinic scores of FMA full score ((P<0.001), FMA S/E (P< 0.001), FMA W/H (P< 0.001), ARAT (P<0.001), and FIM (P<0.01) in the clinic group. Significant decreases were evident in the MAS finger (P<0.001), MAS wrist (P<0.01) and MAS elbow (P<0.01). Major increases could be seen in the FMA full score s(P<0.001), FMA S/E (P<0.001), FMA W/H (P<0.001) and ARAT (P<0.001) of the lab group. The only area in which a major decrease was seen was the MAS elbow (P<0.05). Nonetheless, there were no major differences to post-assessment scores (P>0.05) were evident. It was not possible to employ a one-way ANCOVA test to assess post-clinical scores for the groups' FIM, since there was a significant interaction between the group factor of FIM score and pre-clinical scores (P<0.05). For this reason, differences in clinical scores had to be investigated and intergroup comparison relating to the FIM scores had to be made.

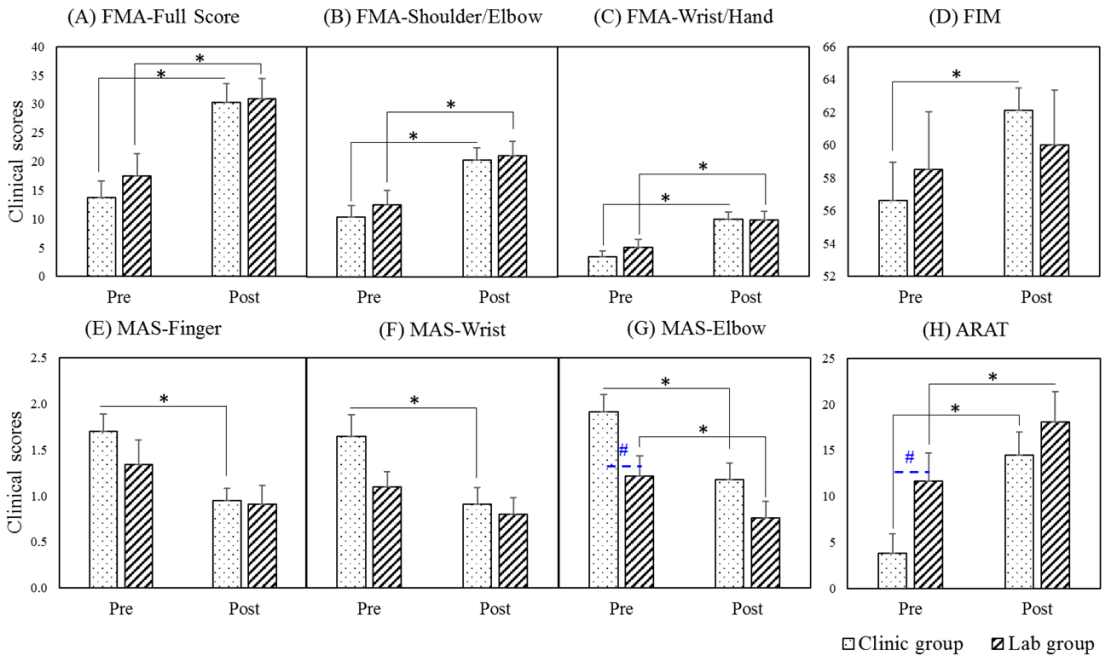


Figure 2-5. The clinical scores (evaluated before the first and after the 20th training session) of the participants in both clinic group and lab group: (A) Fugl-Meyer Assessment (FMA) full scores, (B) FMA shoulder/elbow scores, (C) FMA wrist/hand scores, (D) Functional Independence Measure (FIM) scores, (E) Modified Ashworth Scale (MAS) scores at the fingers, (F) MAS scores at the wrist, (G) MAS scores at the elbow and (H) Action Research Arm Test (ARAT) scores, presented as mean values and SE (error bar) in each evaluation session. The significant intragroup difference is indicated by "*" ($p < 0.05$, paired t-test), and "#" is used to indicate the significant intergroup difference ($p<0.05$, independent t-test). Adapted from [119].

Table 2-4. The clinical assessments of both clinic and lab groups. Adapted from [119].

Assessment	Group	PRE	POST	Paired T Test	1-way ANCOVA
		Mean Value (95% Confidence Interval)		*P (Cohen's d)*	*P (Partial η2)*
FMA Full score	Clinic	13.75 (8.09~19.41)	30.31 (23.88~36.75)	0.000*** (-1.45)	0.550 (0.012)
	Lab	17.50 (9.95~25.05)	30.88 (23.92~37.83)	0.000*** (-1.46)	
FMA Shoulder/Elbow	Clinic	10.31 (6.28~14.34)	20.31 (16.18~24.44)	0.000*** (-1.35)	0.782 (0.003)
	Lab	12.44 (7.25~17.63)	21.06 (16.16~25.97)	0.000*** (-1.18)	
FMA Wrist/Hand	Clinic	3.44 (1.37~5.51)	10.00 (7.52~12.48)	0.000*** (-1.36)	0.333 (0.032)
	Lab	5.06 (2.34~7.78)	9.81 (6.75~12.87)	0.000*** (-1.35)	
ARAT	Clinic	3.81 (-0.30~7.92)	14.50 (9.56~19.44)	0.000*** (-1.22)	0.175 (0.063)
	Lab	11.69 (5.66~17.72)	18.06 (11.43~24.69)	0.000*** (-1.44)	
FIM	Clinic	56.63 (52.05~61.20)	62.13 (59.41~64.84)	0.004** (-0.86)	Nil
	Lab	58.50 (51.53~65.47)	60.00 (53.39~66.61)	0.161 (-0.37)	
MAS Finger	Clinic	1.70 (1.32~2.08)	0.95 (0.68~1.22)	0.000*** (1.12)	0.622 (0.009)
	Lab	1.34 (0.81~1.87)	0.91 (0.52~1.31)	0.085 (0.46)	
MAS Wrist	Clinic	1.65 (1.18~2.12)	0.91 (0.56~1.26)	0.001*** (0.97)	0.443 (0.020)
	Lab	1.10 (0.77~1.43)	0.80 (0.45~1.15)	0.075 (0.48)	
MAS Elbow	Clinic	1.91 (1.54~2.28)	1.18 (0.82~1.53)	0.001*** (1.08)	0.892 (0.001)
	Lab	1.21 (0.77~1.66)	0.76 (0.40~1.12)	0.013* (0.71)	

The mean and 95% confidence intervals for each measurement of the clinical assessments, and the probabilities with the estimated effect sizes of the statistical analyses. Intragroup differences with statistical significance are marked with '*' ("*" for paired t-tests). Significant levels are indicated as, 1 asterisk for <0.05, 2 asterisks for ≤0.01, and 3 asterisks for ≤0.001.

The changes to each clinical assessment for both groups after the relevant training are shown in Figure 2-6. Furthermore, Table 2-5 shows the values and the statistical findings of comparisons. Significantly higher differences in FIM scores were evident in the clinic group than the lab group ($P<0.05$). No significant differences could be obtained between the clinical scores of both groups as far as ARAT, FMA, and MAS ($P>0.05$) were concerned.

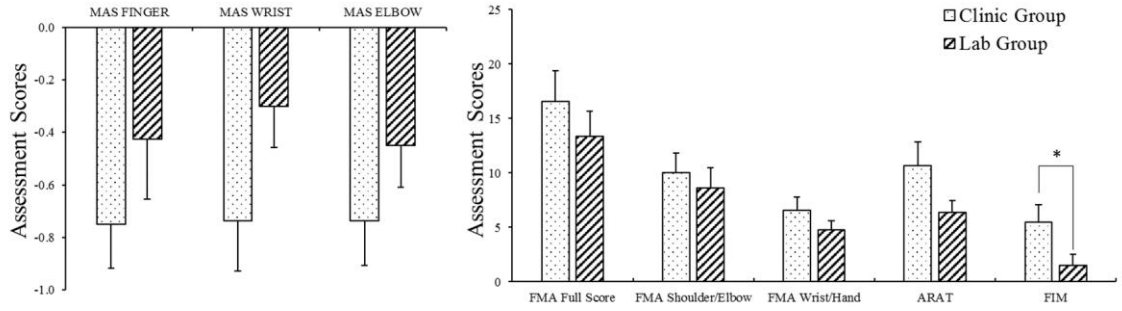


Figure 2-6. The changes of each clinical assessment after the treatments in both clinic and lab groups: Fugl-Meyer Assessment (FMA) full scores, FMA shoulder/elbow, FMA wrist/hand, Action Research Arm Test (ARAT), Functional Independence Measure (FIM) and Modified Ashworth Scale (MAS) scores at the fingers, the wrist and the elbow, presented as mean value with SE (error bar) in each evaluation session. The significant difference is indicated by "*" ($p < 0.05$, independent t-test). Adapted from [119].

Table 2-5: The changes of each clinical assessment of each group. Adapted from [119].

Clinical Score	Clinic Group	Lab Group	P value **(Cohen's d)**
FMA $_{\text{Full score}}$	16.56±11.38	13.38±10.29	0.390(0.29)
FMA $_{\text{Shoulder/Elbow}}$	10.00±7.39	8.63±7.29	0.600(0.19)
FMA $_{\text{Wrist/Hand}}$	6.56±4.83	4.75±3.51	0.234(0.43)
ARAT	10.69±8.73	6.38±4.44	0.088(0.62)
FIM	5.50±6.41	1.50±4.07	0.043* (0.75)
MAS $_{\text{Finger}}$	-0.75±0.67	-0.43±0.92	0.263 (0.40)
MAS $_{\text{Wrist}}$	-0.74±0.76	-0.30±0.63	0.226 (0.63)
MAS $_{\text{Elbow}}$	-0.74±0.68	-0.45±0.63	0.086 (0.44)

The mean and standard deviations (SD) for the changes of each clinical assessment, and the probabilities with the estimated effect sizes of the statistical analyses. Intergroup difference with statistical significance is marked with '*' ("*" for independent t-test).

2.4 Discussion

Following the 20-session upper limb rehabilitation program involving the use of an EMG-driven robotic hand, all participants showed improved clinical scores relevant to motor functions, and such improvements were demonstrated in the elbow, shoulder and fingers following the training.

It was apparent from the major increase in the FMA S/E score following treatment that robotic hand training is largely beneficial for improving motor control of the shoulder and elbow joints, with comparable training effects in both groups. Despite the fact that no specific robotic system was used on the elbow and shoulder in the present research, the greater FMA S/E scores following the application of robotic hand training is still evident. There are many potential reasons for this, the first of which is that other joints that play a part in training tasks could help the entire upper limb [122]. In the present research, the

elbow-related and shoulder-related muscles were exercised in the program through both lateral and vertical task training. Secondly, the adjacent proximal joint improves if the surrounding muscle is trained, which has been demonstrated in our prior work [87, 99]. This means that the wrist training could generate improvements to elbow movement [87], and that shoulder movement may be enhanced via elbow training [99]. Since there is no evident proximal to distal gradient of motor deficit [123], it is indicative that task-oriented upper limb training is far more effective than individual joint training, and this is in line with findings by other researchers such as Susanto et al. [122] and Oujamaa et al. [124]. There was a significant increase in the FMA W/H scores for both group, suggesting that the present work's EMG-driven robotic hand may help stroke survivors to enhance their motor functions throughout the wrists and hands, since a comparable achievement has been identified between the clinic group and the lab group. The primary purpose of the ARAT score is to assess finger movements, as well as to assess the extent of movements, such as pinching, gripping, and grasping. The significantly increased ARAT scores for the two groups indicated that there was improved finger coordination to aid in fine precision grasping and joint stability in fingers. which was in line with the increased FMA W/H score.

Comparisons between the functional improvements of both groups have shown that the effectiveness of the robotic hand in a private clinic setting can be statistically the same as in the research laboratory setting, where the clinic service group showed more improvements even when had a lesser training frequency than the lab group. In addition, improvements to the ADLs, as evident from the FIM scores, showed that the clinic group had significantly better ADLs than the lab group. The key purpose of the FIM score is to

assess the fundamental quality of day-to-day life tasks that patients with stroke must encounter. In the clinic group, the significant increase in FIM scores demonstrated the effectiveness of the EMG-driven robotic hand in enhancing the independence of ADLs for patients of chronic stroke in the clinic group. Nonetheless, no significant improvements to the FIM scores of the lab group were evident following robotic hand training. What's more, the evident decline in the MAS score at elbow, wrist and fingers in the clinic group is suggestive that the robotic hand treatment may help with muscle coordination and joint stability of the proximal and distal joints in arm reaching movements, as well as in hand grasp and release movements. However, significant decrease in the MAS scores for lab group was only observed at the elbow joint, and no apparent decrease in the MAS scores for the fingers and wrist after robotic hand training.

It is therefore important to question the reason why the clinic group obtained better ADLs and released muscle tone in their hand even though they were exposed to less training frequency per week. A potential reason is that those in the clinic group carried out daily exercise independently outside of the clinic. It is always recommended by therapists in clinical service that stroke patients practice the hand grasp and release actions and arm reaching on a daily basis in order to generalize the learnt motor skill to daily activities. Such patients adhered to the professional advice and carried out daily living activities, including feeding, dressing and bathing themselves using the injured limb. However, it was revealed that the research staff in the lab group did not recommend the patients to practice ADLs independently. Meanwhile, the significant decrease in MAS wrist amongst the clinic group following training with the robotic hand indicated a release of spasticity in the wrist joint, while the lab group did not demonstrate similar findings. Nonetheless,

the wrist joints were fixed on the palm-wrist module (see Figure 2-1), and, in the present research, no tasks were especially assigned to wrist joints. The lowered spasticity in the wrist joint that was evident amongst the clinic group might thus not be a direct result of using the robotic hand, but rather a result of stroke patients owns self-practice. What's more, in comparison to the lab group, the vastly improved FIM scores within the clinic group could be caused by participants' independent practice with day-to-day tasks.

In this study, one feature of the clinical service was that richer somatosensory stimulation was applied, and that might be effective for improving motor function after stroke [27, 125]. Sensory deficiency after stroke will reduce sensory input to the brain, which is particularly important for the brain to plan and execute voluntary movements and provides access to the external world of physical objects [41, 126]. In light of recent neurophysiological research, it is reported that sensory stimulation may assist in enhancing sensory input for stroke patients, which can facilitate motor movements and further improve motor functions [40]. In addition, Gallien et al.[46] reported poorer rehabilitation outcomes for stroke patients when there was insufficient sensory stimulation, while Huang et al. [47] suggested that improvements in neurological scores can be obtained when increasing activation of MI and SI by somatosensory stimulation for both acute and chronic stroke patients. As a result, it is considered that sensory stimulation is a crucial component for motor recovery. In this study, various target objects were prepared in the clinic group to provide different sensory stimulations to the paretic hand. For instance, the sponge provides the soft textile perception with a very light weight, while the alloy tube provides a feeling of hard and cold. Meanwhile, the tennis ball provides a perception of fluffy and rough, while the toy carrot provides a smooth tactile

sensation. However, only the sponge could be used by the participants in the lab setting, with the absence of variety in sensory stimulation compared with the clinic group.

A further distinct feature of clinical service is that the pace of training is largely flexible and is often referred to as voluntary exercise. Throughout robotic training, participants can voluntarily control the pace of training by taking a break when they desired or choosing to carry on the robotic training without resting. On average, the range of the practicing time per session was between 45 minutes to over 60 minutes. In the initial training sessions, clinic group participants typically requested a break every five minutes. After familiarizing themselves with the training program, they were gradually able to enhance their practicing time to approximately one hour per session. Patients who were able to perform well using the robotic hand had practicing times that would surpass 60 minutes, and what's more, they even stated that they would practice more if time was not limited. On the other hand, those in the lab group rested for ten minutes after every twenty minutes, meaning that the accumulated practice time per session was 60 minutes. Despite their being a lack of research into the impacts of voluntary exercise on stroke rehabilitation, a number of studies carried out on post-stroke mice have shown that results are better when voluntary exercise is conducted than when forced exercise is conducted. Ke et al, [127] for example, trained rats after a stroke by using three approaches that involved the voluntary exercise of wheel running (V-Ex), forced exercise of treadmill running (F-Ex), and involuntary exercise of FES (I-Ex). The V-Ex rats were kept separately in a cage and allowed to run freely around a running wheel assembled in the cage, very much like the flexible training in our clinic group. On the other hand, F-Ex rats were forced to run for half an hour on a motor-driven treadmill every day, very much like the fixed training in

the lab group of the present research. Findings revealed that voluntary exercise was much more advantageous for enabling motor recovery, and that forced exercise group was less effective. This is in line with Lin et al. [128] findings. This could justify the greater improvements achieved by the clinic group, and thus is a possible aspect that could be further explored in future in the field of post-stroke rehabilitation.

Motivation is regarded as the key of stroke rehabilitation and is crucial in determining recovery outcomes [129]. Many people opine that those with more motivation will have better outcome than those who possess less enthusiasm for the treatment [130, 131]. It was found in the present work that stroke patients in the clinical service were more motivated than the participants in the lab group. Motivation has been found to be a multi-determined phenomenon that involves a variety of factors, including patient characteristics (such as personality traits, age, anxiety, socio-economic status), social factors (like practitioner traits and patient-practitioner interaction) and the rehabilitation setting [132, 133]. It is therefore possible that the socio-economic status of those in the clinic group could have impacted the patients' motivation. For instance, four stroke patients in the clinic group continued to go to work and thus had a strong drive to regain motor functions. On the other hand, all participants in the lab group had left their jobs, and thus may be doubtful of their capacity to carry out daily tasks and may also possess lower motivation to regaining function. The practitioner's traits, as well as patient-practitioner interaction have also been found to be related to patient motivation [134]. A practitioner that is very confident in the program and who is a good communicator can enhance patient motivation, whereas practitioners who seem more uncertain could decrease patient motivation [135, 136]. A professional physical therapist clads in a

doctor's coat and who offers professional rehabilitation advice within a clinic environment can subconsciously create positive motivation in the clinic group patients. Moreover, treatments given in different rehabilitation settings can impact the extent to which a patient believes in the treatment. A qualitative analysis of stroke professionals' attitudes [133] found that motivation can be positively influenced by a stimulating rehabilitation setting and a well-maintained treatment room. An encouraging, stimulating and interactive environment is thus crucial in boosting patients' motivation. Some studies have also shown that training devices that offer reward schemes in a gaming environment can also enhance patient's determination [137, 138]. Nonetheless, further research into how to employ motivational therapy within rehabilitation in order to achieve the best outcomes is crucial [139].

The present research revealed that the ARAT and MAS Elbow scores amongst the clinic group fell significantly below those of the lab group. Nonetheless, no significant difference was identified between the pre-assessment groups in terms of clinical scores and this may suggest that upper limb motor function of those in the clinic group is less than that of the lab group throughout admission. The rehabilitation outcomes for the clinic group participants in the post-assessments were either on par with or better (e.g., FIM) than the lab group. This could thus signify that the robotic hand had more positive outcomes for severely injured patients. The present research had the key limitation that a small sample was used. In our future studies, large scale clinical trial will be carried out with stratified randomization in multi-centers being used, as this will be important in further validating the effectiveness of using assistance devices for rehabilitation after a stroke.

