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UNIVERSITY OF SOUTHAMPTON

FACULTY OF HEALTH SCIENCES

Centre for Innovation and Leadership in Health Sciences

**Prediction of upper limb recovery
post-stroke using wrist motor impairments**

by

Waroonnapa Srisoparb

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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PREDICTION OF UPPER LIMB RECOVERY POST-STROKE USING WRIST MOTOR IMPAIRMENTS

Waroonnapa Srisoparb

More than 70% of people with stroke exhibit upper limb disability at one year. An understanding of upper limb motor recovery, and prediction of upper limb functional activity (ULFA) based on motor impairment, are important to inform rehabilitation.

Recovery of upper limb motor impairment (measured by short form of the Fugl-Meyer motor scale), wrist motor impairments (measured by the redesigned wrist rig), and ULFA (measured by the Streamlined Wolf Motor Function Test for use with sub-acute patients) at 2, 4, 8, 12 and 26 weeks were investigated. Relationships between ULFA at 26 weeks and wrist motor impairments at each assessment point are reported, as well as prediction values for ULFA at 26 weeks, based on wrist motor impairments at 2, 4, 8 and 12 weeks.

Three motor impairment phenomena, sub-divided into eight categories, were measured from 11 impairment indices. These were: 1) negative (a reduction of motor activity): range of active movement; muscle weakness; motor control accuracy; delayed muscle onset timing; 2) positive (excessive motor activity): spasticity and coactivation; and 3) secondary (later changes associated with negative and positive impairments): contracture and non-neural stiffness. Test-retest reliability of each impairment index was tested with 14 stroke participants at 8 weeks. Construct validity was tested in 25 stroke participants at two and 26 weeks post-stroke and with 25 matched pair healthy controls. All impairment indices demonstrated good to excellent test-retest reliability (intra-class correlation coefficient 0.78-0.99). The minimal detectable change of each index was established as a benchmark value. Wrist active range of motion (AROM), flexor and extensor isometric force (IF), sine and step tracking index (TI), path length, muscle onset timing and stretch index were statistically significantly different ($p < 0.05$) between stroke and healthy participants, representing good construct validity.

Fifty-two stroke participants were recruited into a longitudinal study. Upper limb motor impairment, ULFA, range of active movement and muscle weakness improved rapidly between weeks two and four with considerably slower improvement between weeks 4 and 26. Recovery profiles could be divided into three categories: 1) high scores at 2 weeks with continuous improvement over 26 weeks; 2) low to moderate scores at 2 weeks with continuous improvement over 26 weeks; and 3) zero scores at 2 weeks with little or no improvement at 26 weeks. Generally, ULFA at 26 weeks was more related to the negative (r_s 0.39 to 0.78; $p < 0.05$) than to the positive (r_s -0.40 to -0.54; $p < 0.05$) or the secondary (r_s 0.37 to 0.66; $p < 0.05$) motor impairments. Range of active movement, muscle weakness spasticity and contracture are good predictors of ULFA at 26 weeks (OR between 1.02, 95%CI 1.01-1.04 to OR 7.00, 95%CI 2.19-22.48).

This is the first exploratory study to demonstrate a prediction of ULFA based on a variety of wrist motor impairments. The findings may assist therapists to customise rehabilitation programmes during the 26 weeks of stroke recovery.

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DECLARATION OF AUTHORSHIP

I, Waroonnapa Srisoparb, declare that this thesis entitled “Prediction of upper limb recovery post-stroke using wrist motor impairments” and the work presented in it are my own and have been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:
Poster presentation: Srisoparb W, Turk R, Burridge JH (2015) Delayed wrist extensor muscle onset timing in people with acute and chronic stroke, World Confederation for Physical Therapy Congress 2015, 1-4 May, Singapore.

Signed:

Date: 20 December 2016

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Glossary of Abbreviations

AMAT – Arm Motor Ability Test

ARAT – Action Research Arm Test

AROM – active range of motion

AS – Ashworth scale

BI – Barthel index

CI – coactivation index

(s)EMG – (surface) electromyography

FM-UE – Fugl-Meyer Motor Scale

FAI – Frenchay activity index

FAS – functional ability scale

FAT – Frenchay Arm Test

ICC – intra-class correlation coefficient

IF – isometric force

LBL – Local baseline

LED – light emitting diode

MAE – mean absolute error

MAS – Motor Assessment Scale

MBI – modified Barthel Index

MCA – motor control accuracy

MDC – minimal detectable change

MMAS - modified motor assessment scale

mRS - modified Rankin scale

MVC – maximal voluntary contraction

MTI – mean torque index

MVC – maximal voluntary contraction

PROM – passive range of motion

S-FM - short form of the Fugl-Meyer Motor Scale

SI – stretch index

SR – stretch response

SWMFT-S FAS - Streamlined Wolf Motor Function Test for use with sub-acute for the functional ability scale

TI - tracking index

ULFA - upper limb functional activity

UMN - upper motor neuron

Glossary of Terms

Active range of Motion (AROM)	Range of movement capable without assistance
Motor control accuracy (MCA)	An ability to control the limbs by coordinating muscle activity to solve a task adequately in order to meet environmental demands (some research used the term 'dexterity') (Ada et al. 1996; Canning et al. 2004)
Muscle coactivation	The simultaneous activation of agonist and antagonist muscle (Gribble et al. 2003) crossing the same joint, that activates in phases and increase the stiffness of the joint (Turk 2011)
Muscle weakness	An inability of muscle to produce the necessary tension for maintaining, initiating, or controlling movement (Bourbonnais and Noven 1989)
Passive range of motion (PROM)	Range of movement capable with assistance
Sine tracking task	Rhythmic movement to follow the target
Spasticity	Disordered sensory-motor control, resulting from an upper motor neuron lesion, presenting as intermittent or sustained involuntary activation of muscle (Pandyan et al. 2005)
Step tracking task	Discrete movement to follow the target
Stretch response test	Neural response of flexor EMG to passive stretch
Torque	Rotational force around an axis
Upper limb functional activity (ULFA)	The execution of a task or action involving an upper limb by an individual in the current or a standardised environment (World Health Organisation 2001)

Chapter 1: Introduction

This Chapter outlines the justification for this study and provides an overview of it. The structure of the thesis is explained and the conference presentations resulting from the study are listed.

1.1 Justification for this study

1.1.1 The impact of stroke

Stroke is a clinical disorder, caused by interruption of the blood supply to the brain. The two main causes of stroke are ischemia (blood clots blocking arteries) and haemorrhage (arteries bursting) (National Audit Office 2010). It has been observed that, stroke is a major cause of disability worldwide and that the life expectancy of stroke patients has been shown to have increased in the last 20 years (from 1990 to 2010) (Vos et al. 2013). As a result, standardised approaches to tackle the burden of stroke are needed.

The population of the UK increased to 64.1 million in 2013 (Office for National Statistics 2014). The annual incidence of stroke in the UK was 150,000 (Townsend et al. 2012) and the average numbers of stroke deaths in the UK in 2012 was 44,069 (Townsend et al. 2014). Due to the improvements in hyper-acute care, such 'progress' can potentially increase the burden of stroke disability (Scarborough et al. 2009). In 2013, approximately 1.3 million of people in the UK were living with stroke (Townsend et al. 2014). Direct care costs, which is the treatment cost, of the stroke patients in the UK comes to about £4 billion a year (Saka et al. 2009). In Thailand, a country located in South East Asia, the population was predicted to be over 65 million in 2014 (Institute for Population and Social Research 2009). It is estimated that there are around 150,000 new cases of stroke per year in Thailand (Poungvarin 2007). The incidence of stroke caused a 48,000 Thai deaths in 2005 (Porapakkham et al. 2010). It has been reported that there were 1.9 million stroke disabled people in Thailand in 2007 (Khiaocharoen et al. 2012). The direct care cost of stroke patients was found to be in excess of 100,000 Baht (£2,000) per patient per year based on the financial rate in 1999 (Youngkong S et al. 2002).

Stroke has a multi-dimensional effect on the patient including physical, mental, and social factors (Baumann et al. 2012). More than 25% of stroke patients are disabled in some way, post-stroke (Adamson et al. 2004; Patel et al. 2006). People with stroke may be unemployed due to the stroke's impact (Baumann et al. 2012). This can lead to economic loss for both the victim's family and society (Feigin et al. 2008). Hence, it can be argued that stroke is a major healthcare issue in the UK and Thailand.

1.1.2 Upper limb functional activity (ULFA) following stroke

Following stroke, problems affecting upper limb functional activity (ULFA) are often persistent. In a study by Houwink et al. (2013), approximately 50% of stroke patients had no hand capacity on admission. Less than 20% of stroke people exhibited complete ULFA at one year following stroke as indicated by full Upper Extremity Motor Index (UEMI) and Motor Assessment Scale (MAS) scores (Kong et al. 2011). ULFA dysfunction is caused by a combination of impairments. The primary motor impairments following stroke are: a reduction of motor activity including weakness, fatigue and loss of motor control accuracy (MCA) (negative features), and abnormal involuntary activity (positive features) such as spasticity and increased tendon reflexes. Long-term secondary changes, which negative and positive features can lead to, may include muscle shortening, stiffness and contracture (Barnes, 2001)

The estimation of the patient's potential for recovering ULFA is important for stroke management. It is essential to make an accurate prognosis of stroke survivors and to select the most appropriate rehabilitation intervention for each individual patient. A number of wide-ranging studies have identified clinical predictors of ULFA (Katrak et al. 1998; Kwakkel et al. 2003; Smania et al. 2007; Au-Yeung and Hui-Chan 2009; Beebe and Lang 2009; Nijland et al. 2010b; Suzuki et al. 2011; Veerbeek et al. 2011; Prager and Lang 2012; Kong and Lee 2013; Kwakkel and Kollen 2013). Despite a number of variables being investigated, baseline upper limb motor impairment and function measures are constantly identified as strong predictors of ULFA following stroke (Chen and Winstein, 2009; Coupar et al., 2012; Kwakkel and Kollen, 2013).

In particular, muscle weakness and the ability to move (active range of motion; AROM) have been found to be accurate predictors of ULFA recovery (Katrak et

al. 1998; Kwakkel et al. 2003; Smania et al. 2007; Au-Yeung and Hui-Chan 2009; Beebe and Lang 2009; Nijland et al. 2010b; Suzuki et al. 2011; Prager and Lang 2012; Kong and Lee 2013; Kwakkel and Kollen 2013). In addition, there are other upper limb motor impairment, which are potential predictors of ULFA. Several studies have demonstrated an association between wrist motor impairments and ULFA. There is consensus that a loss of motor control (Canning et al. 2004; Burridge et al. 2009; Turk 2011), delayed muscle onset timing (Chae et al. 2002a; Wagner et al. 2007b; Turk 2011), muscle coactivation (Chae et al. 2002a; Turk 2011), spasticity (Ada et al. 2006; Turk 2011), contracture (Ada et al. 2006; Malhotra et al. 2011; Turk 2011) and non-neural stiffness (Turk 2011) correlate with ULFA. However, the debate is still on-going about whether motor impairment, such as spasticity, is associated with ULFA (Ada et al. 2006; Turk 2011) or not (Burridge et al. 2009; Malhotra et al. 2011). Although the causal relationships between these motor impairments and ULFA have not yet been evaluated, they are important associations to consider when diagnosing problems and prescribing therapeutic exercise programmes for people with stroke.

Spontaneous recovery of ULFA occurs rapidly over the first three months with slow improvement after that until six months (Ada et al. 2006; Verheyden et al. 2008; Kong and Lee 2013). Therefore, in most clinical settings, therapists carry out intensive rehabilitation for the first three months to capitalise on this vital window of opportunity in order to maximise the recovery of patients. We predicted ULFA at six months since the recovery of ULFA appears to have reached a plateau at six months. In addition, most patients are living in their home environment by then and so the results might reflect real-world ULFA.

1.1.3 A framework of measurement in rehabilitation interventions

The International Classification of Functioning, Disability and Health (ICF), a classification of issues in health and health related domains, developed by the World Health Organization specified the domains of health evaluation. These domains are categorised into body functions and structures, the activity limitations, and the participation restrictions. The impairment of the body system refers to the problem in body function or structure as a significant loss.

Activity limitation is defined as any dysfunction in task performance such as activities of daily living (ADL) and leisure tasks. Participation restriction describes the involvement of the people in their society (World Health Organisation 2001). These domains are widely used as the basis for evaluating stroke patients. This study focuses on body functions and structures and the activity limitation of the upper limb.