2.5 Periodic Summary

Motor improvements of the EMG-driven robotic hand training achieved in the clinical service were in line with those using the same robotic hand performed in a laboratory setting, whereas the integration of enriched tactile sensory inputs in the clinic service led to a more efficient release in muscle spasticity and greater independence in daily living. This could also be a result of flexible training, higher motivation, and self-exercise. The current work serves as a valuable contribution demonstrating the importance of robot assisted upper limb rehabilitation in clinic service for stroke survivors. Moreover, this work has shown that a robotic hand assisted device can be both viable and efficient for helping with upper limb therapy and for enhancing motor function in distal joints, and this further translates into motor recovery in the proximal joints like shoulder and elbow.

CHAPTER 3

A COMPARISON OF REHABILITATION EFFECTIVENESS OF EMG-DRIVEN NMES ROBOTIC HAND TRAINING AND PURE ROBOTIC HAND TRAINING AFTER STROKE

3.1 Introduction

Motor deficits in the upper limbs are frequent following a stroke, with approximately 80% of stroke survivors experiencing this [107, 108]. A number of devices to assist rehabilitation have been created to help physical therapists manage the long-term rehabilitation process [78-80]. Rehabilitation robots are the most common types of devices used for stroke rehabilitation, with a highly efficient and cost-effective alternative to traditional rehabilitation services since they can provide intensive and repetitive training [85, 100, 140, 141]. The use of voluntary effort (e.g. electromyography, EMG) in robotic design has been found to play a key part in motor recovery of stroke patients [112, 140], as EMG-driven approaches are able to optimize voluntary effort in training. Evidence has been found to support EMG's effectiveness in enhancing upper limb voluntary motor functions [98, 142, 143], but it is important to note that rehabilitation robots cannot directly activate the targeted muscle groups, and thus only serve to assist (or dominate) limb motion, for example through continuous passive motions (CPM) [87]. What's more, stroke patients tend to activate the target muscles through compensatory motions from other muscular tasks, and this can cause 'learned disuse' [88]. On the other

hand, the rehabilitation robots usually lack the sensory stimulation during the training when the sensory inputs may contribute to a more effective strategy for stroke rehabilitation. Neuromuscular electrical stimulation (NMES), as a direct sensory stimulation, could activate the targeted muscles through cyclic electrical currents and generate sensory feedback [89]. The key benefit of NMES is that it can offer repetitive sensorimotor experiences and effectively limit compensatory motions, as well as enhancing muscular power and ultimately improving motor function in stroke patients [93, 94]. However, training programs that rely solely on NMES can be suboptimal as a result of the difficulty involved in controlling movement trajectories and early onset fatigue [95, 96].

Accordingly, various NMES robot-assisted upper limb rehabilitation programs which combining sensory stimulation into motor rehabilitation have been proposed to take advantage of the benefits and lower the disadvantages [87, 97-100]. The effectiveness of the combined systems for rehabilitation has been proved in a number of investigations to enhance motor recovery. Several studies have made comparisons between the training outcomes of NMES robot-assisted training and different training programs. Qian et al. [99], for instance, found that NMES-robot-assisted upper-limb training may offer more effective motor outcomes when compared with traditional treatments for those having suffered subacute strokes. Meanwhile, a further piece of research which has explored the comparisons between the impact of robot-aided training with NMES and robot-aided training using only InMotion ARMTM Robot in the subacute period has found significantly higher active movement ranges for the robot training with NMES than the robot training alone [101]. What's more, studies into chronic stroke patients and relevant

assistance applications have also been conducted. For example, Hu et al. [87] put forward an EMG-driven NMES robot system that can be used for wrist training. It is a combined device that can enhance muscular activation levels around the wrist and lower the compensatory muscular activation around the elbow. It is important to note that such training outcomes were not found using the EMG-driven robot in isolation. A similar study carried out by a different researcher also found more enhanced rehabilitation outcomes for various clinical assessments when the combined system was used as opposed to the robot-assisted therapy alone [97].

Research into current rehabilitation applications that use NMES and robotic systems tend to focus on elbow and wrist joints [97, 99-101], with very little investigation into the hand and fingers specifically [103]. In addition, comparison on the training effects between the NMES robots for hand rehabilitation and other hand rehabilitation devices, have not been adequately investigated yet. The loss of hand movement is the most common upper-limb disability that is encountered following a stroke, with the rehabilitation of the distal joints being significantly more challenging than the motor recovery of proximal joints, and this is because a result of the proximal compensatory movements. For this reason, creating effective rehabilitation devices that can limit the compensatory motions in hand motor recovery and provide sensory experience is very important for stroke rehabilitation. We proposed an EMG-driven NMES robotic hand to be used in rehabilitation following a stroke in our prior work [102]. The devices allow hand movements to be precisely controlled, delivering sensory inputs and activate the target muscles directly to enable finger extension/flexion selectively. A single group trial has provided evidence to support its feasibility and effectiveness [98]. Nonetheless, the extent to which long-term

rehabilitation impacts this EMG-driven NMES robotic hand after generating the sensory stimulations can be considered comparable or better than alternative hand rehabilitation devices is unclear and requires further research. Hence, the present work aims to explore the effectiveness of an EMG-driven NMES robotic hand and an EMG-driven robotic hand, which it will achieve by carrying out a randomized controlled trial and a follow up after three months (3MFU).

3.2 Methodology

3.2.1 Participants

The Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University gave their approval for this research. Altogether, 53 stroke survivors from local areas were screened, with 30 chronic stroke patients meeting the inclusion criteria as follows: (1) At least 6 months must have passed since the onset of a singular and unilateral brain lesion caused by a stroke, (2) participant must be able to extent metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints to 180° passively, (3) the participant's muscle spasticity during finger extension at the wrist and finger joints must be under 3 on the Modified Ashworth Scale (MAS) [50] (the scale ranges from 0 (no increase in muscle tone) to 4 (affected part rigid)), (4) the detectable voluntary EMG signals coming from the dominant muscle on the impaired side must be three times the standard deviation (SD) above the EMG baseline, and (5) no visual deficit and in capacity to understand the instructions, which will be evaluated using the Mini-Mental State Examination (MMSE > 21) [121].

The study used a randomized controlled trial and conducted a follow up after three months (3MFU). Firstly, potential participants were informed that, in the training program, they would be using either an NMES robotic hand or a pure robotic hand. All participants had to provide written and informed consent prior to randomization. After this, the selected patients were randomly allocated to two groups, which was determined using a computer-based random number generator (this means that the computer program generated either "1" (referring to the NMES robotic hand training group) or "2" (the pure robotic hand group). Both outcomes had an equal probability of 0.5 (Matlab, 2017, Mathworks, Inc.). The CONSORT flowchart relating to the training program is presented in Figure 3-1.

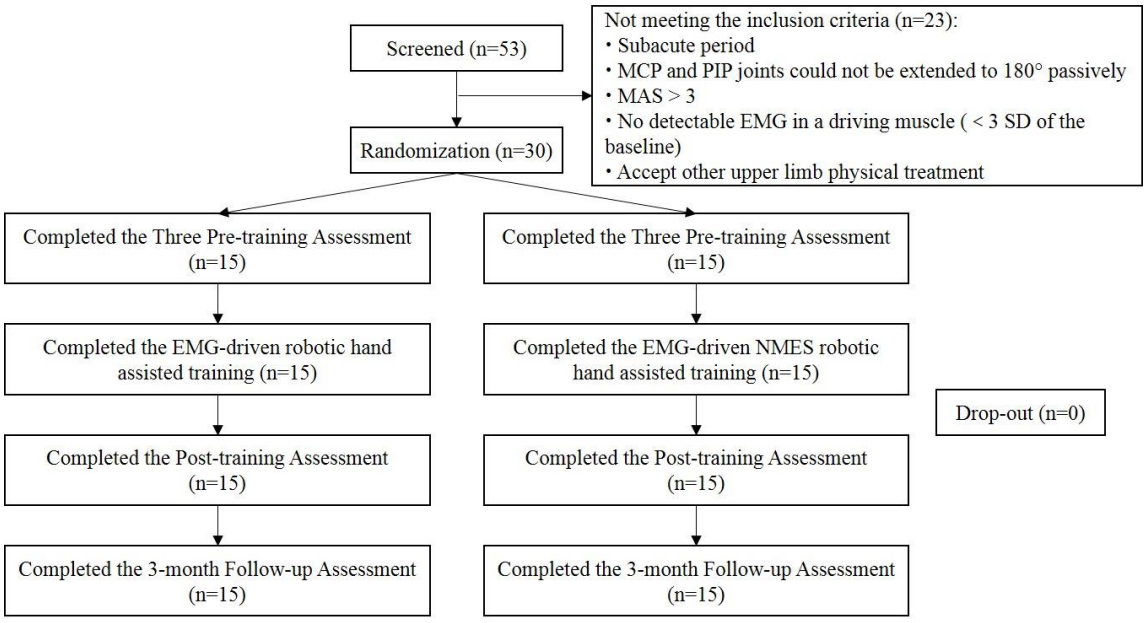


Figure 3-1. The consolidated standards of reporting trials flowchart of randomized controlled trial in chronic stroke patients.

3.2.2 Interventions

Participants in both groups were invited to attend twenty sessions of robotic hand training at a frequency of 3-5 sessions per week, which were to be completed over seven consecutive weeks. Figure 3-2 shows the training setup for the two groups. The use of this robotic hand training system can help to improve finger extension and impaired limb flexion following a stroke. In the present work, to control the hand opening and closing motions, real-time voluntary EMG detected from the abductor pollicis brevis (APB) and extensor digitorum (ED) muscles were employed. The threshold for each motion stage was thrice the SD above the EMG baseline at resting state [98]. To give an example, when flexing the finger, the EMG activation level of the APB muscle met the pre-determined threshold, with the robotic hand thus assisting in hand closing. Likewise, when extending the finger, the robotic hand could help the patient to open their hand if the EMG activation of the ED muscle met the predetermined threshold. In the group that used the NMES robot, synchronized support was given from the NMES and the robot. The pair of NMES electrode (30 mm diameter; Axelgaard Corp., Fallbrook, CA, USA) were joined to the ED muscle as a means of stimulating finger extension, with the NMES producing square pulses at a consistent 70 V amplitude and a stimulation frequency of 40 Hz. Furthermore, they had a manually adaptable pulse width varying from 0–300 μs. The pulse width was pre-determined at a minimum intensity prior to commencing the training, which allowed fingers of each participant to be fully extended. Throughout the program, NMES was triggered by the EMG, firstly by the ED muscle, and then would stimulate the ED muscle to open the hand throughout the whole process of finger extension. However, there was no assistant provided by NMES throughout finger flexion to minimize the changes of

finger spasticity following stimulation [144]. In terms of the pure robot group, NMES was not used in the pure robot group. Our prior research has provided an in-depth account of how the robotic hand functions [98, 118, 119].

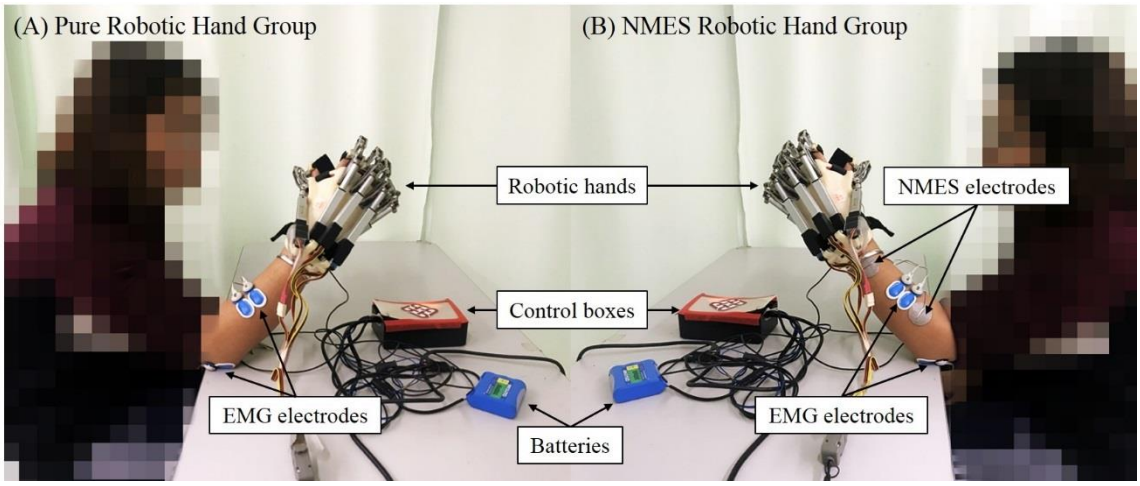


Figure 3-2. The experimental setup of the robotic hand training: (A) pure robotic hand group; (B) neuromuscular electrical stimulation (NMES) robotic hand group.

In each session, patients in the two groups had to carry out a maximum voluntary contraction (MVC) on the five target muscles as follows: APB, ED, flexor digitorum (FD), biceps brachii (BIC), and triceps brachii (TRI) muscles. Every contraction for the MVC test had to be held for 5 seconds and carried out two times. Then, the participants were requested to use the affected limbs (without NMES or the robotic hand help) to carry out bare-hand assessment tests. These tests included lateral and vertical arm reaching-grasping tasks. In the lateral task, participants had to grasp a sponge (5 cm thick and weighing 30 g), which they then had to move 50 cm horizontally to the other side of the table. After this, they were asked to release it, pick it up again and place it back in its original place. In the vertical task, Participants had to pick up the sponge from a position

in the middle of lower layer of a shelf, lifted it by 17 cm and put it in the middle of upper layer of the shelf. They then had to pick it back up and replace it in its original position. The lateral and vertical tasks were carried out three times, with a two-minute break between every two consecutive contractions throughout both the bare-hand assessment test and the MVC test to minimize muscle fatigue. Details relating to the MVC and the bare-hand assessment tests' evaluation processes have been presented in our prior work [98, 118]. Once the pre-training assessment test had been completed, participants had to perform repetitive upper-limb motions, similar to lateral and vertical tasks carried out in the evaluation using support from either the EMG-driven robotic hand or the EMG-driven NMES robotic hand. The duration of the lateral and vertical tasks in each training session was 30 minutes, with a 10-min break in between tasks so as to minimize muscle fatigue.

3.2.3 Evaluation of Training Effects

3.2.3.1 Clinical Assessments

A blinded assessor performed the functional assessments for all of the participants, and the evaluation process employed the Fugl-Meyer Assessment [48] (FMA using a full score of 66 for the upper-limb assessment, and was then further narrowed down to shoulder/elbow (FMA-S/E, 42/66) and wrist/hand (FMA-W/H, 24/66)).The Modified Ashworth Scale (MAS) [50] was used to evaluate the flexors of fingers, wrist and elbow, as well as the Action Research Arm Test (ARAT) [49], and Functional Independence Measure (FIM) [51]. The present study employed a multiple baseline design, with 5 time points being established in total for the clinical assessment. This was inclusive of three pre-training evaluations, a post-training evaluation and the 3MFU. The frequency of pre-

training evaluations was three times per fortnight prior to the training session and was carried out every 2-3 days to make sure the baseline was secure. The post-training evaluation was carried out straight away following the final training session, with the 3MFU being evaluated three months after the final training session.

3.2.3.2 EMG Parameters

The EMG signals from the APB, ED, FD, TRI and BIC muscles of participants in both groups each session was recorded in the present research. Two parameters were worked out and applied to quantitatively monitor any differences to muscle activation and coordination patterns throughout the course of training sessions. These were the normalized EMG Co-contraction Index (CI) between muscle pairs [145, 146] and the normalized EMG activation level for each target muscle. The EMG activation level of a muscle was calculated as follows:

$$\overline{\mathrm{EMG}} = \frac{1}{T}\int_0^T EMG_i(t)dt \qquad \text{(Eq. 3.1) [112, 147]}$$

where $\overline{\mathrm{EMG}}$ referred to the EMG activation level of a muscle *i*, EMG*i*(t) was the EMG envelope signal after normalization with respect to the EMG maximum value of the muscle, and *T* was the length of the signal. To avoid any differentiations in patients' EMG activation levels, further normalization of the EMG activation level value was carried out every session for each participant. This was in terms of the maximal and minimal EMG activation levels of every participant that had been noted down throughout the course of the twenty training sessions (Eq. 3.2). Subsequently, we measured the tendency of the EMG activation level values (varying from 0 to 1) of one participant throughout the whole course of the 20 training sessions.

$$\mathrm{EMG_N} = \frac{\overline{\mathrm{EMG}} - \overline{\mathrm{EMG}}_{\mathrm{min}}}{\overline{\mathrm{EMG}}_{\mathrm{max}} - \overline{\mathrm{EMG}}_{\mathrm{min}}} \qquad \text{(Eq. 3.2) [112, 147]}$$

where $\mathrm{EMG_N}$ was the normalized EMG activation level of muscle *i*. $\overline{\mathrm{EMG}}$ referred to the averaged EMG envelope value of muscle *i*. $\overline{\mathrm{EMG}}_{\mathrm{min}}$ was the minimum value of the averaged EMG envelope across the 20 training sessions, and $\overline{\mathrm{EMG}}_{\mathrm{max}}$ was the maximum value of the averaged EMG envelope across the 20 training sessions.

The CI between a pair of muscles was calculated as follows:

$$\mathrm{CI} = \frac{1}{T}\int_0^T A_{ij}(t)dt \qquad \text{(Eq. 3.3) [112, 147]}$$

where Aij(t) was the overlapping activity of EMG linear envelopes for muscles i and j, and T was the length of the signal. CI denotes the level of co-contraction occurring between a muscle pair. A heightened CI value is suggestive that the overlapping area of a muscle pair is growing, whereas a lowered CI value indicated that the overlapping area is becoming smaller. In order to work out the tendency of muscle coordination, it was crucial to further normalize the CI value through a similar operation at the EMG activation level, in terms of working out both the maximal and minimal CI values of each participant recorded across the 20 training sessions respectively. The varying patterns of the two EMG parameters across the training sessions provided a complete picture of the recovery progress of the affected limb. In our prior work, we have discussed and used the EMG parameters relating to the normalized EMG activation level and CI values [87, 98, 99].

3.2.4 Statistical Analysis

The Fisher exact test and the independent T-test were used to assess the differences in participants' demographic features between the two groups. Additionally, the Lilliefors method applied insignificant probabilities ($P > 0.05$) to carry out normality tests on the clinical scores and EMG data [148]. Then, a two-way analysis of variance (ANOVA) was conducted to compare the baselines of the clinical scores for both groups, showing an insignificant statistical difference ($P > 0.05$) regarding the primary clinical assessments (namely pre-training evaluations of FMA). To lower the potential for baseline differences between the groups as much as possible, a two-way analysis of covariance (ANCOVA) was conducted to explore the independent group factors (i.e., the NMES group and the pure group) and given time points (i.e., the three pre-training evaluations, post-training evaluation and the 3MFU assessment) by taking the mean of the three pre-assessments as a covariate. Subsequently, to assess intra-group variations at different time points, a one-way ANOVA test with Bonferroni post hoc tests were carried out. To evaluate the post hoc intra-group comparisons of clinical scores for the relevant post- and 3MFU assessments, one-way ANCOVA test was conducted, with the mean of the three pre-assessments as a covariate. Nonetheless, a significant score was found for the interaction between the three pre-training assessments pre-scores and MAS wrist score ($P < 0.05$), meaning it was not possible to conduct another one-way ANCOVA to assess the 3MFU MAS wrist scores evaluations for the groups. Thus, in order to compare intergroup MAS wrist scores, an independent t-test had to be carried out. Over the twenty sessions, the EMG parameters (i.e., EMG activation levels and CI values) were assessed through a two-way ANOVA test, the aim of which was to explore the recovery process for all training

sessions in both groups. Subsequently, an assessment of the intra-group differences for the two groups over the 20 sessions was conducted via a one-way ANOVA with Bonferroni post hoc tests. An independent t-test was used to assess intergroup variations at each training session. In this study, the level of statistical significance was set at 0.05, and was further indicated at 0.01 and 0.001.

3.3 Results

A total of 53 stroke survivors were screened to take part in the robotic hand training, with 30 fitting the required inclusion criteria and thus being recruited to take part in the research. Every participant was allocated to one of two groups on a random basis, and these two groups were the NMES group (n = 15) and the pure group (n = 15). Demographic details relating to the participants after the randomization process can be seen in Table 3-1. No statistical variations were evident between groups in terms of age, gender, stroke side and onset time.

Table 3-1. Demographic characteristics of the participants in the randomized controlled trial.

Characteristics	NMES group (n=15)	PURE group (n=15)	P value
Gender[a] (male/female)	12/3	12/3	1
Stroke side[a] (right/left)	7/8	5/10	0.710
Type of stroke[a] (ischemic/hemorrhagic)	8/7	10/5	0.710
Age[b] in years (mean±SD)	57.33±9.19	60.07±6.88	0.353
Times since stroke[b] in years (mean±SD)	8.27±4.32	6.20±3.41	0.296

No statistical differences are found between the groups (P>0.05, independent t-test).

[a] Fisher's exact test.

[b] Independent t-test.

3.3.1 Clinical scores

Figure 3-3 shows the clinical scores (i.e., FMA, ARAT, MAS, and FIM) of participants in the NMES and the pure group at five different times, including three pre-training assessments, the post-training assessment, and the 3MFU assessment. The mean scores and 95% intervals of confidence for each clinical evaluation is presented in Table 3-2. We obtained the two-way ANCOVA probabilities scores and estimated effect sizes (EFs) at every interval and for both groups. Furthermore, the one-way ANOVA probabilities are provided alongside the EFs during the intragroup evaluations. Table 3-3 presents the probabilities and EFs of inter-group comparisons, which are linked to the respective post- and 3MFU assessment scores that were obtained through the one-way ANCOVA test using adapted baseline effects and an independent t-test. In terms of variations, none of significance were found within or between the groups in the baseline tests for any clinical

score. In the FMA full score, there was a significant increase in both groups following the sessions, and such improvements were still evident three months later in the follow up ($P<0.05$). In addition, the FMA full scores of the NMES group during post-evaluation and 3MFU were significantly greater than those of the pure group ($P<0.05$). Significant improvements were identified for the FMA S/E and W/H scores in the NMES group post-training ($P<0.05$), an improvement which was still evident in the three months follow up evaluation. However, it is noted that no significant intragroup difference appeared to occur in the pure group's FMA S/E and W/H scores. Moreover, the FMA S/E scores for the NMES group was much more elevated than those of the pure group following the training program, which continued to be the case three months later ($P<0.05$). A further significant improvement to the ARAT was also seen after training in both groups ($P<0.05$), despite this vast increase only being evident in the three months follow up for the NMES group ($P<0.05$). Post-evaluation scores of ARAT between two groups were similar, but in the three months follow up, those of the NMES group were much higher than those of the pure group ($P<0.05$). A significant decline in MAS scores for the elbow, wrist, and finger joints of the NMES group was evident following training, and the decrease was still apparent three months later ($P<0.05$). However, for the pure group, the MAS scores related to the finger, wrist, and elbow joints decreased, but no significant significance was recorded. In terms of the MAS scores for wrist, elbow and finger joints, there were found to be significant intergroup differences ($P<0.05$), and it seems that, for the NMES group, there were significantly lower post-evaluation and 3MFU scores than those of the pure group ($P<0.05$). Additionally, in the NMES group, significantly lower scores were revealed in the three months follow up in the MAS scores for finger and wrist joints than

in the pure group (P<0.05). Both of the two groups demonstrated enhanced FIM scores following the training, although no statistical significance was found.

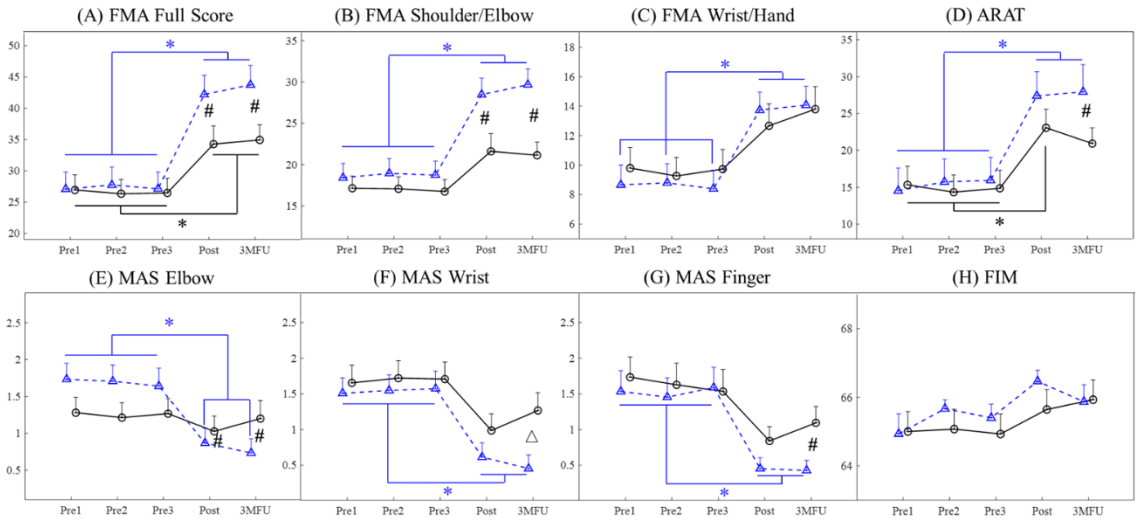


Figure 3-3. The clinical scores [evaluated before the first and after the 20th training session, as well as the 3-month follow-up (3MFU)] of the participants in both NMES robotic hand and pure robotic hand groups: (A) Fugl-Meyer Assessment (FMA) full scores, (B) FMA shoulder/elbow scores, (C) FMA wrist/hand scores, (D) Action Research Arm Test (ARAT) scores, (E) Modified Ashworth Scale (MAS) scores at the elbow (F) MAS scores at the wrist, (G) MAS scores at the fingers, and (H) Functional Independence Measure (FIM) scores, presented as mean value with SE (error bar) in each evaluation session. The solid lines are for the pure group, and the dashed lines are for the NMES group. The significant inter-group differences are indicated by "#" ($P < 0.05$, one-way analysis of covariance) and "△" ($P < 0.05$, independent t-test), and "*" is used to indicate the significant intragroup difference ($P < 0.05$, one-way analysis of variance with Bonferroni post hoc tests).

Table 3-2. The clinical assessments of each group in the randomized controlled trial.

Assessment	Group	PRE1	PRE2	PRE3	POST	3MFU	1-way ANOVA	2-way ANCOVA		
		Mean Value (95% Confidence Interval)					*P* (*Partial η2*)	*P (Partial η2)*		
								Time point	Group	T*G
FMA Full score	NMES	27.07 (21.22~32.91)	27.73 (21.57~33.89)	27.13 (21.44~32.83)	42.20 (35.67~48.73)	43.73 (37.10~50.37)	0.000*** (0.337)	0.000### (0.640)	0.000### (0.111)	0.000### (0.157)
	PURE	26.93 (21.69~32.18)	26.33 (21.41~31.25)	26.47 (21.51~31.43)	34.27 (28.01~40.52)	34.93 (29.75~40.11)	0.000*** (0.337)			
FMA Shoulder/Elbow	NMES	18.40 (14.70~22.10)	18.93 (15.09~22.77)	18.73 (15.13~22.34)	28.47 (24.18~32.76)	29.67 (25.52~33.81)	0.000*** (0.357)	0.000### (0.552)	0.000### (0.124)	0.000### (0.174)
	PURE	17.13 (14.02~20.25)	17.07 (14.00~20.25)	16.73 (13.61~19.86)	21.60 (16.98~26.22)	21.13 (17.74~24.53)	0.081 (0.110)			
FMA Wrist/Hand	NMES	8.67 (5.80~11.53)	8.80 (6.04~11.56)	8.40 (5.68~11.12)	13.73 (11.13~16.33)	14.07 (11.32~16.82)	0.001*** (0.227)	0.000### (0.493)	0.114 (0.018)	0.239 (0.039)
	PURE	9.80 (6.81~12.79)	9.27 (6.57~11.97)	9.73 (6.88~12.58)	12.67 (9.45~15.88)	13.80 (10.52~17.08)	0.089 (0.107)			
ARAT	NMES	14.53 (7.96~21.11)	15.73 (9.07~22.40)	15.93 (9.21~22.66)	27.40 (20.41~34.39)	27.93 (19.98~35.89)	0.004** (0.196)	0.000### (0.634)	0.001### (0.075)	0.001### (0.126)
	PURE	15.33 (9.92~20.75)	14.33 (9.30~19.37)	14.87 (9.63~20.11)	23.07 (17.69~28.44)	20.93 (16.41~25.46)	0.032* (0.138)			
MAS Finger	NMES	1.53 (0.91~2.16)	1.45 (0.88~2.03)	1.59 (0.97~2.20)	0.45 (0.13~0.78)	0.43 (0.12~0.73)	0.000*** (0.265)	0.000### (0.500)	0.011## (0.046)	0.032# (0.072)
	PURE	1.73 (1.12~2.34)	1.63 (0.98~2.28)	1.53 (0.88~2.19)	0.84 (0.41~1.27)	1.09 (0.60~1.58)	0.099 (0.104)			
MAS Wrist	NMES	1.51 (0.94~2.08)	1.55 (0.97~2.12)	1.57 (1.01~2.14)	0.61 (0.22~1.01)	0.45 (0.13~0.78)	0.000*** (0.247)	0.000### (0.533)	0.002## (0.069)	0.002## (0.112)
	PURE	1.65 (1.12~2.19)	1.72 (1.20~2.24)	1.71 (1.19~2.22)	0.99 (0.49~1.48)	1.27 (0.73~1.80)	0.136 (0.094)			
MAS Elbow	NMES	1.73 (1.27~2.20)	1.71 (1.24~2.18)	1.64 (1.12~2.16)	0.87 (0.43~1.30)	0.73 (0.32~1.14)	0.001*** (0.230)	0.000### (0.283)	0.001### (0.080)	0.000### (0.184)
	PURE	1.28 (0.83~1.73)	1.21 (0.78~1.65)	1.27 (0.83~1.70)	1.03 (0.58~1.47)	1.20 (0.67~1.73)	0.925 (0.013)			
FIM	NMES	64.93 (63.69~66.18)	65.67 (65.13~66.21)	65.40 (64.54~66.26)	66.47 (65.78~67.16)	65.87 (64.80~66.93)	0.145 (0.092)	0.155 (0.046)	0.276 (0.008)	0.871 (0.009)
	PURE	65.00 (63.84~66.16)	65.07 (63.91~66.23)	64.93 (63.77~66.09)	65.64 (64.49~66.80)	65.93 (64.78~67.09)	0.673 (0.032)			

The mean and 95% confidence intervals for each measurement of the clinical assessments, and the probabilities with the estimated effect sizes of the statistical analyses. Differences with statistical significance are marked with superscripts beside the P values ("*" for 1-way-ANOVA intragroup tests, "#" for 2-way ANCOVA tests on the time point and group effects with the mean value of three pre-assessments as the covariate). Significant levels are indicated as, 1 superscript for <0.05, 2 superscripts for ≤0.01, and 3 superscripts for ≤0.001.

Abbreviations: FMA, Fugl-Meyer Assessment; ARAT, Action Research Arm Test; FIM, Functional Independence Measurement; MAS, Modified Ashworth Scale; ANOVA, analysis of variance; ANCOVA, analysis of covariance; T*G, the interaction between the time point and group; 3MFU, 3-month follow-up.

Table 3-3. The statistical probabilities and the estimated effect sizes of the intergroup comparison on the respective post-assessment and 3-month follow-up (3MFU).

Evaluation	Post- and 3MFU assessments between the groups	
	Post (Partial $\eta 2$/Cohen's d)	3MFU (Partial $\eta 2$/Cohen's d)
FMA $_{\text{Full score}}$ [a]	$0.005^{\#\#}$ (0.256)	$0.005^{\#\#}$ (0.258)
FMA $_{\text{Shoulder/Elbow}}$ [a]	$0.013^{\#}$ (0.208)	$0.001^{\#\#\#}$ (0.344)
FMA $_{\text{Wrist/Hand}}$ [a]	0.128 (0.084)	0.379 (0.029)
ARAT [a]	0.069 (0.117)	$0.007^{\#\#}$ (0.239)
MAS $_{\text{Finger}}$ [a]	0.114 (0.090)	$0.001^{\#\#\#}$ (0.328)
MAS $_{\text{Wrist}}$ [b]	0.220 (0.459)	$0.009^{\triangle\triangle}$ (1.021)
MAS $_{\text{Elbow}}$ [a]	$0.040^{\#}$ (0.148)	$0.005^{\#\#}$ (0.257)
FIM [a]	0.050 (0.135)	0.536 (0.014)

Differences with statistical significance are marked with superscripts beside the P values ("#" for 1-way ANCOVA intragroup tests, "△" for independent t-test). Significant levels are indicated as, 1 superscript for <0.05, 2 superscripts for ≤0.01, and 3 superscripts for ≤0.001.

[a] 1-way ANCOVA.

[b] Independent t-test.

3.3.2 EMG parameters

The EMG parameters of EMG activation level and normalized CI are presented in Figure 3-4, and the differences in statistical significance over the course of the assessment and the twenty sessions can be seen. Table 3-4 shows the two-way ANCOVA probabilities, in addition to the estimated EFs of the EMG parameters for training sessions and groups. Figure 3-4(A) and Figure 3-4(B) present the variations in the normalized EMG activation levels during the whole program for both groups, with FD and BIC showing significantly lowered EMG activation levels in the NMES group (P<0.05). However, there was only a

significant decrease in the EMG activation level in the pure group for the values of the FD muscle ($P<0.05$). During the whole training program, the EMG activation level gradually decreased, and no equilibrium was able to be established. There were significant group differences evident in the EMG activation levels of BIC muscle, which was identified during the 2-way ANOVAs ($P < 0.05$). At the start, the EMG has a far higher activation level in the NMES group than in the pure group. Nonetheless, this level seemed to decrease after the 14^{th} session in the NMES group to below that of the pure robot group. As can be seen in both Figure 3-4(C) and Figure 3-4(D), significant differences in CI values for the FD&TRI and BIC&TRI muscle pairs were revealed during the evaluation process for both groups. The NMES group appeared to have much lower CI values for the FD&TRI and BIC&TRI muscle pairs over the course of the training program ($P<0.05$). A significant decrease was only seen in the pure group for the CI values of the FD&TRI muscle pairs ($P<0.05$). No descending plateau was reached for CI values of the FD&TRI and BIC&TRI muscle pairs within the 20 training sessions. Furthermore, significant intergroup differences were found between the CI values of FD&TRI and BIC&TRI muscle pair through the employment of the 2-way ANOVAs ($P < 0.05$). As far as the CI value for the FD&TRI muscle pair was concerned, it was far greater in the first session than the pure group CI value ($P < 0.05$). Over the course of the subsequent five sessions, a rapid decrease in CI values for the NMES group became apparent, and this fell below the values of the pure group. After this, the CI values for both groups declined over time and became similar towards the end of the training program (i.e., after 10 sessions). As for the CI values relating to BIC&TRI muscle pair, the NMES group demonstrated better scores in the initial sessions than the pure group, yet this declined to become lower scores

in later sessions (i.e., after 16 sessions). No notable increases or decreases were seen in the EMG parameters of other target muscles or muscle pairs.

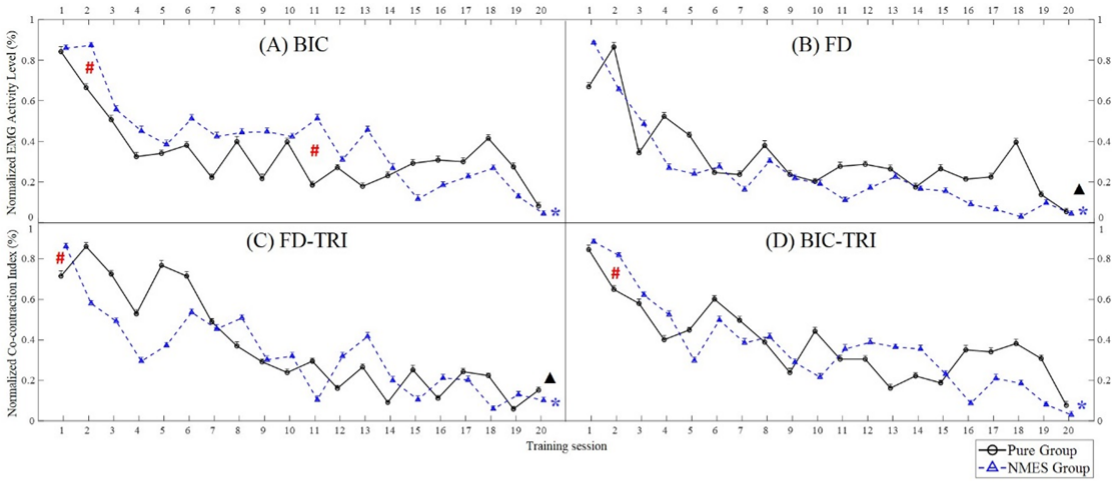


Figure 3-4. The variation of electromyography (EMG) parameters recorded across the 20 training sessions in both NMES robotic hand and pure robotic hand groups: **(A)** The normalized EMG activation levels of the biceps brachii (BIC) muscles during the bare-hand evaluation. **(B)** The normalized EMG activation levels of the flexor digitorum (FD) muscles during the bare-hand evaluation. **(C)** The changes of the normalized Co-contraction Indexes (CI) of the FD and triceps brachii (TRI) muscle pairs during the bare-hand evaluation. **(D)** The changes of the normalized CIs of the BIC and TRI muscle pairs during the bare-hand evaluation. The values are presented as mean values with SE (error bar) in each session. The significant inter-group difference is indicated by "#" ($P < 0.05$, independent t-test), and "*" is used to indicate the significant intragroup difference in NMES group and "▲" is used to indicate the significant intragroup difference in pure group ($P < 0.05$, one-way analysis of variance with Bonferroni *post hoc* tests).