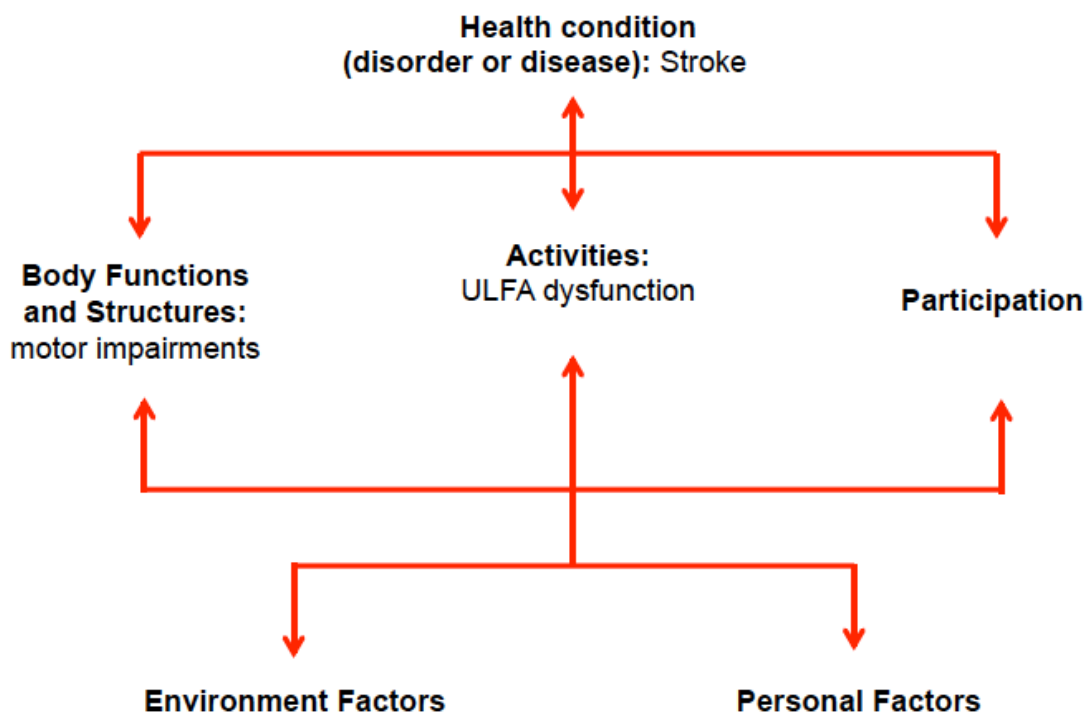


Figure 1.1 An example of the ICF framework and how it can be used to evaluate people with stroke, adapted from WHO International Classification of Functioning, Disability and Health (ICF) (World Health Organisation 2001)

Physical assessment of patients, that provides quantitative information, which can decrease error and bias in measurement, is a critical part of stroke rehabilitation for identifying problems and assisting therapists to plan a customised treatment programme (Freeman 2002). Motor impairment is a domain that needs to be assessed in stroke patients for identifying the cause of their ULFA dysfunction. The interventions aim to improve ULFA by targeting the underlying motor impairments, thereby contributing to better rehabilitation programmes for patients with neurological disorders (Qiyu et al. 2011).

1.1.4 Measurement of motor impairment

An objective and valid neuromechanical measurement tool, known as the wrist rig, can be used to assess motor impairments at the wrist in a single assessment (Turk et al. 2008). The wrist rig was developed to measure torque and angle in a horizontal plane of the wrist joint combined with surface electromyography (sEMG) of wrist flexors and extensors muscles. This wrist rig was modified from the Strathclyde wrist rig (Pandyan et al. 1997) based on biomechanical and neurophysiological principles for measuring wrist motor impairments. In previous studies the wrist rig was used to measure range of motion, muscle weakness, delayed muscle onset timing, MCA, muscle activation, spasticity, contracture and non-neural stiffness at the wrist joint. It is an objective reliable tool to distinguish wrist impairments between stroke and healthy participants or between acute and chronic stroke participants (Turk et al. 2008; Turk 2011). Further details of the results of a study by Turk (2011) are outlined in Chapter 3 section 3.2.

The assessment of the wrist with the wrist rig involves simple wrist flexion and extension movements in a horizontal plane. This is much easier, compared to the assessment of the shoulder and fingers, which involves more complex movements, which are difficult to measure. The wrist rig has been redesigned to use in this study (Chapter 3). Some indices were further modified from Turk (2011). However, a test-retest reliability and minimal detectable change (MDC) of the impairment indices generated by the redesigned wrist rig have not been investigated yet.

1.2 Rehabilitation services for stroke patients in Thailand

The research data was collected from Thai stroke patients, who were receiving rehabilitation as part of a programme at the Department of Physiotherapy, Buddhachinaraj Hospital, Phitsanulok Province, Thailand. This section introduces Buddhachinaraj Hospital and offers information to improve understanding of the rehabilitation services that the hospital provides.

Buddhachinaraj Hospital is a government centre hospital in Phitsanulok Province, Thailand. It provides 933 beds for more than 800,000 people in

Phitsanulok Province and nearby areas. In addition, there are eight community hospitals in Phitsanulok Province to service people in the rural areas (Buddhachinaraj Hospital 2012). Stroke was the sixth most prolific cause of death in Phitsanulok Province in 2008 (Buddhachinaraj Hospital 2008). The number of stroke patients involved in the rehabilitation programme run by the Department of Physiotherapy, Buddhachinaraj Hospital is increasing continuously. The number of admissions for stroke cases were 881, 883 and 966 in 2009, 2010 and 2011, respectively (Buddhachinaraj Hospital 2011).

The process for rehabilitating stroke patients in Buddhachinaraj Phitsanulok Hospital, is illustrated in Figure 1.2.