Table 3-4. The statistical probabilities and the estimated effect sizes of the 2-way ANOVA test on the electromyography (EMG) parameters with respect to the independent factors of the group and session.

EMG parameters		2-way ANOVA		
		P (Partial η2)		
		Session	Group	S*G
EMG Activity Level	FD	$0.000^{###}$ (0.211)	0.876 (0.000)	0.644 (0.028)
	BIC	$0.000^{###}$ (0.118)	$0.004^{##}$ (0.015)	0.469 (0.033)
Co-contraction Index	FD-TRI	$0.000^{###}$ (0.130)	$0.005^{##}$ (0.014)	0.867 (0.022)
	BIC-TRI	$0.000^{###}$ (0.137)	$0.031^{#}$ (0.008)	0.067 (0.050)

Differences with statistical significance are marked with '#' beside the P values. Significant levels are indicated as, #for <0.05, ## for ≤0.01, ### for ≤0.001.

Abbreviations: FD, flexor digitorum muscle; BIC, biceps brachii muscle; TRI, triceps brachii muscle; S*G, the interaction between the session and group.

3.4 Discussion

The clinical assessment findings showed that improved motor function was achieved in both groups following the training program for both the EMG-driven robotic hand and the EMG-driven NMES robotic hand. It seemed that the NMES group improved more in the area of muscle coordination and voluntary motor function. The FMA full score and FMA subscores indicated that the NMES group experienced the significant improvements with regards to their entire impaired upper limb following the training of an EMG-driven NMES robotic hand, with such improvements still being evident at the three months follow up. In the pure group, there only appeared to be a significant improvement to

voluntary motor function for the FMA full score post training and at 3MFU, but no notable improvements to motor function was evident in the FMA subscores (FMA S/E and FMA W/H scores). The NMES group also seemed to have a much better functional recovery than the pure group as far as both the FMA full score and FMA S/E score were concerned during post-evaluation and 3MFU assessment. Nonetheless, both groups demonstrated similar motor restoration in the FMA W/H score following the training and 3MFU. This thus indicated that both robotic devices could be beneficial in enhancing functional recovery of the entire upper limb, but that the most improvements were seen to the proximal part (e.g., shoulder and elbow joints) as opposed to the distal part (e.g., wrist and finger joints). This is in line with other findings that have been revealed in similar studies into both conventional rehabilitation and robot assisted training as outlined in our prior work [98, 112, 119], as well as the work of others [149-151]. There are several possible reasons for the lesser improvements to functional recovery of the distal parts. Firstly, chronic stroke typically uses proximal joint muscles to carry out distal limb tasks, which can ultimately cause compensatory muscular activation that divert from unimpaired area [89, 149]. Secondly, motor recovery between the proximal parts and distal parts requires the coordination of both muscles [152]. What's more, if the compensatory actions of the proximal muscles control distal movements, this would result in the distal muscles being used less often and thus will remain damaged. However, better outcomes were achieved by the proximal muscles with the more training that they received. It was revealed that, the NMES group saw significant motor improvements around the distal joints despite proximal compensation. This is thus indicative that, by incorporating NMES

into the robotic system, this could foster more effective motor restoration for the entire upper limb, especially in the distal muscles.

The key purpose of the ARAT score is to assess finger movements including grasping, gripping, and pinching actions. There were vast improvements seen to the ARAT scores following training, suggesting that there was joint stability and fine precision in grasping. Nonetheless, at the three months follow up, this improvement was only still evident in the NMES group. A decline e of 2.14 points in the ARAT at 3MFU was evident for the pure group in comparison to the post-assessment score. The improvements to the long-term hand movement recovery using EMG-driven NMES robotic hand may be due to the limited compensatory motions experienced by the NMES group, who often practiced using the impaired limb in their daily livings, causing the enhancements to 3MFU.

Figure 3-3 presents MAS scores that show how the EMG-driven robot and EMG-driven NMES robot can ease muscle spasticity in the elbow, wrist, and finger joints. It is, however, only the NMES group showed statistically significant decreases in MAS scores following the training. Significantly lower MAS scores at the elbow joint for the NMES group were revealed following the training when compared with the pure group, suggesting that the NMES group experienced more reduced muscle spasticity in the elbow joint after training. At the 3 months follow up, significantly higher MAS scores were apparent for each joint in the pure group than the NMES group. What's more, recovery patterns of muscle spasticity varied between both groups following the training. In terms of the NMES group, muscle spasticity at the joints was slightly decreased, yet there often tended to stiffness present in the upper limb of those in the pure group. Higher MAS scores are typically indicative of improved muscle tone but a lesser control of synergic muscle

activity [93]. Findings thus implied a higher effectiveness of NMES robot training in easing muscle spasticity than using robotic training in isolation.

The vast enhancements to muscle coordination throughout the training program were also seen in the EMG parameters differences (such as the normalized EMG activation levels and the normalized CIs). The reduced normalized EMG activation levels tended to suggest an ease in muscle spasticity, with muscle over-activation being lowered when carrying out a skilled task [153, 154]. Both groups showed significantly lowered EMG activation levels relating to FD muscle, which suggesting a release in spasticity of distal joints like wrist and finger. That is also in line with the decreased MAS scores for the wrist and finger joints (see Figure 3-3). Moreover, this also indicated that the excessive muscular activities of the FD muscle were reduced when carrying out bare-hand assessment tasks in both groups. What's more, the lowered excessive muscular activities were indicative that the voluntary motor controls and muscle coordination had been improved throughout hand-grasping tasks, with arm transportation being achieved using both forms of robotic hand training. The additional improvements in the elbow joint shown through the significant decline in the BIC muscle's EMG activation level was seen in the NMES group, although it was absence in the pure group. The EMG-driven NMES robotic hand was more beneficial for the elbow joint and led to improvements in the wrist and finger joints. Despite there being no significant intergroup differences in BIC and FD muscle EMG activation levels when finishing the program (seen in the independent t-test results), reduced normalized EMG activation levels were apparent in the NMES group following 14 training sessions. This could suggest that NMES robotic training can accelerate the recovery process after a stroke, which is in line with Hu et al.'s findings [87].

The decreased CI value of a muscle pair may demonstrate a release in co-contraction between the two muscles, meaning they can contract more independently when engaging in a specific task. The CI values of both the FD&TRI muscle pairs were significantly reduced throughout the course for both groups. Findings indicated a decrease in muscle coactivity between the proximal and distal joint, which is further suggestive of there being less compensation movement from the elbow joint following both training programs when carrying out hand movements. In addition, there was a major decline in CI values of the BIC&TRI muscle pair within the NMES group, suggesting that the NMES group may experience enhanced muscular coordination between the elbow extension and flexion when reaching out compared to the pure group. This could also play a part in the significantly increased FMA S/E and W/H scores. A quicker release of muscle co-contraction for the NMES group was presented for the CI of FD&TRI muscle pairs in the first 5 sessions and the CI of BIC&TRI muscle pairs in the final 5 sessions. This could imply that the NMES robotic training is better in encouraging muscular coordination for the upper limbs. Nonetheless, the EMG parameters presented in Figure 3-4 failed to achieve a plateau throughout the 20 sessions, and extra training sessions based on motor relearning theory may be able to generate further improvements [155].

The effectiveness of EMG-driven NMES robotic system and EMG-driven pure robotic system in relation to wrist rehabilitation has been explored in our prior work [87]. Similar findings would be acquired, and this could support more efficient training by combining the NMES and the pure robotic system, with significantly higher clinical scores and reduced EMG parameters of CI. It that particular study [87], the NMES group was found to experience significantly quicker progress in lowering co-contraction in the flexor carpi

radialis (FCR) and extensor carpi radialis (ECR) muscle pairs. Following the twelfth session, most of the CI values of ECR and FCR pairs in the NMES robot group appeared to be much lower than the pure robot group. As the ECR muscle dominates wrist extension and the FCR muscle dominates wrist flexion, the eased co-contraction of the ECR and FCR pairs that was seen with the NMES robot group suggests that the target muscle pairs in the wrist joint slowly separated over the course of the program. Nonetheless, in this study, no significant difference between EMG activation level and CIs of the ED muscle was noticed during the process. This could be due to the different NMES stimulation techniques. In the prior wrist rehabilitation research [87], the NMES was used to target the ECR muscle throughout the wrist extension phase and FCR muscle throughout the wrist flexion phase. However, the NMES was only used on the ED muscle for finger extension during hand training. This may indicate that the NMES targeting the antagonist muscle pairs was more effective than the NMES targeting one single muscle. It is crucial to continue researching the effectiveness of NMES with different stimulation strategies to encourage optimal training efficacy.

Despite no specific robotic system being used to target the shoulder and elbow joints in the present research, it was still possible to acquire and record the proximal joints' functional recovery (as shown in the FMA scores) and released muscle spasticity (as shown in the MAS scores) for both groups, where the NMES robotic hand was clearly more effective. Consistent EMG parameter findings (such as EMG activation level and CI) also indicate an enhancement in muscle coordination in the elbow joint, and this was the case for the two groups. This could be a result of the vertical and lateral task training. When training tasks requiring the use of multiple joints were carried out, rehabilitation

outcome appeared to be present for the whole upper limb [122]. Throughout the vertical and lateral task training, participants had to carry out arm reaching and transportation movements, and such movements required the use of the shoulder and elbow muscles. It may also be due to the fact that the adjacent proximal joint improves simultaneously with the surrounding the joint training. Prior research has revealed similar results when the elbow training resulting in the shoulder improvement and the wrist training leading to elbow improvement [87, 99]. Thus, if there is no apparent motor deficit of a proximal-to-distal gradient, then task-oriented training of the entire upper limb will likely be more effective than conventional joint-per-joint rehabilitation [123, 124].

3.5 Periodic Summary

The present research is the first of its kind to make a head-to-head comparison between the training effects of EMG-driven NMES robotic hand devices and EMG-driven pure robotic hand devices. This was conducted using a randomized clinical trial with chronic stroke patients. The findings (i.e., clinical assessment and EMG parameters) showed both training systems to be effective for enhancing long-term functional motor restoration in the distal part of upper limb, with NMES robotic system appearing to be better in lowering muscle spasticity and enhancing voluntary motor effort and muscle coordination. The research also found more motor improvements in the proximal joints when using the NMES on the distal muscle. This could signify that NMES may foster major enhancements of the whole upper limb even if the stimulation area is small. This research provides evidence to show that the integration of the tactile sensory inputs directly to the muscles into the motor rehabilitation is both viable and effective for upper limb rehabilitation following a chronic stroke, particularly in the distal muscles.

CHAPTER 4

AN INVESTIGATION OF SENSORY DEFICIENCY IN FINE TEXTILE-SKIN PERCEPTION AFTER STROKE

4.1 Introduction

Up to 85% of stroke survivors undergo sensory deficiency, which is usually experienced as a reduced sensation of pain, temperature, touch, and proprioception [9, 10]. Sensory deficiency limits the restoration of motor functions and may inhibit participation in the activities of daily living (ADLs), since fine motor control depends on undamaged somatosensation, which comes via inward-bound (or afferent) inputs [9]. Insufficient or impeded somatosensation usually results in stroke victims having difficulty in moving and exploring their surroundings safely, and that will lower their autonomy, independence, sociability and quality of life, and even lead to learned non-use [10, 27, 28]. In an early longitudinal study, a significantly higher prevalence of severe motor deficiency was found among those stroke survivors with sensory deficiency [36]. In another study [37], sensory deficiency was reported to correlate with poor functional mobility and inhibited ADLs in the subacute period after a stroke, and these results were further supported by others [38, 39]. Recent neurophysiological research has highlighted and demonstrated the significance of both internal and external somatosensation for motor function [40], because the normal motor control can be dramatically altered by the pathological disturbances of sensorimotor processing [41]. Several neurophysiologic mapping studies [42-44] have indicated that the primary motor cortex (MI) is not only a motor structure, but also involved into the somatosensation processing due to its specific anatomical and

functional connections with primary (SI) and secondary (SII) somatosensory cortices [45]. Gallien et al. [46] have also reported the poorer rehabilitation outcomes for stroke patients when sensory stimulation is lost or absent, while Huang et al. [47] suggested that improvements in neurological scores can be obtained when increasing activation of the MI and SI by somatosensory stimulation for both acute and chronic stroke patients. To summarize, sensory deficiency carries out significantly negative effect on the motor recovery and the performance of ADLs, which is frequently underestimated and overlooked in current stroke rehabilitation programs.

To grasp the nature and extent of sensory deficiency after stroke, we need some valid and reliable evaluation method. Those currently used in clinical practice tend to be subjective and superficial, and their reliability and reproducibility have frequently been questioned due to the absence of any standardization of procedures [9, 52, 104]. In clinical practice, levels of fine tactile perception were the most frequently evaluated, because this is one way that clinicians judge the ability to perform normal daily activities and routines and the success of post-training outcomes [52, 156, 157]. The most widely used evaluation methods for the fine touch sensations are the Semmes-Weinstein monofilament test [53] and the two-point discrimination test [55]. These assessments are usually presented along a simple ordinal scale, and the results are relatively subjective and not quantitatively measured [52]. Even for those methods claimed to be reliable and quantitated such as the Rivermead assessment of somatosensory performance [57] and the tactile discrimination test [158] which uses plastic gratings with different surface spatial intervals, they still can only provide limited variations of sensation and cannot be used for those patients with severe cognitive deficits [9]. Another limitation of the current clinical assessments for

tactile impairment is the lack of knowledge on neural response to fine tactile perception. Recently, with the help of some objective measurement such as electromyography (EMG), electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) [159-162], the neuromuscular responses to post-stroke sensory inputs could be measured objectively and quantitively. However, most of the related studies were focused on the brain changes over time during the somatosensory recovery [160-163], and investigation of the use of neurological methods to evaluate the sensory deficiency after stroke are scarce. In sum, currently, the issue of fine tactile perception after stroke has hitherto been poorly evaluated and understood from the neurological standpoint. In this study, therefore, we proposed a new approach of using different textiles to evaluate fine tactile perception in post-stroke via EEG.

Textile-skin perception, as one of modalities of the fine tactile perception [164, 165], is critically common and important in daily living. Textiles could be classified objectively by their physical properties, and different textures of materials could provide a wider sensation variation when compared with other objects, including thermal sensation (e.g., cool-warm) and tactile sensations (e.g., rough-smooth, thick-thin, etc.). Some studies have been done to investigate, via EEG, the accuracy of tactile perception in response to the textile-skin stimulation in the healthy population. For instance, Hoefer et al. [166] tried to use the EEG time domain analysis event-related potential (ERP) to differentiate three different fabric samples on the ventral side of the forearm, and the results showed that the ERP amplitudes could be affected by different textile stimulations. However, the ERP amplitudes are not sensitive enough to distinguish the different textiles. In addition, Singh et al. [167] used EEG frequency domain analysis and suggested that energy changes in

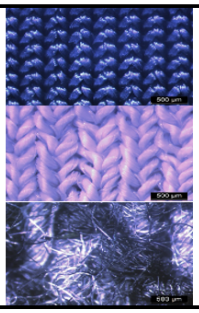
the beta (β) band can differentiate perceived pleasant from unpleasant stimulation from textiles on a single trial basis with satisfactory accuracy. Meanwhile, Wang et al. [168] reported positive correlations between the energy percentages of the alpha (α) band and clothing pressure during static wearing. These studies supported the feasibility of using textiles to stimulate a neural response of tactile perception in a healthy population. Whether the textile-skin stimulation could evoke the same neural response for stroke patients was unknown and needed to be investigated. The objective of this study is to investigate the feasibility of using EEG to evaluate tactile impairment after stroke and then to investigate the extent of tactile impairments in the upper limb during textile fabric stimulation in stroke survivors with hemiplegic sensorimotor disabilities.

4.2 Methodology

4.2.1 Textile description

In this research, we selected three kinds of fabric samples with the main textile elements of 1) cotton, 2) nylon, and 3) a combination of polytester and wool, the detailed specifications of which appear in Table 4-1. Fabric A was 100% cotton with plain weave, commonly regarded as one of the most comfortable and acceptable fabrics to all consumers in the clothing industry. Fabric B was a mixture of 87% nylon and 13% elasthan, and this could result in a cool feeling on the skin due to a relatively high thermal conductivity. Fabric C which was 60% polyester and 40% wool could provide a feeling of warmth like pure wool. All the fabric samples were tailored into 20cm×10cm pieces for stimulation experiments.

Table 4-1. Textile composition of the three fabric samples.

Fabric no.	Fabric Description	Component	Weight (g/m^2)	Thickness (mm)	Fabric Image (5 times)
A	100% Cotton	Plain Woven	127.7±0.8	0.39±0.01	
B	87% Nylon/ 13% Elasthan	Jacquard	113.3±1.3	0.77±0.00	
C	60% Polytester/ 40% Wool	Flannel Woven	340.8±2.4	1.29±0.01	

4.2.2 Participants

This study was approved by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic university. Twelve participants with chronic stroke and fifteen healthy adults were recruited and were labelled as the "stroke group" and the "normal group", respectively. The demographic characteristics of the participants are presented in Table 4-2. Participants for the "stroke group" were recruited from local districts based on the following inclusion criteria: (1) They were at least six months past the onset of a singular and unilateral brain lesion due to stroke; (2) The lesion area was mainly in the subcortex area; (3) They had no visual, cognitive or attention deficits that would prevent them from following instructions or performing the experimental procedures (assessed by the Mini-Mental State Examination (MMSE) score>21) [121]; (4) The spasticity during extension of their wrist and elbow joints was lower than or equal to 2 as measured by the Modified Ashworth Scale (MAS) [50]; (5) they had no history of psychiatric problems. Participants in the normal group were recruited from the Hong Kong Polytechnic university; they must not have had any history of neurological, psychiatric, and/or cardiovascular disease, and they should have sufficient cognition to follow simple instructions and understand the

content. All recruited participants were required to provide a written consent after being informed about the study purpose and its experimental process.

Table 4-2. Demographic characteristics of the participants.