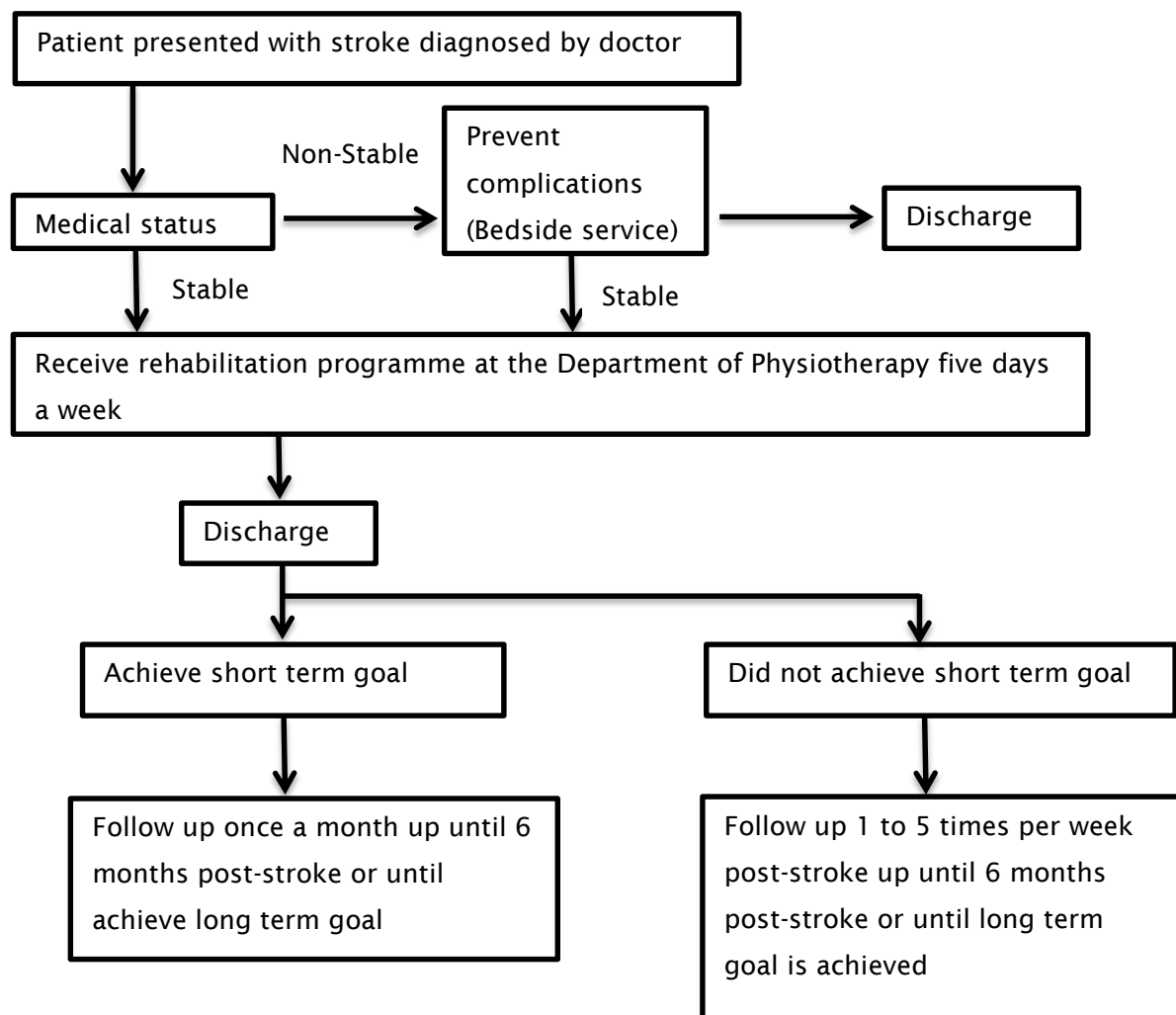


Figure 1.2Flow diagram for stroke surveillance at Buddhachinaraj Hospital, Thailand

After being discharged from the Buddhachinaraj Hospital, people who have had stroke who live in rural areas are followed up by the physiotherapist at the patient's nearest community hospital. The rate of follow up of each patient mainly depends on their socioeconomic status. Generally, the middle to high socioeconomic patients, who do not have problems with transport, are able to visit the therapists at the hospital more than the low socioeconomic patients. There is a small number of patients who are visited in their homes by the therapists because there are limited number of the therapists who work in the community. Although the number of the patients who have been followed up until they achieve their long term goal was not investigated, it was observed that a lot of patients were not followed up. A lack of follow up of those patients might limit the chances of improving their upper limb recovery.

1.3 Summary of the gaps in knowledge

Stroke is an important problem in the health system in the UK (Scarborough et al. 2009; Townsend et al. 2012; Townsend et al. 2014) and Thailand (Poungvarin 2007; Khiaochaoen et al. 2012). It is a major cause leading to long-term deficits in contralesional ULFA (Kong et al. 2011; Kong and Lee 2013). The ULFA limitations are caused by multiple upper limb impairments after stroke, therefore an understanding of the underlying impairments is essential for restoration of ULFA. An investigation of upper limb motor recovery and a prognosis of ULFA are necessary for the therapists to tailor rehabilitation programme for each individual patient.

AROM, muscle weakness, MCA, delayed muscle onset timing, muscle coactivation, spasticity, contracture and non-neural stiffness were found to be related to ULFA improvement. The wrist rig was developed to measure all those motor impairments at the wrist in a single assessment (Turk 2011). A study, which investigates recovery of upper limb motor impairment and prediction of ULFA based on upper limb impairment, has not been fully investigated. There is a lack of this kind of research with Thai stroke patients in Thai rehabilitation services and, thus, it was of benefit to conduct this research in Thailand. In addition, there was a practical recruitment for the author (WS), who has a background as a physiotherapist and, who has collaborated with work with the Department of Physiotherapy, Buddhachinaraj Hospital, Thailand.

Therefore, this study investigated recovery of upper limb impairment, wrist impairments and ULFA after stroke; in particular, the way in which impairments impact on the recovery of ULFA. The research questions and research objectives are demonstrated in Chapter 2.

1.4 Overview of the research studies

The study overview is illustrated in the following flowchart (Figure 1.3). Firstly, a usability test for the redesigned wrist rig was conducted to investigate whether it was fully ready to be used in our study. The modifications to the wrist rig system were made before starting the pilot study 1 and 2; which are feasibility studies to address the following research questions.

Are the redesigned wrist rig tests, the Streamlined Wolf Motor Function Test for use with sub-acute patients (SWMFT-S), short form of the Fugl-Meyer motor scale for upper extremity (S-FM-UE) and the modified Rankin scale (mRS) feasible to be used in sub-acute stroke group?

Pilot study 1 was conducted in the UK with 6 healthy participants and 3 chronic stroke participants. Pilot study 2 was carried out in Thailand with 3 chronic stroke participants and 6 sub-acute stroke participants. It has been observed that the redesigned wrist rig, the SWMFT-S and all clinical measures are feasible for use with healthy participants, chronic stroke and finally sub-acute stroke participants in terms of the comfort and the time needed. Subsequently, the longitudinal study was also conducted in Thailand to address the following research questions:

1. How does upper limb impairment (measured by S-FM-UE), ULFA (measured by the SWMFT-S) and wrist impairments (measured in the redesigned wrist rig) change during the first 26 weeks following stroke?
2. What is the relationship between ULFA at 26 weeks and wrist motor impairments at two, four, eight, 12 and 26 weeks?
3. Which, if any, of the following wrist impairments: range of motion (flexion to extension AROM), muscle weakness (flexor and extensor IF), MCA (sine and step TI, path length), delayed muscle onset timing (extensor onset timing), spasticity (SI; flexor spasticity), coactivation (sine CI), muscle contracture

(PROM; flexor contracture) and non-neural stiffness (MTI; flexor contracture) can predict ULFA at 26 weeks?

The longitudinal study involved six months for recruitment of the participants and another six months for the follow-up period. A test-retest reliability study was conducted as a part of the longitudinal study, in order to address the following questions:

1. Is the redesigned wrist rig reliable?
2. What are minimal detectable changes (MDC) for wrist AROM, flexor and extensor isometric force (IF), sine tracking index (TI), step TI, path length, extensor onset timing, sine coactivation index (CI), stretch index (SI), PROM and mean torque index (MTI)?

In addition, a matched pair study was conducted to address the question:

1. Are there differences in wrist motor impairment indices between healthy, sub-acute and chronic stroke groups in the Thai population (construct validity)?
2. What is a normal range of Thai healthy participants (who matched for age, gender, height and weight with our stroke participants) for wrist AROM, flexor and extensor isometric force (IF), sine tracking index (TI), step TI, path length, extensor onset timing, sine coactivation index (CI), stretch index (SI), PROM and mean torque index (MTI)?