Characteristics	Stroke group (n=12)	Normal group (n=15)
Age in years (mean±SD)	55.13±16.04	46.40±17.39
Gender (male/female)	11/1	5/10
Affected side (right/left)	6/6	Nil
Type of stroke (ischemic/hemorrhagic)	10/2	Nil
Times since stroke in years (mean±SD)	14.92±5.79	Nil
MAS elbow (mean±SD)	1.08±0.69	Nil
FMA full score (mean±SD)	42.5±15.17	Nil

4.2.3 Objective evaluation by EEG

The experiment was conducted in a quiet lab with the room temperature controlled within 24±2°C and the relative humidity at 60%±5%. Each participant was invited to attend the textile-skin tactile perception test evaluated by EEG, and the experimental setup was shown in Figure 4-1(A). Each participant was comfortably seated in front of a table, which was covered with a tablecloth to avoid the bias that may have resulted from the relatively low temperature of the table surface. Then, a 64-channels EEG system (BP-01830, Brain Products Inc.) was placed on the scalp of a participant based on the standard 10-20 system to record the whole brain EEG with the skin impedance of each channel under 5 KΩ [169]. During the EEG test, participants were asked to keep their eyes closed and place their both sides of forearm on the table and remain relaxed and still. Any disturbance from visual and audio stimuli from the surroundings were further minimized by their wearing an eye

mask and ear plugs. Once all the preparations mentioned were set up, the EEG system performed the real-time recording with a sampling frequency of 1000 Hz, and the experimental protocol presented with the timeline is summarized in Figure 4-2. Each single trial contained a 30-second baseline test, three 13-second fabric stimulations respectively and three 60-second resting times after each fabric stimulus. During the fabric stimulation, each fabric sample was statically loaded (i.e., without striking) onto the skin surface of the ventral side of the forearm (Figure 4-1(B)) for 13 seconds with randomized sequence, and the cycle of the tactile perception evaluation was repeated three times for each side of the forearm, respectively.

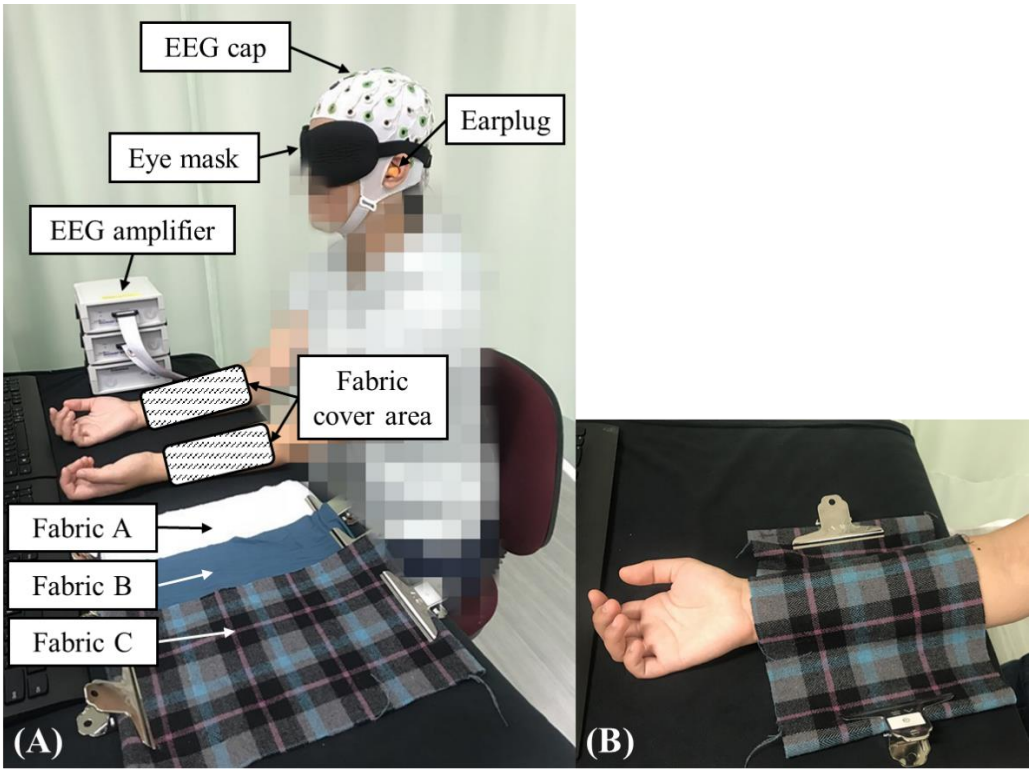


Figure 4-1. The experimental setup for the EEG evaluation during the fabric stimulation.

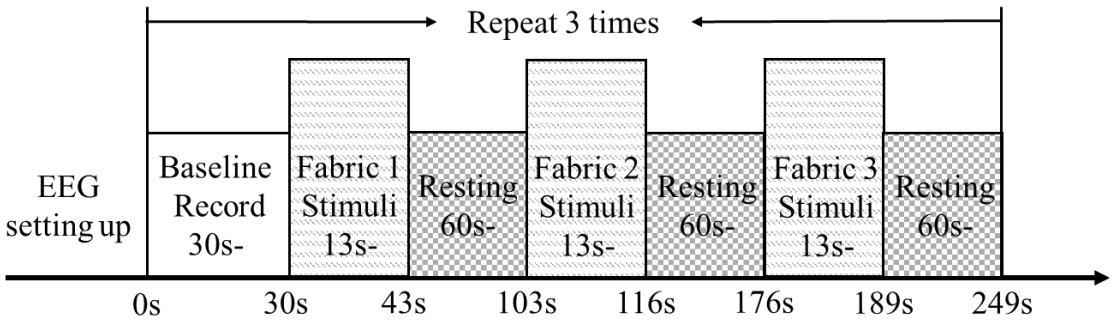


Figure 4-2. The experimental protocol for EEG evaluation presented with timeline.

After acquiring the targeted EEG data, the EEG signals were processed off-line with a band-pass filter from 0.1 Hz to 100 Hz and a notch filter from 49 Hz to 51 Hz to eliminate the 50 Hz noise from the environment. Then, the EEG signals were divided into individual segments according to each baseline test and fabric stimulation. Later, the relative power of each EEG frequency bands, i.e., Delta (δ, 0.1~4Hz), Theta (θ, 4~8 Hz), Alpha (α, 8~13 Hz), Beta (β, 13~30 Hz) and Gamma (γ, 30~100 Hz), were calculated based on the following equation,

$$P_{Relative\ band} = \frac{\int_{F_1}^{F_2} p(f)df}{\int_{0.1}^{100} p(f)df} - \frac{\int_{F_1}^{F_2} p_{Baseline}(f)df}{\int_{0.1}^{100} p_{Baseline}(f)df} \qquad \text{(Eq. 4.1)}$$

where, $P_{Relative}$ band is the relative spectral power percentage change (PPC) of a frequency band; p(f) is the power spectral density of an EEG segment for a fabric stimulating event, estimated by Fast Fourier Transform (FFT); F_1 and F_2 are the cutoff frequencies of a EEG frequency band, as stated above; and $p_{Baseline}(f)$ is the power spectral density of the EEG segments in baselines in each trial. The mean value of the thrice $P_{Relative}$ band was calculated and used in the further statistics. In this study, EEG frequency analysis was

used because it is more closely linked to physiological processes and brain structures when compared with other methods.

4.2.4 Subjective evaluation by questionnaire

After the EEG evaluation, the tactile sensation of three fabric samples were also evaluated by a subjective questionnaire [170] designed according to the American Association of Textile Chemists and Colorists (AATCC) Evaluation Procedure 5 [171]. The questionnaire could be divided into thirteen sub-properties, which includes cool/warm, damp/dry, itchy/non-itchy, scratchy/non-scratchy, prickly/non-prickly, rough/smooth, sticky/non-adhesive, stiff/pliable, thick/thin, hard/soft, inelastic/elastic, non-fullness/fullness and the overall uncomfortable/comfortable. For each sub-property, a numeric rating scale [172] was used in which 1=very weak, 2=weak, 3=slightly weak, 4=normal, 5=slightly strong, 6=strong and 7=very strong. During the subjective sensory test, the participants were seated with the same configuration as in the EEG recording with the testing forearm placed on the table, still wearing the eye mask, but without the ear plugs. Each fabric was statically loaded onto the target skin surface as in the EEG test. Then, the participant was asked about each item in the questionnaire for rating. For the stroke group, the subjective questionnaire was conducted on both sides of the forearm, while for the normal group, only the dominant side of their forearm was evaluated.

4.2.5 Statistical analysis

During the statistical analysis, the stroke group were further divided into the stroke affected group and stroke unaffected group based on the stroke affected side. Two-way Analysis of Variance (ANOVA) was first used to evaluate the differences with respect to

the independent factors of the group (i.e., normal group, stroke-unaffected group and stroke-affected group) and fabric samples (i.e., Fabric A, Fabric B and Fabric C) on the relative power percentage changes of each EEG frequency band. Then, one-way ANOVA was adopted to investigate the intragroup difference on PPC and subjective sensation parameters of each group at different fabric samples with either the Bonferroni post hoc test or the Dunnett's T3 post hoc test. The intergroup comparisons on the PPC of each group at the three different fabric samples were also conducted by one-way ANOVA with either the Bonferroni post hoc test or the Dunnett's T3 post hoc test. Meanwhile, Bivariate Correlation Analysis was used to explore the relationship between the relative PPC of each EEG band and subjective sensation parameters from the questionnaire. The relationship between the relative PPC of each EEG band and functional recovery evaluated by FMA was also investigated via Bivariate Correlation Analysis. The levels of statistical significance were indicated at 0.05, 0.01, 0.001 in this study.

4.3 Result

4.3.1 Textile-skin Perception Detected by EEG

Figure 4-3 shows the EEG relative PPC in response to the fabric stimuli for each group at each EEG frequency band, and the detailed values with means and 95% confidence intervals of each PPC, together with the one-way ANOVA probabilities and the estimated effect sizes (EFs), have been summarized in Table 4-3. In the normal group, the significant PPC differences were observed in the theta and beta bands on the whole brain detection ($P< 0.05$). It was observed that the fabric stimuli increased both the theta and Beta power

compared with the baseline state, and that it resulted in positive relative power values. The PPC of theta band in response to the Fabric C stimuli was significantly higher than those by Fabric A and Fabric B ($P<0.05$), and the theta PPC for Fabric B was significantly higher than that for Fabric A ($P<0.05$). Meanwhile, the beta PPC for Fabric B was significantly higher than that for Fabric A ($P<0.05$), while the beta PPC for Fabric C was comparable to the other two fabrics. In the stroke-unaffected group, the significant PPC differences were observed in the theta, alpha, and gamma bands ($P< 0.05$). The PPC of the theta band in response to the Fabric A stimuli was significantly lower than the that for Fabric B and Fabric C ($P<0.05$), and the alpha PPC for Fabric C was significantly higher than that of Fabric A ($P<0.05$). For the gamma band, the relative power in response to Fabric B and Fabric C were decreased when compared with the baseline state, and the PPC of the Fabric B was significantly lower than the Fabric A and Fabric C ($P<0.05$). However, in the stroke-affected group, no significant intragroup differences of PPC were captured in any of the EEG frequency bands ($P＞0.05$).

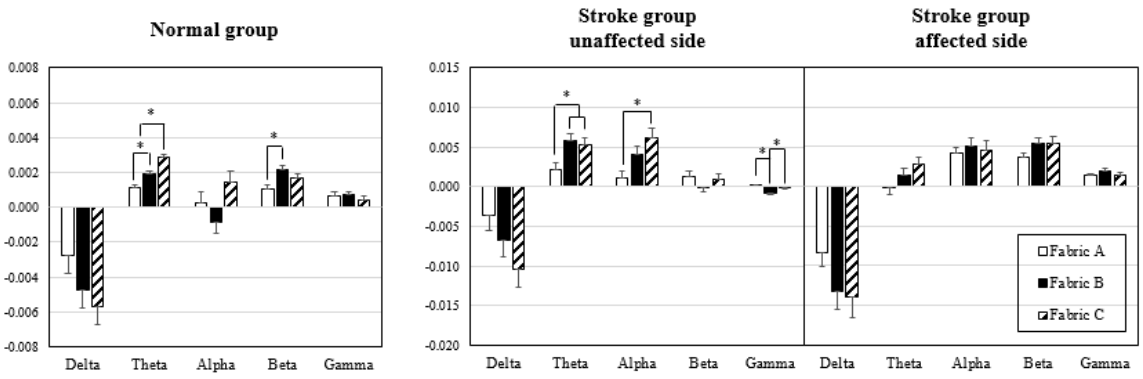


Figure 4-3. The EEG relative power percentage changes (PPC) in response to the fabric stimuli for each group on the whole brain at the delta, theta, alpha, beta and gamma band presented as mean value with SE (error bar). The significant difference is indicated by "*" ($p<0.05$, one-way analysis of variance with Bonferroni post hoc tests and Dunnett's T3 post hoc tests).

Table 4-3. The relative power percentage changes of EEG frequency bands in response to the fabric stimuli for each group.

Bands	Groups	Fabric A	Fabric B	Fabric C	One-way ANOVA
		Mean (95% confidence interval, E-03)			P (Partial η^2)
Delta	Normal Group	-2.7 (-4.8 ~ -0.6)	-4.7 (-6.8 ~ -2.6)	-5.7 (-7.8 ~ -3.6)	0.131 (0.001)
	Stroke Group-affected side	-8.3 (-12.0 ~ -4.6)	-13.0 (-17.0 ~ -9.5)	-14.0 (-17.7 ~ -10.3)	0.144 (0.002)
	Stroke Group-unaffected side	-3.5 (-7.2 ~ 0.2)	-6.8 (-10.5 ~ -3.1)	-10.0 (-14.1 ~ -6.7)	0.062 (0.002)
Theta	Normal Group	1.1 (0.8 ~ 1.5)	1.9 (1.6 ~ 2.2)	2.8 (2.5 ~ 3.2)	0.000*** (0.009)
	Stroke Group-affected side	-0.2 (-1.5 ~ 1.1)	1.4 (0.1 ~ 2.7)	2.7 (1.4 ~ 4.0)	0.054 (0.003)
	Stroke Group-unaffected side	2.2 (0.9 ~ 3.5)	5.8 (4.5 ~ 7.1)	5.4 (4.0 ~ 6.7)	0.002** (0.006)
Alpha	Normal Group	0.2 (-1.1 ~ 1.5)	-0.8 (-2.2 ~ 0.5)	1.4 (0.1 ~ 2.8)	0.052 (0.001)
	Stroke Group-affected side	4.1 (1.9 ~ 6.3)	5.1 (2.9 ~ 7.3)	4.5 (2.3 ~ 6.7)	0.795 (0.000)
	Stroke Group-unaffected side	1.2 (-1.0 ~ 3.4)	4.1 (1.9 ~ 6.3)	6.2 (4.0 ~ 8.4)	0.004** (0.005)
Beta	Normal Group	1.1 (0.6 ~ 1.5)	2.2 (1.8 ~ 2.6)	1.7 (1.3 ~ 2.1)	0.002** (0.002)
	Stroke Group-affected side	3.7 (2.6 ~ 4.7)	5.5 (4.4 ~ 6.5)	5.4 (4.3 ~ 6.4)	0.122 (0.002)
	Stroke Group-unaffected side	1.3 (0.2 ~ 2.3)	-0.1 (-1.2 ~ 0.9)	1.0 (0.1 ~ 2.0)	0.241 (0.001)
Gamma	Normal Group	0.7 (0.3 ~ 1.1)	0.7 (0.3 ~ 1.1)	0.4 (0.0 ~ 0.8)	0.521 (0.000)
	Stroke Group-affected side	1.3 (0.9 ~ 1.8)	1.9 (1.5 ~ 2.4)	1.5 (1.1 ~ 1.9)	0.289 (0.001)
	Stroke Group-unaffected side	0.0 (-0.4 ~ 0.5)	-0.8 (-1.3 ~ 0.4)	-0.1 (-0.6 ~ 0.3)	0.007** (0.004)

Differences with statistical significance are marked with superscripts beside the P values ("*" for one-way ANOVA intra-group tests with Bonferroni post hoc tests and Dunnett's T3 post hoc tests). Significant levels are indicated as, 1 superscript for <0.05, and 2 superscripts for <0.01, 3 superscripts for <0.001.

Figure 4-4 compares the group differences of EEG relative PPC in response to the fabric stimuli each EEG frequency band. The values of statistical results including probabilities and EFs of the two-way ANOVA and one-way ANOVA have been listed in Table 4-4. Significant group differences of PPC between each group could be observed in all of the EEG frequency bands ($P<0.05$). Compared with the normal group, the PPC of stroke affected group in response to all three fabric samples are significantly higher than the PPC of those normal participants in the delta, beta and gamma bands ($P<0.05$). Meanwhile, the significant higher PPC of the affected side of stroke patients could also be found in the alpha band response to the fabrics A and B when compared with that of the normal participants ($P<0.05$). In addition, significant differences of the PPC in response to different fabric samples could also be pointed out between the stroke-affected group and the stroke-unaffected group in the theta, alpha, beta, and gamma bands ($P<0.05$). The theta PPCs of the stroke-affected group were significantly lower than that of the unaffected group when stimulated by fabric A and B ($P<0.05$). For the high frequency band (i.e. beta and gamma bands), the PPC of the stroke-affected group were significantly higher than the unaffected group in response to all three fabric samples ($P<0.05$). When comparing the PPC values between the normal group and the stroke-unaffected group, significant differences could be observed in the theta and alpha bands in response to the fabric B and C ($P<0.05$), and a significant difference could be found in the beta and gamma bands in response to the fabric B ($P<0.05$).

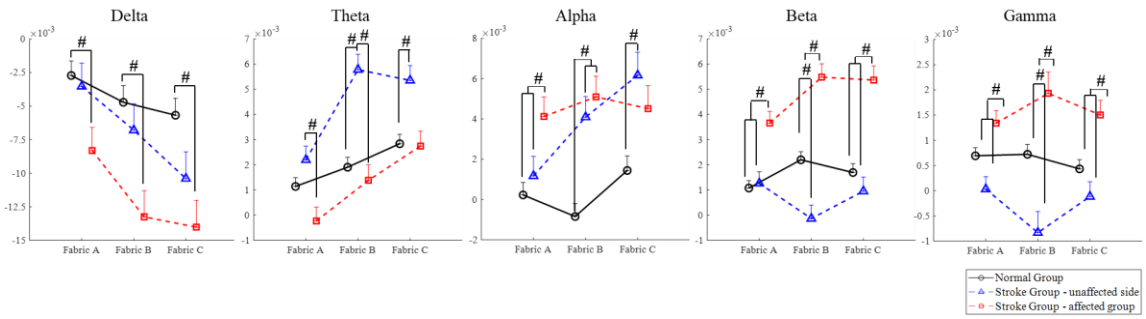


Figure 4-4. The EEG relative power percentages in response to the fabric stimuli for each group on the whole brain at the delta, theta, alpha, beta and gamma band respectively, presented as mean value with SE (error bar). The significant inter-group difference is indicated by "#" ($P<0.05$, one-way analysis of variance with Bonferroni post hoc tests and Dunnett's T3 post hoc tests).

Table 4-4. Group comparisons on the relative power percentage changes of EEG frequency bands in response to the fabric stimuli for each group.