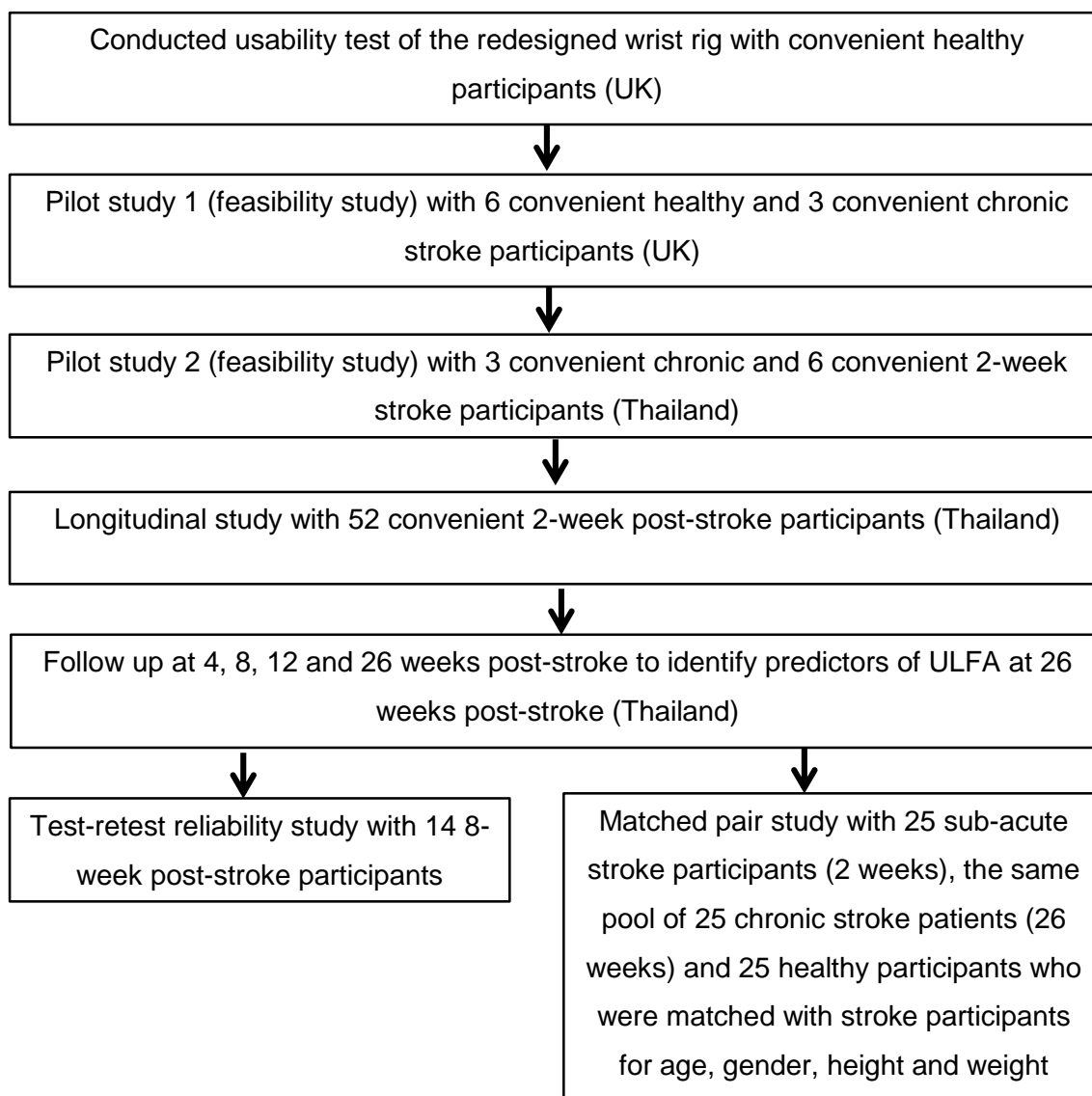


Figure 1.3 Flowchart of the interrelated studies within this PhD thesis

1.5 Thesis structure

This thesis is divided to 9 Chapters. A brief summary of each chapter is presented below.

Chapter 1: Introduction, which outlines the justification for the study, rehabilitation services for Thai stroke patients and an overview of the thesis. The structure of the PhD thesis is explained and the conference presentations resulting from the study are listed

Chapter 2: Literature review, which is divided into six sections to provide a literature review of the issues concerning upper limb impairment, upper limb

functional activity (ULFA), and predictors of ULFA recovery. The summary of the findings from previous studies and the research questions and the research objectives are presented.

Chapter 3: Development of a redesigned wrist rig, which details the modifications, measurement property, safety testing, calibrations and usability of the redesigned wrist rig.

Chapter 4: Methodology, which describes the methodology of each study (pilot, reliability, matched pair and longitudinal studies). The study design, sites and recruitment of participants, study samples, selection criteria, screening assessments, confounding factors, outcome measures, training to conduct the tests, statistical analysis, ethical consideration and data management and storage are presented.

Chapter 5: Pilot studies, which describes the introduction, research questions and objectives of the two pilot studies followed by their research methodologies including testing procedures and statistical analysis. The results, discussions and conclusions of the pilot studies are then presented.

Chapter 6: Reliability study, which details the introduction and research questions for the reliability study. The methodology (testing procedures and statistical analysis), results, summary of results, discussion and conclusions are presented thereafter.

Chapter 7: Matched pair study, which describes the introduction, research question, objectives, methodology (testing procedures and statistical analysis), results, summary of results, discussion and conclusions.

Chapter 8: Longitudinal study, which provides the introduction, research questions and objectives of the longitudinal study. Testing procedures, statistical analysis, results, summary of results, and conclusions are detailed.

Chapter 9: Discussion and Conclusions, which discusses the findings of the longitudinal study and the conclusions of this PhD thesis.

1.6 Presentations

Parts of the work in this thesis were presented at the conferences listed below:

Poster presentation:

Srisoparb W, Turk R, BurrIDGE JH (2015) Delayed wrist extensor muscle onset timing in people with acute and chronic stroke, World Confederation for Physical Therapy Congress 2015, 1st-4th May, Singapore.

Oral presentation:

Srisoparb W, Turk R, BurrIDGE JH (2016) Comparison between upper limb function and arm and wrist impairment recovery profiles during 6 months post-stroke, Postgraduate Research Roundtable and Supper, University of Southampton, United Kingdom, 19th July 2016.

1.7 Summary of Chapter 1

This chapter presents the current gaps in the knowledge related to ULFA in the stroke population. It highlights the justification for this study. The thesis structure is explained and the conference presentations are listed.

The next chapter presents a detailed literature review, providing the background of the research into predictors of upper limb functional activity post stroke, which underpinned this research.

Chapter 2: Literature review

2.1 Introduction

This chapter is divided into six sections. Section 2.2 introduces the issues of upper limb impairment and their measurement. Upper limb functional activity (ULFA) is detailed in section 2.3. Predictors of ULFA recovery are reviewed in section 2.4. A summary of the findings from previous studies is then reported. Finally, the research questions and the research objectives are presented.

2.2 Upper limb motor impairment and how they are measured

Stroke is an upper motor neuron (UMN) lesion. The UMN syndrome comprises a complex group of symptoms that arise following a lesion of the central nervous system. The clinical features of the UMN syndrome can be divided firstly into negative phenomena (a reduction of motor activity), including muscle weakness, loss of dexterity, and fatigue; secondly, there are positive phenomena, which are characterised by excessive or inappropriate motor activity, such as an increase in tendon reflex and spasticity. Lastly, there are long-term secondary changes that might be caused by positive and negative neural phenomena, such as muscle shortening, stiffness and contracture (Barnes 2001; Trochim 2006). This study focuses on motor impairments, which are important to ULFA following stroke.

2.2.1 Negative motor impairments

2.2.1.1 Muscle weakness

Muscle weakness is an inability of muscle to produce the necessary tension for maintaining, initiating, or controlling movement during the loading of the musculoskeletal system. The production of muscle force depends on the types of motor unit recruited, and the character of motor unit discharge. The increased muscle force depends on the number of active, and/or the firing rates of, motor units (Bourbonnais and Noven 1989).

Muscle weakness on the side contralateral to the brain lesion is a clinical consequence after stroke (Ada et al. 1996; Andrews and Bohannon 2000; Andrews and Bohannon 2003; Kamper et al. 2006; Conrad and Kamper 2012). Muscle weakness arises from multiple factors, which include primary impairments of upper motor neurons, secondary adaptations, and the aging effect. The primary impairments are a reduction in the number of motor units, a decrease in firing frequency and/or recruitment order of motor units, changes in the characteristics of contractile properties, specific changes in nerve conduction velocity of agonist muscles and changes in muscle architecture (Bourbonnais and Noven 1989; Sunderland et al. 1989; Ng and Shepherd 2000). The secondary adaptations are adaptive length-associated changes of muscle and disuse of both agonist and antagonist muscle groups (Ng and Shepherd 2000). There are changes of muscle architecture, as a consequence of stroke, such as muscle-fibre length, pennation angle, muscle atrophy and tendon compliance, all of which contribute to muscle weakness (Gray et al. 2012; Hu et al. 2012). Aging is another cause of muscle weakness, due to a reduction of motor neurons, impairment in excitation coupling, loss of fast muscle fibre, and muscle atrophy (Ng and Shepherd 2000).

Stroke patients need to recruit greater numbers of motor units in their paretic limb in order to produce the same magnitude of force, compared to their unimpaired side (Zhou et al. 2007); such patients have difficulty controlling their voluntary force (Chang et al. 2013).

Manual muscle testing (MMT), and the Motricity Index (MI), were used to measure muscle weakness in people with stroke (Au-Yeung and Hui-Chan 2009; Fayazi et al. 2012; Cioncoloni et al. 2013; Pandian and Arya 2013); however these are subjective measurements, which have difficulty in detecting small changes in muscle strength (Conable and Rosner 2011). The typical objective measurement of muscle weakness in stroke patients is the isometric torque or force produced by a maximal voluntary contraction (MVC) (Sunderland et al. 1989; Boissy et al. 1999; Ada et al. 2000; Kamper et al. 2006; Suzuki et al. 2011; Chang et al. 2013). Although isokinetic torque production was recognised as providing a good estimate of the level of motor impairment, compared to isometric torque production (Conrad and Kamper 2012), the IF has been widely established and accepted because of its positive correlation with ULFA (Ada et al. 2006; Burridge et al. 2009; Turk 2011). The IF

was selected for measuring muscle weakness as it is objective, simple and acceptable to be used in a clinic.

There are factors that could limit the reliability of measuring muscle strength using MVC. Firstly, it is noted that stroke patients demonstrated decreased accuracy and increased variability in their force production, when they attempted to maintain a constant force. Lodha et al. (2010) compared force control and force variability between chronic stroke participants and healthy matched controls (N=9 for each group). The participants performed isometric wrist and finger extension at 5%, 25%, and 50% of their MVC for 20 seconds. The accuracy of force production was calibrated by the root mean square error (RMSE), which is the vertical distance between the target force and the force produced by the participants. The variability, calculated by the standard deviation was calculated by measuring the fluctuations around the mean force produced normalized to the magnitude of the produced force. The results showed that the accuracy of force production in the stroke group was statistically significantly reduced compared to the healthy control ($p < 0.05$ at 25% of MVC and $p < 0.005$ at 50% of MVC). In addition, the stroke group had greater variability of force production than the healthy group ($p < 0.05$ at 25% of MVC and $p < 0.005$ at 50% of MVC). Force production at 5% MVC showed the highest variability compared to 25% and 50% (Lodha et al. 2010). The participants in the study by Lodha et al. (2010) were further tested for their force control variability during grip strength for three seconds at 5, 10 and 20% MVC. The findings showed that force production control at 5% MVC had the most variability compared to the other points (Naik et al. 2011). Taken together, stroke patients appear to have more difficulty in controlling low force level for a long duration (20 seconds), rather than high force level in a short period. Our study provided three 5-second contractions with a 10 seconds rest interval to assess muscle strength in stroke patients. The maximum values were recorded as their muscle strength. Less accuracy of force production control and force production variability are unlikely affect our results.

Another factor that could have an effect on the reliability of MVC is spasticity. Spasticity is an involuntary contraction which may increase with voluntary force. Observed agonist muscle weakness may be due to actual antagonist muscle spasticity (Bohannon 1989). Furthermore, involuntary contraction (spasticity) of the antagonist muscle may be inhibiting the voluntary agonist

contraction (Mukherjee and Chakravarty 2010). The way to prevent spasticity of the antagonist muscle may be to undertake nerve blocks to prevent activity of antagonist muscles. However, a study which measured the MVC of the agonist muscle by doing a nerve block of the antagonist muscle has not been found. In addition, it may be not practical to do that in a clinical environment. Therefore, spasticity was not controlled during the muscle strength measurement.

The MVC test can be done against a tester as a fix resistance using a handheld dynamometer (Bohannon and Smith 1987a). A limitation of performing MVC against the tester's resistance is that it requires the tester be stronger than the subject to provide a truly fixed resistance to the patient's effort (Conable and Rosner 2011). If the tester is not strong enough, the results may be less reliable. Another method to measure MVC is to stabilise participants' joint in a standard position to press as hard as possible against stationary position with a force transducer (Conable and Rosner 2011). This method could increase the reliability of measuring MVC, since the resistance is firmly fixed. A neuromechanical wrist rig was designed to have a fixed resistance to the participant's wrist flexor and extensor IF. Therefore, it seems to be more reliable than a hand held dynamometer.