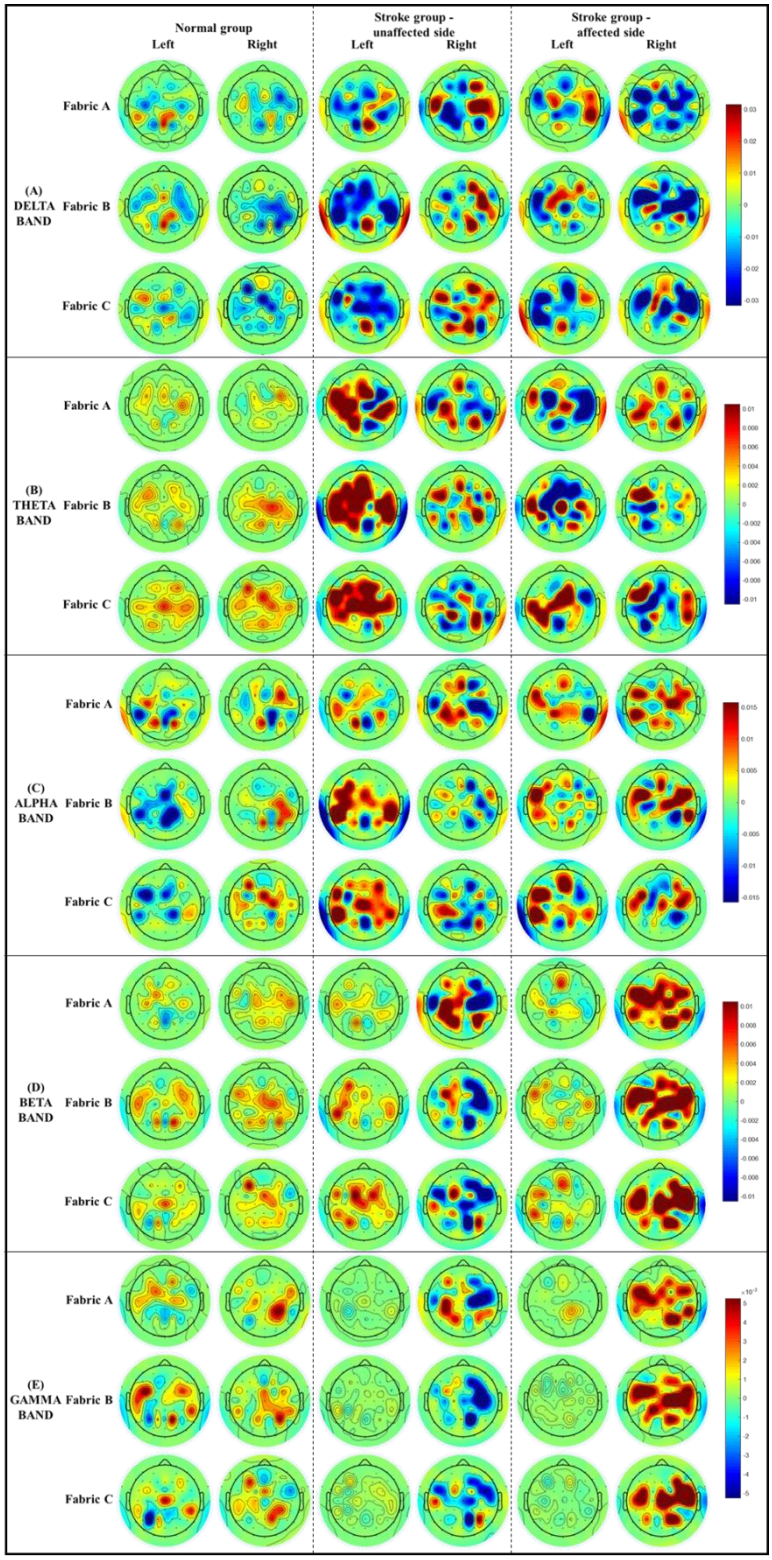
Bands	Fabric	One-way ANOVA	Two-way ANOVA		
		P (Partial η^2)	Fabric	Group	Fabric*Group
Delta	Fabric A	$0.022^{\#}$ (0.002)	$0.001^{\triangle\triangle}$ (0.001)	$0.000^{\triangle\triangle\triangle}$ (0.003)	0.678 (0.000)
	Fabric B	$0.001^{\#\#}$ (0.004)			
	Fabric C	$0.001^{\#\#}$ (0.004)			
Theta	Fabric A	$0.007^{\#\#}$ (0.003)	$0.000^{\triangle\triangle\triangle}$ (0.004)	$0.000^{\triangle\triangle\triangle}$ (0.005)	0.053 (0.001)
	Fabric B	$0.000^{\#\#\#}$ (0.010)			
	Fabric C	$0.001^{\#\#}$ (0.004)			
Alpha	Fabric A	$0.003^{\#\#}$ (0.003)	$0.016^{\triangle}$ (0.001)	$0.000^{\triangle\triangle\triangle}$ (0.005)	0.050 (0.001)
	Fabric B	$0.000^{\#\#}$ (0.009)			
	Fabric C	$0.001^{\#\#}$ (0.004)			
Beta	Fabric A	$0.000^{\#\#\#}$ (0.007)	0.172 (0.000)	$0.000^{\triangle\triangle\triangle}$ (0.011)	$0.013^{\triangle}$ (0.001)
	Fabric B	$0.000^{\#\#\#}$ (0.018)			
	Fabric C	$0.000^{\#\#\#}$ (0.011)			
Gamma	Fabric A	$0.001^{\#\#}$ (0.004)	0.902 (0.000)	$0.000^{\triangle\triangle\triangle}$ (0.007)	0.071 (0.001)
	Fabric B	$0.000^{\#\#\#}$ (0.012)			
	Fabric C	$0.000^{\#\#\#}$ (0.005)			

Differences with statistical significance are marked with superscripts beside the P values ("#" for one-way ANOVA inter-group tests with Bonferroni post hoc tests and Dunnett's T3 post hoc tests, "△" for two-way ANOVA inter-group tests on the fabric and group effects). Significant levels are indicated as, 1 superscript for <0.05, 2 superscripts for <0.01, 3 superscripts for <0.001.

Figure 4-5 demonstrates the whole brain EEG topography of the mean PPC in all frequency bands when stimulated by the three fabric samples for each group and each stimulation side. The hot spots related to the significant PPC in all EEG frequency bands were mainly captured in the parietal and frontal regions bilaterally for both stroke and normal participants. It was observed that the topographic characteristics of the relative PPC during the textile-skin stimulation in the stroke patients differed according to the lesion side. In the delta band, patients with right hemiplegic damage showed increased brain activity over the prefrontal-central region corresponding to the lesion side and decreased brain activities over the occipital region, while patients with left hemiplegic damage showed decreased brain activity in most areas of the brain cortex except the paramedian occipital lobe. In the theta band, the increased brain powers could be obtained mainly in the paramedian central area for the patients with right-side lesion, and the fabric C could arouse the strongest brain activities when compared with the other two fabrics. For those patients with left hemiplegic damage, the theta activities decreased on their lesion side when the fabrics B and C stimulated their affected upper limbs, whereas remarkable increased theta activities could be observed over the frontal and parietal lobe when their unaffected sides were stimulated. Meanwhile, the theta activities of the normal participants were increased over the frontal and parietal regions regardless of the stimulation side. In the alpha band, increased brain powers were observed in the multiple brain regions for the affected side of the stroke patients. When the unaffected sides were stimulated, the alpha activities increased over the central and frontal areas for those stroke patients with left hemiplegic damage, whereas the alpha activities of stroke patients with right hemiplegic damage decreased over the lesion side. In high frequency bands (beta

and gamma), when the right forearms were stimulated, the brain activity of the affected side increased significantly over the frontal and parietal areas, while those of the unaffected side decreased corresponding to the lesion side and increased away from the lesion side. When the left forearms were stimulated, the beta activities were increased over the frontal parietal cortex. For the normal participants, the high frequency activities were also increased in the frontal parietal cortex during the textile-skin stimulation. In addition, the topography demonstrated the significantly higher intensity of the power response toward the textile-skin stimulation for the stroke patients than the normal participants. Additionally, we saw that fabrics B and C could induce stronger power responses than fabric A for the normal group, while for the stroke participants, all three fabrics could achieve strong responses in all bands on both sides.

Figure 4-5. The whole brain EEG topography on the mean relative powers of each EEG frequency bands in response to the fabric stimuli.



4.3.2 Textile-skin Perception Detected by Subjective Questionnaire

Figure 4-6 shows the results on the subjective sensory rating of the three fabric samples for each group as revealed through the questionnaire. Significant intragroup differences were observed in all the sensory properties with respect to the three different fabrics ($P<0.05$) for each group. For the normal group, the significant differences between Fabric A and the other two fabrics could be found in all the subjective sensory properties ($P<0.05$), while the significant subjective sensory differences between Fabric B and Fabric C were found in all the sensation scales ($P<0.05$) except on the fullness. For the unaffected side of the stroke patients, all the subjective sensation properties showed significant differences between fabric A and fabric B, and between fabric B and fabric C ($P<0.05$). When comparing fabric A and fabric C, significant subjective sensory differences could be found in all the sensation scales ($P<0.05$) except on the softness. For the affected side of the stroke group, the significant differences between fabric A and fabric B could be found in almost all the subjective sensory properties ($P<0.05$), expect on the non-itchy, non-scratchy and non-prickly. Significant subjective sensory differences between fabrics A and C were observed in all the sensation scales ($P<0.05$) except on dryness, elasticity and comfort, while the significant subjective sensory differences between fabrics B and C were found in all the sensation scales ($P<0.05$) except on the fullness. The detailed statistical results on the differentiation of subjective sensation evaluated by the questionnaire are listed in Table 4-5.

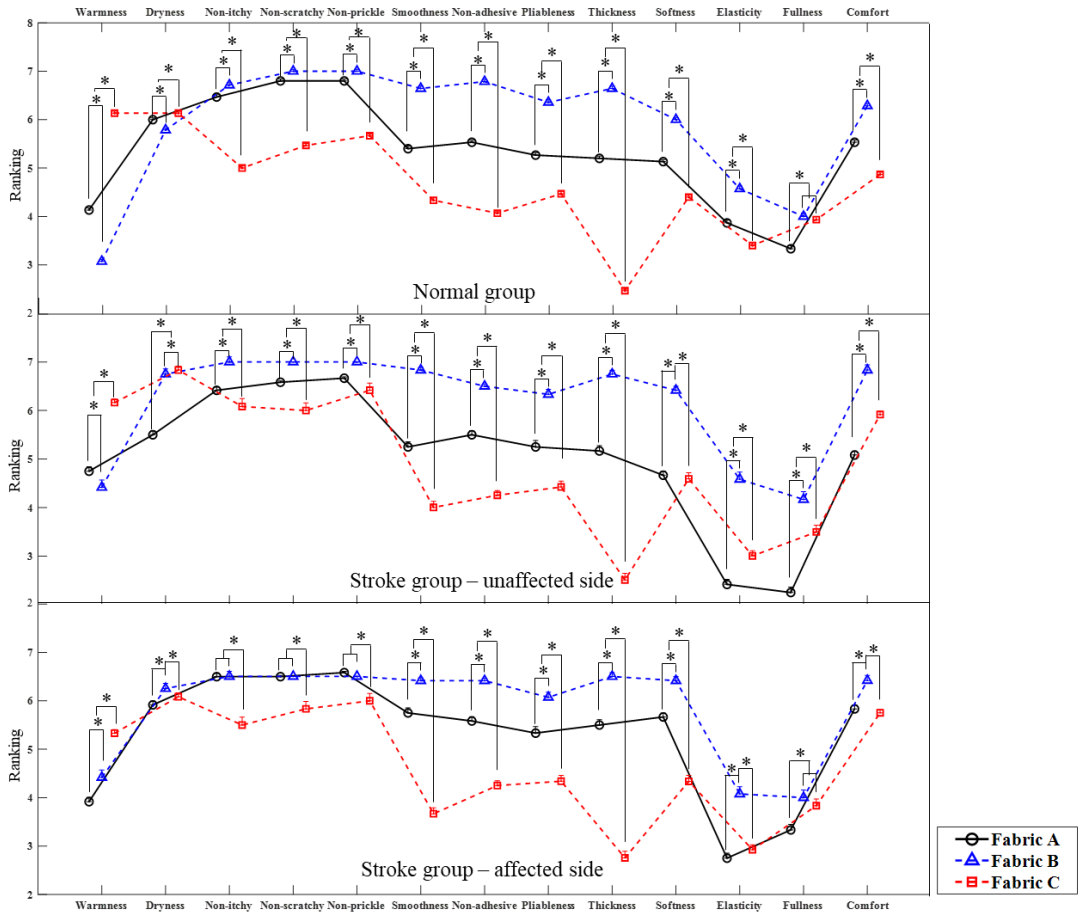


Figure 4-6. The rates of the subjective sensations measured by questionnaire in response to the fabric stimuli for each group presented as mean value with SE (error bar). The significant intra-group differences are indicated by "*" ($P<0.05$, one-way analysis of variance with Dunnett's T3 post hoc tests).

Warmness: cool-warm; Dryness: damp-dry; Non-itchy: itchy-non-itchy, Non-scratchy: scratchy-non-scratchy; Non-prickle: prickle-non-prickle; Smoothness: rough-smooth; Non-adhesive: stick-non-adhesive; Pliableness: stiff-pliable; Thickness: thick-thin; Softness: hard-soft; Elasticity: inelastic-elastic; Fullness: non-fullness-fullness; Comfort: overall uncomfortable-comfortable. Ranking scale is from 1 to 7.

Table 4-5. Subjective sensations evaluated by questionnaire in response to the fabric stimuli for each group.

Subjective sensations	Groups	Fabric A	Fabric B	Fabric C	One-way ANOVA
		Mean (95% confidence interval)			P (Partial η^2)
Warmness	Normal Group	4.13 (4.05 ~ 4.21)	3.07 (2.99 ~ 3.15)	6.13 (6.05 ~ 6.21)	0.000*** (0.508)
	Stroke Group-affected side	3.92 (3.79 ~ 4.05)	4.42 (4.29 ~ 4.55)	5.33 (5.90 ~ 5.46)	0.000*** (0.093)
	Stroke Group-unaffected side	4.75 (4.62 ~ 4.88)	4.42 (4.29 ~ 4.55)	6.16 (6.03 ~ 6.30)	0.000*** (0.148)
Dryness	Normal Group	6.00 (5.93 ~ 6.07)	5.79 (5.72 ~ 5.86)	6.13 (6.07 ~ 6.20)	0.000*** (0.017)
	Stroke Group-affected side	5.92 (5.82 ~ 6.01)	6.25 (6.16 ~ 6.35)	6.08 (5.99 ~ 6.18)	0.000*** (0.010)
	Stroke Group-unaffected side	5.50 (5.41 ~ 5.59)	6.75 (6.66 ~ 6.84)	6.83 (6.75 ~ 6.92)	0.000*** (0.208)
Non-itchy	Normal Group	6.47 (6.38 ~ 6.56)	6.71 (6.62 ~ 6.81)	5.00 (4.91 ~ 5.09)	0.000*** (0.222)
	Stroke Group-affected side	6.50 (6.40 ~ 6.61)	6.50 (6.40 ~ 6.61)	5.50 (5.40 ~ 5.61)	0.000*** (0.095)
	Stroke Group-unaffected side	6.42 (6.33 ~ 6.51)	7.00 (6.91 ~ 7.09)	6.08 (5.99 ~ 6.17)	0.000*** (0.085)
Non-scratchy	Normal Group	6.80 (6.72 ~ 6.88)	7.00 (6.92 ~ 7.08)	5.47 (5.39 ~ 5.54)	0.000*** (0.242)
	Stroke Group-affected side	6.50 (6.40 ~ 6.60)	6.50 (6.40 ~ 6.61)	5.83 (5.73 ~ 5.94)	0.000*** (0.048)
	Stroke Group-unaffected side	6.58 (6.50 ~ 6.67)	7.00 (6.91 ~ 7.09)	6.00 (5.91 ~ 6.09)	0.000*** (0.103)
Non-prickle	Normal Group	6.80 (6.73 ~ 6.88)	7.00 (6.92 ~ 7.08)	5.67 (5.59 ~ 5.74)	0.000*** (0.203)
	Stroke Group-affected side	6.58 (6.49 ~ 6.68)	6.50 (6.41 ~ 6.60)	6.00 (5.90 ~ 6.10)	0.000*** (0.034)
	Stroke Group-unaffected side	6.67 (6.59 ~ 6.74)	7.00 (6.92 ~ 7.08)	6.42 (6.34 ~ 6.49)	0.000*** (0.047)
Smoothness	Normal Group	5.40 (5.30 ~ 5.50)	6.64 (6.54 ~ 6.75)	4.33 (4.23 ~ 4.43)	0.000*** (0.271)
	Stroke Group-affected side	5.75 (5.63 ~ 5.87)	6.42 (6.30 ~ 6.53)	3.67 (3.55 ~ 3.78)	0.000*** (0.340)
	Stroke Group-unaffected side	5.25 (5.13 ~ 5.37)	6.83 (6.71 ~ 6.96)	4.00 (3.88 ~ 4.13)	0.000*** (0.317)
Non-adhesive	Normal Group	5.53 (5.45 ~ 5.62)	6.79 (6.70 ~ 6.87)	4.07 (3.99 ~ 4.15)	0.000*** (0.431)
	Stroke Group-affected side	5.58 (5.46 ~ 5.71)	6.42 (6.29 ~ 6.54)	4.25 (4.13 ~ 4.37)	0.000*** (0.213)
	Stroke Group-unaffected side	5.50 (5.37 ~ 5.63)	6.50 (6.37 ~ 6.63)	4.25 (4.13 ~ 4.38)	0.000*** (0.213)
Pliableness	Normal Group	5.27 (5.17 ~ 5.36)	6.36 (6.26 ~ 6.46)	4.47 (4.37 ~ 4.56)	0.000*** (0.207)
	Stroke Group-affected side	5.33 (5.19 ~ 5.47)	6.07 (5.93 ~ 6.21)	4.34 (4.20 ~ 4.48)	0.000*** (0.119)
	Stroke Group-unaffected side	5.25 (5.10 ~ 5.40)	6.33 (6.18 ~ 6.48)	4.42 (4.27 ~ 4.57)	0.000*** (0.124)
Thickness	Normal Group	5.20 (5.11 ~ 5.29)	6.64 (6.55 ~ 6.74)	2.47 (2.38 ~ 2.56)	0.000*** (0.612)
	Stroke Group-affected side	5.50 (5.40 ~ 5.60)	6.50 (6.40 ~ 6.61)	2.76 (2.65 ~ 2.86)	0.000*** (0.548)
	Stroke Group-unaffected side	5.17 (5.07 ~ 5.26)	6.75 (6.66 ~ 6.85)	2.51 (2.41 ~ 2.60)	0.000*** (0.636)
Softness	Normal Group	5.13 (5.05 ~ 5.22)	6.00 (5.91 ~ 6.09)	4.40 (4.32 ~ 4.48)	0.000*** (0.198)
	Stroke Group-affected side	5.67 (5.55 ~ 5.78)	6.42 (6.30 ~ 6.53)	4.34 (4.22 ~ 4.45)	0.000*** (0.217)
	Stroke Group-unaffected side	4.67 (4.54 ~ 4.79)	6.42 (6.29 ~ 6.54)	4.59 (4.47 ~ 4.72)	0.000*** (0.191)
Elasticity	Normal Group	3.87 (3.76 ~ 3.98)	4.57 (4.46 ~ 4.68)	3.40 (3.29 ~ 3.51)	0.000*** (0.074)
	Stroke Group-affected side	2.75 (2.60 ~ 2.90)	4.08 (3.93 ~ 4.23)	2.92 (2.77 ~ 3.08)	0.000*** (0.072)
	Stroke Group-unaffected side	2.42 (2.26 ~ 2.57)	4.58 (4.43 ~ 4.74)	3.00 (2.85 ~ 3.16)	0.000*** (0.155)
Fullness	Normal Group	3.33 (3.20 ~ 3.47)	4.00 (3.86 ~ 4.14)	3.93 (3.80 ~ 4.07)	0.000*** (0.021)
	Stroke Group-affected side	3.33 (3.19 ~ 3.48)	4.00 (3.85 ~ 4.15)	3.83 (3.69 ~ 3.98)	0.000*** (0.019)
	Stroke Group-unaffected side	2.25 (2.10 ~ 2.40)	4.17 (4.02 ~ 4.32)	3.50 (3.35 ~ 3.65)	0.000*** (0.124)
Comfort	Normal Group	5.53 (5.45 ~ 5.62)	6.29 (6.20 ~ 6.38)	4.87 (4.78 ~ 4.95)	0.000*** (0.157)
	Stroke Group-affected side	5.83 (5.75 ~ 5.92)	6.42 (6.33 ~ 6.51)	5.75 (5.66 ~ 5.84)	0.000*** (0.055)
	Stroke Group-unaffected side	5.08 (4.99 ~ 5.17)	6.83 (6.74 ~ 6.92)	5.92 (5.83 ~ 6.01)	0.000*** (0.249)

Differences with statistical significance are marked with superscripts beside the P values ("*" for one-way ANOVA intragroup tests with Bonferroni post hoc tests). Significant levels are indicated as, 1 superscript for <0.05, 2 superscripts for <0.01, 3 superscripts for <0.001.

4.3.3 Correlation between the relative EEG PPC, Subjective Sensation, and Motor Dysfunction

The correlation analysis between the EEG PPC of representative frequency bands and the subjective sensations rated by the questionnaire is described in Table 4-6. For the normal participants, the relative PPC of the theta and beta bands showed more significant correlations with the subjective sensory properties ($P<0.05$). The power in the theta band was significantly correlated with all subjective sensory properties ($P<0.05$) except warmness and pliableness, while the power of the beta band had significant correlations with all subjective sensory properties ($P<0.05$) except warmness, dryness, smoothness, non-adhesive and thickness. For the unaffected side of stroke patients, the relative EEG parameters in alpha and beta could achieve more significant correlations with the subjective sensory properties ($P<0.05$). The power in the alpha band was significantly correlated with all subjective sensory properties ($P<0.05$) except dryness, non-scratchy, and pliableness, while the power in the beta band was significantly correlated with the sensory properties ($P<0.05$) of dryness, non-scratchy, and pliableness etc. For the affected side of the stroke patients, the alpha and beta bands were significantly correlated with the subjective sensory properties ($P<0.05$). For the alpha band, significant correlations with all subjective sensory properties ($P<0.05$) except warmness, thickness and elasticity could be found, while significant correlations with all subjective sensory properties ($P<0.05$) except the non-scratchy could be observed in the beta band.

Table 4-6. Summary of correlations between the EEG relative power percentage changes and the subjective sensations measured by questionnaire on each group.

Group	Bands	Statistic	Warmness	Dryness	Non-scratchy	Smoothness	Non-adhesive	Pliableness	Thickness	Softness	Elasticity	Fullness	Comfort
Normal group	Theta	Correlation coefficient	-	-0.057**	-0.040*	-0.089**	-0.091**	-	-0.101**	0.086**	-0.123**	-0.143**	-0.053**
		P value	-	0.003	0.039	0.000	0.000	-	0.000	0.000	0.000	0.000	0.006
	Alpha	Correlation coefficient	-	-0.065**	-	-	-	-	-0.039*	0.073**	-0.067**	-0.104**	-
		P value	-	0.001	-	-	-	-	0.044	0.000	0.001	0.000	-
	Beta	Correlation coefficient	-	-	0.049*	-	-	0.060**	-	0.123**	-0.101**	-0.076**	0.056**
		P value	-	-	0.011	-	-	0.002	-	0.000	0.000	0.000	0.003
Stroke Group-unaffected side	Theta	Correlation coefficient	0.091**	-	-	0.068**	-	-	-	0.085**	0.124**	0.161**	0.101**
		P value	0.000	-	-	0.001	-	-	-	0.000	0.000	0.000	0.000
	Alpha	Correlation coefficient	0.092**	-	-	0.085**	-0.062**	-	-0.058**	0.084**	0.095**	0.191**	0.085**
		P value	0.000	-	-	0.000	0.003	-	0.006	0.000	0.000	0.000	0.000
	Beta	Correlation coefficient	-	-0.069**	-0.047*	0.053*	-	0.112**	-	0.108**	-	-	0.061**
		P value	-	0.001	0.028	0.013	-	0.000	-	0.000	-	-	0.004
Stroke Group-affected side	Theta	Correlation coefficient	-	-	-	-	-	-	-	-	-0.043*	-0.056**	-0.049*
		P value	-	-	-	-	-	-	-	-	0.043	0.008	0.022
	Alpha	Correlation coefficient	-	-0.133**	-0.066**	-0.048*	-0.075**	-0.085**	-	-0.068**	-	0.059**	-0.118**
		P value	-	0.000	0.002	0.025	0.000	0.000	-	0.001	-	0.006	0.000
	Beta	Correlation coefficient	0.064**	-0.045*	-	-0.058**	-0.075**	-0.220**	-0.100**	-0.184**	-0.079**	-0.069**	-0.046*
		P value	0.003	0.035	-	0.006	0.000	0.000	0.000	0.000	0.000	0.001	0.031

Note: only correlation coefficients with $p<0.05$ are presented in the table.

Table 4-7 summarized the correlation between the relative EEG PPC on each band and the clinical assessment of the functional recovery. Significant negative correlation was found between the delta PPC and the FMA scores ($P<0.05$), while the EEG power in the alpha, beta, and gamma bands were found to be significantly positively correlated with the FMA scores ($P<0.05$). No significant correlation could be observed between the theta PPC and the FMA scores ($P>0.05$).

Table 4-7. Summary of correlations between the EEG relative power percentage changes and the motor dysfunction measured by FMA on the affected side of stroke group.

Clinical scores	Statistic	EEG frequency band				
		Delta	Theta	Alpha	Beta	Gamma
FMA	Correlation coefficient	-0.210**	0.028	0.117**	0.301**	0.327**
	P value	0.000	0.226	0.000	0.000	0.000

4.4 Discussion

This study was carried out to establish whether textile-skin perception could be used to measure the degree of lack of sensibility to fine tactile contact in a post-stroke situation. We used both objective measurement (EEG) and a subjective sensation questionnaire. We also examined the response to the tactile perception of different fabrics in the impaired neural circuits after stroke and made comparison with non-stroke sufferers and the unaffected side of the stroke patients.

The EEG results of the normal people showed the relative power of EEG frequency bands had significant variations when stimulated by different fabrics, and it supported the feasibility of using EEG to evaluate fine tactile perception. Interestingly, the intensity of the theta and beta band could distinguish the differences between three fabric samples. We found that both theta and beta bands were positively activated with increased power during the stimuli, and these results were consistent with Michail et al.'s work on touch stimuli [173]. In general, the theta band is considered to be correlated with mental operations, and the theta activity will be aroused during focused attention and information

uptake, processing, and learning. Higher theta oscillations have been reported as the reflection of involuntary attention when receiving salient sensory stimulations [174, 175]. Meanwhile, we also noted that theta power will be raised with the increasing difficulty of the task [176]. In our study, we selected three different fabric samples representing different stimulus intensity to draw the participants' attention during the EEG recording. Fabric A is widely regarded by the clothing industry as one of the most comfortable and so provides the minimum stimulus intensity compared with the other two fabrics, one delivering a cool, the other, a warm feeling. The stimulus intensity of fabric C with the sensation properties of warm and rough was even higher than fabric B with the properties of cool and smooth. Therefore, the theta power variations caused by fabrics B and C were significantly larger than the theta power variations evoked by fabric A, and the theta power change of fabric C was more prominent than fabric B. Beta oscillation is widely considered important to the motor responses [177, 178], and in recent years it was also found to be a fundamental characteristic of the somatosensory system and showed an on/off like feature for the touch sensation [173, 179]. According to Singh et al. [167], the increased beta power could potentially reflect the emotional response to distinguishing the feeling of pleasant and unpleasant from different textile-skin perceptions. In this study, significant increased beta power variations in the fabric differentiation were observed, and the relative EEG power of fabric B was the highest among the three fabrics and significantly higher than fabric A. Meanwhile, on the subjective sensation questionnaire, fabric B was scored as the most comfortable among the three. That might suggest the intensity of the beta oscillation could be a reason to evaluate some of the affective responses. In this study, though, all the fabrics were rated as relatively comfortable (the

scores were all above 4 in the sub-property "comfort") in the subjective questionnaire, and we could not investigate the neural responses on beta power of uncomfortable textile-skin perception. Therefore, more fabrics ranging from uncomfortable to comfortable should be involved in a future study to further verify the relationship between the beta power and emotional states in textile-skin perception.

We also examined the sensory precision on the affected side of stroke patients. The power variations in all the frequency bands in response to the fabric stimuli could be observed and compared with the baseline state, and this result implied that the textile-skin stimulation was able to arouse the cognitive processes for the affected side of stroke patients. However, the touch discrimination towards different fabrics on the affected side was poor since no significant power variation could be found between the different fabric samples in any frequency band. Meanwhile, the intensity of the EEG oscillations of the stroke patients were significantly higher in each band than that of the healthy participants. We do not find this surprising since the tactile impairments are widely presented after stroke, and these results could still provide us with data on the scope of the neural response towards the textile-skin perception for stroke patients. As for the spectrum analysis, during the textile-skin stimulations, the relative PPC values of the affected side of the stroke patients were lower in the delta and theta, and higher in the alpha, beta, and gamma frequency bands when compared with the normal controls. The results suggested that brains affected by stroke showed a much faster physiological behavior and an increased power intensity when processing information from the affected side. Similar findings were found by Thibaut et al. [180] in motor performance after stroke. They reported increased high-frequency EEG oscillation (i.e., beta) for stroke patients when performing

motor tasks, and that phenomenon is associated with poor motor function. These power spectrum abnormalities during both motor and sensory tasks might have several explanations. One could be that the increased activity in higher frequency bands is associated with excessive brain activity after stroke. That excessive brain activity usually implies that stroke patients have difficulty in completing the desired task, and further reflects the pathological reorganization during the recovery [180]. Another possible reason is that the weaker interhemispheric connectivity following stroke leads to impaired tactile perception because activity on both hemispheres plays an important role during sensory processing [181-183]. The disrupted interhemispheric connectivity has been proved to have a negative effect on the attention and movement functions [184-187]. We also found that older people exhibit higher frequency activity in compensation for the disabling effects. The beta activity of elderly subjects during the motor tasks were higher than those of younger participants, and this differential is even greater with the more complex the desired task [188-190]. Our findings from the shifts in the power spectrum during the tactile stimulation after stroke further verified the hypothesis that stroke patients manifest higher-level attention and behavioral processes to compensate for the impaired somatosensory perceptual functions, which is in line with the findings of others [162, 181].

Another main finding of this study relates to stroke patients' unaffected side, which clinicians tended to overlook. We observed significant changes in tactile perception in the unaffected side of the stroke patients. As shown in Figure 4-3, although significant EEG power variations on the theta, alpha, and gamma bands could be found in response to the fabric stimulations, some of the textile sensory precision was absent. Using the theta band

as representative, the intensity of power variations in the healthy sample suggests that these participants can distinguish the different fabric samples from each other. Regarding the unaffected side of stroke patients, however, significant power differences could be only noticed between the fabrics A and B, and between the fabrics A and C. Differences between fabrics B and C could not be identified by EEG power. Meanwhile, the power spectrum of the unaffected side was also shifted to the higher frequency band similar to the affected side. Additionally, significant larger EEG power variations in the stroke-unaffected group than the normal group were also pointed out in Figure 4-4. All these evidences demonstrated that the textile sensory precision of the unaffected side of the stroke patients was influenced and limited by the stroke effect on the hemiplegic side, and similar findings on both motor and sensory function have been reported [191-193]. This study indicated that EEG could enable the assessment of the tactile sensory impairment of the unaffected side of stroke survivors, and this might help clinicians to consider and understand the role of the unaffected side in stroke rehabilitation, and thus promoting daily living independence for stroke survivors.

We also explored the alterations in sensory cortical centers after stroke in textile-skin stimulation. Based on the whole brain EEG topography (Figure 4-5), the cortical locations of the significant changes in all EEG frequency bands for healthy people were mainly in the frontal and central brain which covers premotor cortex, primary motor cortex (MI), and primary somatosensory cortex (SI). This finding further proved the inseparable relationship between the MI and SI when somatosensation processing [45]. For the stroke patients, the relevant activated cortex in response to the fabric stimulation was located not only in the MI and SI, but also in the relatively posterior area of the somatosensory

association cortex. The somatosensory association cortex is involved with tactile recognition such as temperature and pressure, and it usually integrates the sensory information from the SI and then constructs an understanding of the object being felt [194]. The activation of the somatosensory association cortex in stroke patients might imply that stroke patients with sensory impairments need to combine different aspects of information to recognize a single object. Another interesting post-stroke topographic characteristic we observed was that the neural response during the textile-skin stimulation of the stroke patients differed with the different lesion side, especially in the high frequency band. During the textile stimulations on the affected upper limb, the beta and gamma activities of stroke patients with left side damage were significantly higher than those patients with damage to the right side. A number of previous studies have explored the relationship between the lesion side and recovery [195-197], and found that the functional recovery of stroke patients affected on the left side was better than those affected on the right [198]. The positive correlations between the EEG relative beta and gamma PPC values and the FMA scores (Table 4-7), might reinforce the belief that the higher beta and gamma activities activated by textile stimulations in those stroke patients with left-side damage have better motor recovery when compared with those whose damage is located in the right side. Additionally, we observed much stronger high frequency activities during the textile stimulations on the right rather than on the left forearm. We note that all the participants in this study were right-handed, and that more neural responses were induced when the arm of the dominant hand was stimulated.

In this study, the subjective scales were also used to evaluate the textile-skin tactile perception. Surprisingly, significant differences among the three fabric samples were

obtained from this in the case of both healthy participants and stroke patients. This result indicated that the resolution of touch discrimination for different fabrics was evaluated subjectively on the affected side of the stroke patients. The EEG relative power variations did not, however, reveal differences between the different fabric samples on the affected side of the stroke patients. We might attribute this to the unlimited stimulation time when doing the questionnaire, rather than the fixed 13 seconds of stimulation time when recording EEG. With the much longer stimulation time, the stroke patients could have adequate time to receive and process the fabric information, and further identify the subjective sensation properties. From that we hypothesized that significant EEG power variations in the high frequency band towards different fabric samples might be achieved through providing longer tactile stimulation time for the affected side of the stroke patients.

The correlations between the EEG parameters, subjective scales, and clinical assessment were also investigated. The results demonstrated that the high frequency brain activities (alpha, beta, and gamma) were positively correlated with the FMA scores, and this suggested that the stroke patients exhibiting stronger brain activities toward the tactile stimulation on their affected upper limbs had the better functional recovery. When establishing the relationship between the EEG and subjective scales, it was observed that the brain activities were positively correlated with most of the subscales of the subjective questionnaire for normal participants and the unaffected side of the stroke patients. These positive correlations might also suggest the higher brain activity is related to the fine tactile perception. On the contrary, the brain activity for the affected side of the stroke patients showed a negative correlation with the subjective scales. Interestingly, the intensity of these stroke patients' brain activity is much higher than that of the healthy

participants and the stroke patients on their unaffected side. This could further verify that the active brain indicates good functioning, while the excessive brain activity after a stroke has a negative effect on the recovery [180]. In addition, the significant correlations between the relative EEG band powers and the subjective sensation properties, suggested that there were some mathematical relationships between the EEG power variations and the subjective scales. It could further imply that EEG power might have the potential to predict the subjective sensation for those people with linguistic or cognitive problems such as infants, stroke, and Alzheimer's patients. Nevertheless, it was also noticed that the correlation coefficients between the EEG power and subjective sensation properties were not high (e.g., >0.5), which meant that the relationships between EEG power and subjective sensation properties could not be simply linear. Therefore, further studies need to focus on investigating the relationships of the EEG powers with the subjective sensory properties via mathematical modeling.

4.5 Periodic Summary

In this study, we investigated the extent of tactile impairments in the upper limb using textile fabric stimulation via electroencephalography (EEG) in stroke survivors. The results supported the feasibility of using EEG to investigate tactile impairments following a stroke. Textile-skin stimulations could evoke the neural responses in multiple brain cortices for the affected side of stroke patients, whereas their ability of sensory precision towards different fabrics in a limited time was deficient. The findings also suggested that the tactile impairments after stroke could be represented by a shifted power spectrum to a higher frequency band, increased power intensity, and remapped sensory cortical areas. In addition, we observed that stroke patients' textile sensory precision was limited even on their unaffected side. Our study contributes to the volume of description of sensory precision in fine textile perception, a crucial step in understanding sensory deprivation for stroke patients. In future work, a wider range of textile stimuli will be employed to further enhance the resolution of the fine textile-skin perception after stroke.

CHAPTER 5

CONCLUSIONS

Tactile perception plays a crucial role during the process of motor restoration, and the integration of tactile sensory inputs into motor rehabilitation may effectively promote functional recovery for stroke patients. In this study, three independent experiments were conducted to investigate the training effects of robot-assisted upper limb rehabilitation integrated with sensory inputs via enriched tactile sensory inputs and those induced by NMES, and to further evaluate the extent of tactile impairments in the upper limbs during textile fabric stimulation in stroke survivors.

In the first experiment, the rehabilitation effects of robot-assisted upper limb rehabilitation in a clinical service setting, integrated with enriched tactile sensory inputs, were compared with those in a well-controlled research setting. Comparable functional improvements in the entire upper limb were obtained after robot-assisted upper limb training in both clinical service setting with enriched tactile sensory input and research setting. Higher independence in daily living activities and more released muscle spasticity could be achieved in the clinical service setting with enriched tactile sensory inputs. These results support the superiority of robot-assisted training integrated with enriched tactile sensory inputs, and verify that enriched tactile stimulations to the skin surface could facilitate motor recovery.

In the second experiment, the rehabilitation effects of robot-assisted upper limb rehabilitation integrated with NMES were compared with those of pure robot-assisted training. Both training systems achieved significant long-term improvements in functional

recovery of the distal joints of the upper limb. Noticeably, stroke patients using the robotic training integrated with NMES showed better voluntary motor effort and muscle coordination, as well as greatly lowered muscle spasticity. Meanwhile, more motor improvements in the proximal joints were obtained for those stroke patients using the NMES robotic system. These results suggested that NMES as a direct sensory stimulation to the desired muscle could be integrated with motor rehabilitation and promote a more effective post-stroke upper limb rehabilitation.