2.2.1.2 Motor control accuracy (MCA)

Loss of dexterity is one of the negative features of the UMN syndrome, and is usually known as the inability to demonstrate skilled use of the hands or a whole upper limb (manual dexterity) (Kiyama et al. 2011; Kong et al. 2011; Thompson-Butel et al. 2014). However, some research used the term dexterity that investigated the ability of precise muscle use to control upper limb movement in a follow-the-target task at the elbow joint (Ada et al. 1996; Canning et al. 2000; Canning et al. 2004). These researchers suggested that dexterity refers to adroitness and competency in use of the limbs by coordinating muscle activity to adequately solve a task in order to meet environmental demands. Because of this confusion in the understanding of the term dexterity Turk (2011) therefore, suggested the term 'motor control accuracy (MCA)' for use in her research on motor control at the wrist joint, also using target tracking. The term MCA is used throughout this research.

Tracking tasks, through using a biomechanical approach, coupled with surface electromyography (sEMG) were suggested for measuring MCA in stroke patients (Ada et al. 1996; Canning et al. 2000; Canning et al. 2004; Turk et al. 2008; Turk 2011). This approach could investigate both accuracy of tracking and muscle activation patterns.

Sine tracking (rhythmic movement) and step tracking (discrete movement) were both used to measure MCA, since they appeared to be related to ULFA (Turk 2011). A sine tracking task was used to represent rhythmic movements of the wrist. It is potentially more reliable than step tracking, because it generates multiple similar cycles of data that can be averaged. The rhythmic movements of the wrist are presented in the performance of daily living activities, such as hammering. However, most everyday movements are not repetitive in this way and therefore sine tracking is not representative of everyday motor performance. There is also evidence that the cortical control of sine tracking involves different pathways from discrete tracking (Schaal et al. 2004). Therefore, a step tracking task was developed and used to represent discrete movements in a study by Turk (2011). The step tracking task involves complex acceleration and deceleration, demanding cognitive control for which higher-level planning areas of the cortex are recruited. In addition, the step tracking task may be more related to the functional activities of the wrist than repetitive movements. The step tracking task could also provide additional insights into tracking accuracy (path length at the end-point target position) and extensor onset timing (Turk 2011).

The accuracy of tracking tasks could be calculated from the target and angle signal of the joint movement by different methods including root mean square (RMS) error, mean absolute error (MAE) and cross-correlation (Notley et al. 2007; Turk et al. 2008; Turk 2011). Cross-correlation was found to offer the highest agreement with ULFA (Notley et al. 2007).

The path length is the MCA at the target end point, specifically the amount of corrective sub-movements. It is a useful assessment, which was used to measure ability to control movement in patients with multiple sclerosis, who presented with intention tremor (Feys et al. 2006).

2.2.1.3 Muscle onset timing

Muscle onset timing is the time interval between onset of target and onset of the surface electromyography (sEMG) signal. Alteration of muscle activation has been found in people with stroke. Initiation and termination of muscle contraction were delayed in the hemiparetic arm (Dewald et al. 1999; Chae et al. 2002a). Delayed muscle onset timing may contribute to upper limb impairment and ULFA disability (Chae et al. 2002a; Turk 2011). The onset of muscle activation in stroke is affected by three components of a simple motor task: i) signal detection ii) motor processing and selection of motor strategy and iii) task execution (Ghez 1991). Delayed muscle onset timing may therefore be affected by stroke, which impact on motor performance.

Chae et al. (2002a) defined muscle activation time as the earliest visually observed rise in EMG activity beyond the steady state. However, this subjective method depends on the assessors' skill and experience, which may be unreliable. A computer based method to quantify muscle onset timing was used later by comparing the EMG envelope with a threshold, based on the envelope during a baseline period. The magnitude of the deviation from the baseline was required to indicate a threshold (Turk 2011).

2.2.2 Positive impairments

2.2.2.1 Spasticity

People with brain lesion such as stroke often experience increased stiffness of their limbs. Passive movement resistance that is manifested in stroke survivors may be attributed to neural and non-neural components. Neural stiffness is often referred to as spasticity. Spasticity has been found with approximately one third of all stroke survivors (Sommerfeld et al. 2012; Zorowitz et al. 2013) and it is more likely to occur in chronic phase (> 3 months) (Wissel et al. 2013).

The common definition of spasticity found in the literature is “...motor disorder characterized by a velocity dependent increase in the tonic stretch reflex (muscle tone) with exaggerated tendon jerks, resulting from hyper excitability of the stretch reflex, as one component of the upper motor neurone syndrome” (Lance 1980). This definition is used widely in the research (Malhotra et al. 2009; Li and Francisco 2015). However, the standard definition

by Lance (1980) relates only to passive movement and does not refer to spasticity during active movement. The definition of spasticity was revised and redefined by a European working group as “disordered sensory-motor control, resulting from an upper motor neuron lesion, presenting as intermittent or sustained involuntary activation of muscle” (Burridge et al. 2005; Pandyan et al. 2005).

In the healthy people, stretch reflex is mediated by excitatory connections between Ia afferent fibres from muscle spindles and homonymous α -motoneurons. Passive stretch of the muscle excites the muscle spindles, leading Ia fibres to discharge and send inputs to the α -motoneurons through monosynaptic pathways. There is also disynaptic inhibition of α -motoneurons innervating antagonist muscle (reciprocal inhibition). Subsequently, the α -motoneurons send an efferent impulse to the muscle, causing it to contract (Mukherjee and Chakravarty 2010; Trompetto et al. 2014). Stretch reflex in stroke survivors has lower threshold and increased amplitude compared with healthy subjects (Yelnik et al. 2010). Normally, a stretch reflex is not present in a healthy subject, even at rates of passive movement as high as 500 degrees per second, whereas stretch reflexes in stroke patients could be elicited with relatively slow movements, as slow as 35 degrees per second (Sheean 2001). Hyperexcitability stretch reflex in stroke patients could be mediated by two categories of mechanism, which are abnormal descending regulations and/or abnormal intraspinal processing of the stretch reflex (Li and Francisco 2015). Descending tracts that provide balanced excitatory and inhibitory descending regulation of the stretch reflex are mainly reticulospinal (RST) and also vestibulospinal (VST) tracts. Any imbalance of these tracts influences a cause of abnormal stretch reflex and thus spasticity (Trompetto et al. 2014; Li and Francisco 2015). Isolated pyramidal lesions, such as destruction of motor cortex (area 4), have not resulted in spasticity. However, the lesions of area 4, including the premotor and supplementary motor areas, may cause spasticity (Sheean 2001; Mukherjee and Chakravarty 2010). Abnormal intraspinal processing could result from (1) increased afferent input to spinal motoneurons: the sensitivity of Ia and II afferent fibres (sensory axons arising from muscle spindles) are enhanced through activation of the gamma fusimotor system and/or adaptive changes after immobilization, resulting in increased excitability of the stretch reflex (Gracies 2005b; Li and Francisco

2015); (2) altered inter-neural reflex circuits resulting in motoneuronal excitability including disynaptic reciprocal Ia inhibition, Ib inhibition (autogenic inhibition from Golgi tendon organs), recurrent (Renshaw) inhibition and Ib facilitation (Burke et al. 2013; Trompetto et al. 2014). These changes result in less inhibition from intraspinal reflex circuits on spinal motor neurons; (3) changes in intrinsic properties of the spinal motor neurons lead to α -motorneural hyperexcitability and thus a decreased reflex threshold (Li and Francisco 2015).