In the third experiment, the extent of tactile impairments in the upper limb during textile fabric stimulations by EEG in stroke survivors was investigated. The feasibility of using EEG to investigate tactile impairments after stroke was supported. Textile-skin stimulations are capable of inducing neural responses in multiple brain cortices for stroke patients, whereas their sensory precision with regard to different textiles was limited on both affected and unaffected upper limbs. In addition, the extent of tactile impairments after stroke could be further quantitively summarized as a shifted power spectrum, increased power intensity, and remapped sensory cortical areas. This finding could provide crucial evidence for the understanding of sensory deficiency following a stroke.

In conclusion, the integration of tactile sensory inputs into robot-assisted upper limb training via providing enriched tactile sensory inputs and NMES could promote more effective training outcomes in the entire upper limb for chronic stroke patients. This finding further implies that motor rehabilitation after stroke should not be considered as an isolated component but, rather, that sensory and motor integrated training might offer more effective stroke rehabilitation. Moreover, the sensory precision in fine textile perception evaluated by EEG could describe the extent of tactile impairment following a

stroke, and further contributes to the neurological understanding of sensory deficiency after a stroke.

In future study, we would like to arrange further investigations on:

(1) Explore the training effectiveness of NMES robot-assisted hand rehabilitation with different NMES positions (i.e., NMES for thumb opposition/abduction);

(2) Compare the differences of tactile sensory impairments between the different types of stroke (i.e., ischemic/hemorrhagic);

(3) A wider range of textile fabric stimuli will be employed to further enhance the resolution of the tactile discrimination after stroke;

(4) Use the EEG to evaluate the post stroke tactile sensory impairments by textile fabric stimulation, and further apply it to evaluate the sensorimotor integrated rehabilitation.

APPENDICES

Appendices 1: Clinical Assessments

1.1 Mini-Mental State Exam (MMSE)

Mini-Mental State Examination (MMSE)

Patient's Name: _____ Date: _____

Instructions: Score one point for each correct response within each question or activity.

Maximum Score	Patient's Score	Questions
5		"What is the year? Season? Date? Day? Month?"
5		"Where are we now? State? County? Town/city? Hospital? Floor?"
3		The examiner names three unrelated objects clearly and slowly, then the instructor asks the patient to name all three of them. The patient's response is used for scoring. The examiner repeats them until patient learns all of them, if possible.
5		"I would like you to count backward from 100 by sevens." (93, 86, 79, 72, 65, ...) Alternative: "Spell WORLD backwards." (D-L-R-O-W)
3		"Earlier I told you the names of three things. Can you tell me what those were?"
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		"Repeat the phrase: 'No ifs, ands, or buts.'"
3		"Take the paper in your right hand, fold it in half, and put it on the floor." (The examiner gives the patient a piece of blank paper.)
1		"Please read this and do what it says." (Written instruction is "Close your eyes.")
1		"Make up and write a sentence about anything." (This sentence must contain a noun and a verb.)
1		"Please copy this picture." (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.) 
30		TOTAL

Interpretation of the MMSE:

Method	Score	Interpretation
Single Cutoff	<24	Abnormal
Range	<21	Increased odds of dementia
	>25	Decreased odds of dementia
Education	21	Abnormal for 8th grade education
	<23	Abnormal for high school education
	<24	Abnormal for college education
Severity	24-30	No cognitive impairment
	18-23	Mild cognitive impairment
	0-17	Severe cognitive impairment

Interpretation of MMSE Scores:

Score	Degree of Impairment	Formal Psychometric Assessment	Day-to-Day Functioning
25-30	Questionably significant	If clinical signs of cognitive impairment are present, formal assessment of cognition may be valuable.	May have clinically significant but mild deficits. Likely to affect only most demanding activities of daily living.
20-25	Mild	Formal assessment may be helpful to better determine pattern and extent of deficits.	Significant effect. May require some supervision, support and assistance.
10-20	Moderate	Formal assessment may be helpful if there are specific clinical indications.	Clear impairment. May require 24-hour supervision.
0-10	Severe	Patient not likely to be testable.	Marked impairment. Likely to require 24-hour supervision and assistance with ADL.

Source:

- Folstein MF, Folstein SE, McHugh PR: "Mini-mental state: A practical method for grading the cognitive state of patients for the clinician." *J Psychiatr Res* 1975;12:189-198.

https://pdfs.semanticscholar.org/4370/72f1421146674eaf98e11cc9079311f23fcb.pdf

1.2 Fugl-Meyer Assessment for Upper Extremity (FMA-UE)

FMA-UE PROTOCOL — Rehabilitation Medicine, University of Gothenburg

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 (at least one) **Extensors**: triceps			0 0	2 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). **Extensor synergy:** Hand from ipsilateral ear to the contralateral knee	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
	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 hand on lap	cannot perform or hand in front of ant-sup iliac spine hand behind ant-sup iliac spine (without compensation) hand to lumbar spine (without compensation)		0	1	2
Shoulder flexion 0°- 90° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 90°, no shoulder abduction or elbow flexion		0	1	2
Pronation-supination elbow at 90° shoulder at 0°	no pronation/supination, starting position impossible limited pronation/supination, maintains starting position full pronation/supination, maintains starting position		0	1	2
Subtotal III (max 6)					
IV. Volitional movement with little or no synergy			**none**	**partial**	**full**
Shoulder abduction 0 - 90° elbow at 0° forearm pronated	immediate supination or elbow flexion supination or elbow flexion during movement abduction 90°, maintains extension and pronation		0	1	2
Shoulder flexion 90° - 180° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 180°, no shoulder abduction or elbow flexion		0	1	2
Pronation/supination elbow at 0° shoulder at 30°- 90° flexion	no pronation/supination, starting position impossible limited pronation/supination, maintains start position full pronation/supination, maintains starting position		0	1	2
Subtotal IV (max 6)					
V. Normal reflex activity assessed only if full score of 6 points is achieved in part IV; compare with the unaffected side			**0 (IV), hyper**	**lively**	**normal**
biceps, triceps, finger flexors	2 of 3 reflexes markedly hyperactive or 0 points in part IV 1 reflex markedly hyperactive or at least 2 reflexes lively maximum of 1 reflex lively, none hyperactive		0	1	2
Subtotal V (max 2)					
Total A (max 36)					

B. WRIST support may be provided at the elbow to take or hold the starting 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 tolerated maintains dorsiflexion 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 tolerated maintains dorsiflexion 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 elbow at 90°, forearm pronated shoulder at 0°	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. Hook grasp 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. Pincer grasp, 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 grasp cylinder shaped object (small can) tug upward, opposition of thumb and fingers	cannot be performed can hold cylinder but not against tug can hold cylinder against a tug	0	1	2
e. Spherical grasp fingers in abduction/flexion, thumb opposed, tennis ball, tug away	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, sitting, after one trial with both arms, eyes closed, tip of the index finger from knee to nose, 5 times as fast as possible		marked	slight	none
Tremor	at least 1 completed movement	0	1	2
Dysmetria at least 1 completed movement	pronounced or unsystematic slight and systematic no dysmetria	0	1	2
		≥ 6s	**2 - 5s**	**< 2s**
Time start and end with the hand on the knee	at least 6 seconds slower than unaffected side 2-5 seconds slower than unaffected side less than 2 seconds difference	0	1	2
	Total D (max 6)			

TOTAL A-D (max 66)	

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

J. PASSIVE JOINT MOTION, upper extremity, sitting position, compare with the unaffected side				**J. JOINT PAIN** during passive motion, upper extremity		
	only few degrees (less than 10° in shoulder)	decreased	normal	pronounced pain during movement or very marked pain at the end of the 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

https://neurophys.gu.se/digitalAssets/1520/1520773_fma-ue-protocol-english-updated-20150315.pdf

1.3 Action Research Arm Test (ARAT)

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	

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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http://www.strokecenter.org/wp-content/uploads/2011/08/action_research_arm_test.pdf

1.4 Functional Independent Measurement (FIM)

APPENDIX D
Functional Independence Measure (FIM) Instrument

	ADMISSION	DISCHARGE	FOLLOW-UP
Self-Care			
A. Eating			
B. Grooming			
C. Bathing			
D. Dressing - Upper Body			
E. Dressing - Lower Body			
F. Toileting			
Sphincter Control			
G. Bladder Management			
H. Bowel Management			
Transfers			
I. Bed, Chair, Wheelchair			
J. Toilet			
K. Tub, Shower			
Locomotion			
L. Walk/Wheelchair			
M. Stairs			
Motor Subtotal Score			
Communication			
N. Comprehension			
O. Expression			
Social Cognition			
P. Social Interaction			
Q. Problem Solving			
R. Memory			
Cognitive Subtotal Score			
TOTAL FIM Score			

LEVELS		
	Independent 7 Complete Independence (Timely, Safely) 6 Modified Independence (Device)	**NO HELPER**
	Modified Dependence 5 Supervision (Subject = 100%+) 4 Minimal Assist (Subject = 75%+) 3 Moderate Assist (Subject = 50%+) **Complete Dependence** 2 Maximal Assist (Subject = 25%+) 1 Total Assist (Subject = less than 25%)	**HELPER**
Note: Leave no blanks. Enter 1 if patient is not testable due to risk.		

https://www.strokengine.ca/pdf/FIMappendixD.pdf

1.5 Modified Ashworth Scale (MAS)

Modified Ashworth Scale

The Modified Ashworth Scale (MAS) measures resistance during passive soft-tissue stretching. It is a quick and easy measure that can help assess the efficacy of treatment. The following conventions prevail:

- The MAS is performed in the supine position (this will garner the most accurate and the lowest score as any tension anywhere in the body will increase spasticity)
- Because spasticity is "velocity dependent" (the faster the limb is moved, the more spasticity is encountered), the MAS is performed while moving the limb at the "speed of gravity"; this is defined as the same speed at which a non-spastic limb would naturally drop (fairly fast)
- The test is performed a maximum of three times for each joint; if more than three times, the short-term effect of a stretch can influence the score
- The MAS is performed prior to goniometric testing; goniometric testing provides a stretch, and the short-term effect of a stretch can influence the score

Scoring

0 = Normal tone, no increase in tone
1 = Slight increase in muscle tone, manifested by a catch and release or minimal resistance at the end of the range of motion (ROM) when the affected part(s) is moved in flexion or extension
1+ = Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM
2 = More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved
3 = Considerable increase in muscle tone, passive movement difficult
4 = Affected part(s) rigid in flexion or extension

Positions

The positions used for an MAS assessment are as follows:

Score_____Elbow. *Start position:* Elbow fully flexed, forearm neutral. Movement: Extend elbow from maximum possible flexion to maximum possible extension. (Triceps would be in the same position, opposite direction.)

Score_____Wrist. *Start position:* Elbow as straight as possible, forearm pronated. Movement: Extend the patient's wrist from maximum possible flexion to maximum possible extension.

Score_____Fingers. *Start position:* Elbow as straight as possible, forearm neutral. All fingers are done at once. Movement: Extend the patient's fingers from maximum possible flexion to maximum possible extension.

Score_____Thumb. *Start position:* Elbow as straight as possible, forearm neutral, wrist neutral. Movement: Extend the thumb from maximum possible flexion (thumb against index finger) to maximum possible extension (in anatomical position, "abducted").

Score_____Hamstrings. *Start position:* Prone so that ankle falls beyond end of the plinth, hip in neutral rotation. Movement: Extend the patient's knee from maximum possible flexion to maximum possible extension

Score_____Quadriceps. *Start position:* Prone so that ankle falls beyond end of the plinth, hip in neutral rotation. Movement: Flex the patient's limb from maximum possible flexion to maximum possible extension

Score_____Gastrocnemius. *Start position:* Supine, ankle plantarflexed, hip in neutral rotation and flexion. Movement: Dorsiflex the patient's ankle from maximum possible plantarflexion to maximum possible dorsiflexion not more than three consecutive times and rate the muscle tone.

Score_____Soleus. *Start position:* Supine, ankle plantarflexed, hip in neutral rotation and flexion and with the knee flexed to –15°. Movement: Dorsiflex the patient's ankle from maximum possible plantarflexion to maximum possible dorsiflexion.

Reprinted with permission from Peter G. Levine. Testing spasticity: the Modified Ashworth Scale. June 2, 2009. http://physical-therapy.advanceweb.com/Article/Testing-Spasticity-The-Modified-Ashworth-Scale.aspx. and Bohannon R, et al. Interrater reliability of a Modified Ashworth Scale of muscle spasticity. *Phys Ther.* 1987;67(7):206-207.

https://www.med-iq.com/files/noncme/material/pdfs/DOC%201--Modified%20Ashworth%20Scale.pdf

Appendices 2: Textile Subjective Questionnaire

2.1 International Subjective Sensory Evaluation

Institute of Textiles and Clothing, The Hong Kong Polytechnic University

"Fast Fabric Hand Measurement Technology" – International Subjective Sensory Evaluation

Terminologies Definition:

Subjects are required to clearly understand definitions of each pair of descriptors before the evaluation.

Cool-Warm: At relatively low/high temperature.

Itchy-NonItchy: Affected with itching or the itch.

Scratchy-NonScratchy: Of work executed with the pen or brush: Composed of scratches, as opposed to bold, firm lines.

Prickle-NonPrickle: That causes a prick or puncture

Smooth-Rough: Having a surface free from projections, irregularities, or inequalities

Sticky-Nonadhesive: Having the property of sticking or adhering

Stiff-Pliable: Rigid; not flexible or pliant.

Thin-Thick: Having relatively little extension between opposite surfaces

Soft-Hard: Presenting a yielding surface to the touch; not offering absolute resistance to pressure.

Fullness-Nonfullness: That spontaneously resumes its normal bulk after having been contracted by external force.

* All definition comes from Oxford English Dictionary.

2.2 Subjective Questionnaire

Please put forearm straight on the table, palm up, release, and keep stable. Then three different textiles will be statically loaded (i.e., without striking) onto the skin surface of the ventral side of the forearm.

Please fill in all descriptors with a numeric rating scale (1 = very weak, 2 = weak, 3 = slightly weak, 4 = normal, 5 = slightly strong, 6 = strong and 7 = very strong).

Cool	1=====2=====3=====4=====5=====6=====7	Warm
Damp	1=====2=====3=====4=====5=====6=====7	Dry
Itchy	1=====2=====3=====4=====5=====6=====7	Non-itchy
Scratchy	1=====2=====3=====4=====5=====6=====7	Non-scratchy
Prickle	1=====2=====3=====4=====5=====6=====7	Non-prickle
Rough	1=====2=====3=====4=====5=====6=====7	Smooth
Sticky	1=====2=====3=====4=====5=====6=====7	Non-adhesive
Stiff	1=====2=====3=====4=====5=====6=====7	Pliable
Thick	1=====2=====3=====4=====5=====6=====7	Thin
Hard	1=====2=====3=====4=====5=====6=====7	Soft
Inelastic	1=====2=====3=====4=====5=====6=====7	Elastic
Nonfullness	1=====2=====3=====4=====5=====6=====7	Fullness
Uncomfortable	1=====2=====3=====4=====5=====6=====7	Comfortable

All personal information is anonymous collected and will be used in scientific research only.

------- End of Test! Thank You Very Much! -------

Appendices 3: Consent Form

3.1 Consent form for Chapter 2 and Chapter 3

Consent Form

I, _____ (name of subject), hereby consent to participate as a subject for the project entitled "Biomechatronic System Using Electromyography (EMG)-driven Neuromuscular Electrical Stimulation (NMES) for Upper Limb Rehabilitation".

- I have understood the experimental procedures presented to me.
- I have given an opportunity to ask questions about the experiment, and these have been answered to my satisfaction.
- The testing should not result in any undue discomfort, I realize that I can discontinue the experiment with no reasons given and no penalty received during the experiment.
- I realize the experiment will possibly benefit my upper limb motor functions.
- I agree that the PI and the project research members, who obtained the authorization from the PI, can use my experimental data for this project study.
- I realize that the results of this experiment are the properties of The Hong Kong Polytechnic University
- I realize that the results of this experiment may be published, but that my own results will be kept confidential.

Subject name: _____ Signature: _____ Date: _____

Witness: _____ Signature: _____ Date: _____

Investigator: Huangyanhuan Signature: _____ Date: _____

同意書

我，_____(受試者姓名)，在此同意作為受試者參加"上肢互动机械训练系统"的研究。

- 我已明白到這個測試的所有步驟。
- 我已給予機會詢問有關該測試的問題，並已獲得滿意的回答。
- 如果實驗給我帶來不適，我已明白在實驗中我可以隨时終止測試而無需給予任何理由，或由此而受到任何懲罰。
- 我已明白這個實驗的結果有可能可以改善我的上肢运动功能。
- 我同意本項目負責人及其受權的項目研究人員使用我的實驗記錄以作此項目的研究。
- 我已知道這個測試的結果屬香港理工大學。
- 我已知道這個測試的結果可被發表，但有關我個人的結果將獲得保密。

受試者姓名_____ 簽署_____ 日期_____

作證人姓名_____ 簽署_____ 日期_____

研究員姓名 黃琰欢 簽署_____ 日期_____

3.2 Consent form for Chapter 4

THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學

Consent form

I, _____ (name of subject), hereby consent to participate as a subject for the project entitled "The Investigation of Sensory Deficiency in Fine Textile-Skin Perception after Stroke"

- I have understood the experimental procedures presented to me. I have understood the information presented in the information sheet.
- I have given an opportunity to ask questions about the experiment, and these have been answered to my satisfaction.
- The testing should not result in any undue discomfort, I realize that I can discontinue the experiment with no reasons given and no penalty received during the experiment.
- This research may shed lights on the pathology of stroke in order to help doctors develop better rehabilitation strategies, but this cannot be guaranteed.
- I agree that the PI and the project research members, who obtained the authorization from the PI, can use my experimental data for this project study.
- I realize that the results of this experiment are the properties of The Hong Kong Polytechnic University.
- I realize that the results of this experiment may be published, but that my own results will be kept confidential.

Subject name: _____ Signature: _____ Date: _____

Witness: _____ Signature: _____ Date: _____

Investigator: Huangyanhuan Signature: _____ Date: _____

同意書

我，_____(受試者姓名), 在此同意作為受試者參加 "中風之後皮膚织物觸覺感知障碍" 的研究。

- 我已明白在資料單張上所寫的所有內容。
- 我已給予機會詢問有關該測試的問題, 並已獲得滿意的回答。
- 如果實驗給您帶來不適, 我已明白在實驗中我可以終止測試而無需給予任何理由, 或由此而受到任何懲罰。
- 我已明白這個實驗的結果可以帮助医生在未来更好的了解中风的病理以及制定更佳的康复策略訓練，但是這無法被保證。
- 我同意本項目負責人及其受權的項目研究人員使用我的實驗記錄以作此項目的研究。
- 我已知道這個測試的結果屬香港理工大學。
- 我已知道這個測試的結果可被發表, 但有關我個人的結果將獲得保密。

受試者姓名_____ 簽署_____日期_____

作證人姓名_____ 簽署_____日期_____

研究員姓名 黃琰欢_____ 簽署_____日期_____

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