One characterisation of spasticity measurement is measuring resistance to passive stretch (Platz et al. 2005). The original or modified Ashworth scale (AS) and Tardieu scale (TS) are most commonly used in clinics as the measurement of resistance to passive motion (Rekand 2010; Sommerfeld et al. 2012; Thibaut et al. 2013; Wissel et al. 2013; Aloraini et al. 2015). The AS is an ordinal scale that is effective in clinical practise because of its ease and speed of use (Bohannon and Smith 1987b). However, it exhibited insufficient validity and reliability for measuring spasticity (Fleuren et al. 2010; Li et al. 2014). In comparison with the AS, the TS does take into account the velocity of passive joint movement (Thibaut et al. 2013). However, it may not be considered as an objective assessment since it is subject to the assessors' interpretation. Inter- or intra-rater reliability of the modified TS was insufficient in cases where the assessors were not trained adequately (Ansari et al. 2013). In addition there was the modified TS is not a valid tool to evaluate muscle spasticity since it did not have statistically significant correlations with H-reflex tests, which is a noninvasive electrophysiological method that established link to spasticity (Naghdi et al. 2014).

The findings from the measurement of resistance to passive stretch in stroke survivors demonstrated that they do not measure only the resistance caused by neural component (spasticity). Pandyan et al. (2006) investigated the resistance to passive extension (RPE) and electromyography (EMG) activity of the elbow flexors in chronic stroke participants who presented with spasticity (measured by the modified AS) as identified by the biomechanical device. They found that EMG activity during fast stretch was significantly higher than during the slow stretch ($p < 0.05$). This result supported the phenomenon of spasticity defined by Lance (1980). There was no association between the modified AS and either RPE or EMG activity. Therefore, the modified AS appeared not to be valid, since

it did not respond to the stretch reflex, as defined by Lance (1980). Furthermore, there was only a weak association between EMG activity and the RPE. These results suggested that there were other factors (both neural and non-neural) involved with the RPE (Pandyan et al. 2006). Therefore, a biomechanical measurement tool, which can characterise and distinguish between neural and non-neural factors, would be appropriate to measure spasticity (Burridge et al. 2005).

The combination of biomechanical and neurophysiological measurements appears to be more accurate to quantify spasticity than the clinical scale (such as the AS or the TS) (Wood et al. 2005; Pandyan et al. 2006; Malhotra et al. 2008). The Hoffmann reflex (H-reflex), the Tendon reflex (T-reflex), and the stretch reflex are the three most commonly used neurophysiological methods to measure spasticity. However, the H-reflex could become involved with the oligosynaptic pathways rather than just the monosynaptic reflex. The tendon reflex is mainly characterised as a spinal reflex (Voerman et al. 2005). Therefore, the stretch reflex was used to quantify wrist flexor spasticity.

Neurophysiological measurement of the stretch reflex could quantify spasticity by various terms, such as latency and amplitude of the reflex. The previous study by Turk (2011) measured the SI at the wrist during fast passive sinusoidal displacement (follow a blue light target) at $3.5 \text{ Hz} \pm 5$ degrees around the subject's midpoint of their AROM. The SI was quantified as a ratio of the mean EMG area of the flexor divided by EMG area of the flexor over an interval of 0.1 second prior to extension (local baseline) by fast passive sinusoidal displacement around the subject's midpoint of the wrist joint. It was reported that the SI of wrist flexors during passive extensor movement was statistically significant different ($p < 0.001$) between stroke and healthy participants (Turk 2011). Therefore, this method was selected to measure spasticity.

2.2.2.2 Muscle coactivation

Coactivation is the simultaneous contraction of agonist and antagonist muscle (Gribble et al. 2003). Normal coactivation is essential for stabilising joints or fixation of a body part (Sheean 2001; Frey-Law and Avin 2013). For example, wrist coactivation is modulated to stabilise the wrist when hitting a tennis ball. Coactivation may be reduced after training to perform a task (Prange et al.

2012). Abnormal coactivation is the point where mechanical joint stiffness creates impaired movement; it can be a consequence of central nervous system (CNS) lesions such as those resulting from stroke (Prange et al. 2012). Stroke survivors may present with spastic coactivation, which is defined as excessive levels of antagonist muscle activity during voluntary command on agonist muscle. It may be facilitated by the loss of reciprocal inhibition during voluntary agonist contraction. Consequently, stroke patients have difficulty in generating movement or alternate movement direction resulting in slow movement (Yelnik et al. 2010; Kheder and Padmakumari Sivaraman Nair 2012).

A study by (Turk 2011) found that wrist coactivation was not statistically significantly correlated with spasticity, whereas Ohn et al. (2013) found that muscle coactivation was positively correlated with spasticity ($r = 0.944$ on shoulder flexion, $r = 0.741$ on hand grasping, $p < 0.01$). However, there was a small sample size in those two studies ($N=13$ and 12 respectively), so the data may not be representative of stroke population. A study with a larger sample size is needed to support the results.

There are several ways to measure muscle coactivation. For example, Chae et al. (2002b) quantified wrist coactivation during isometric wrist flexion and extension. A ratio of root mean square of agonist and antagonist muscles was used as a measure of coactivation. However, measuring coactivation during isometric contraction was not considered to be used since dynamic movement appears to be much more clinically relevant.

Canning et al. (2000) quantified coactivation at elbow during voluntary sinusoidal tracking tasks. However, the coactivation analysis by using correlation of EMG through the whole test (flexion and extension movements) did not distinguish differences between normal healthy and stroke participants who had high motor control performance ($p=0.68$). A recent study by Turk (2011) compared four methods of coactivation analysis and found that the correlation coefficients of wrist flexor EMG and wrist extensor EMG when the wrist extensor EMG is increasing could distinguish differences between normal healthy and stroke participants. Hence, normal coactivation in unimpaired and spastic coactivation in impaired participants was differentiated. Therefore, this method of analysis was chosen to quantify coactivation.

2.2.3 Secondary impairments

2.2.3.1 Non-neural stiffness

Non-neural stiffness is the resistance to passive movement due to biomechanical changes in muscle tendons or joints as a result of prolonged muscle shortening. Non-neural stiffness is much less velocity dependent and is still present during couch examination and under anaesthesia (Hutchinson and Graham 2001). Soft tissue stiffness could reduce compliance and can contribute to hypertonia; therefore, it is difficult to distinguish such hypertonia from that caused by spasticity (Sheean and McGuire 2009). Changes in paretic muscles include adaptive to changes in the intrinsic properties of the innervating motoneurons and/or a change in the impulse traffic transmitted along the motor axon to the muscle (Burke et al. 2013). Muscles, which are maintained in shortened position, adapt to their resting length and loss of sarcomeres until those remaining enable the muscle to contract at maximal tension at the immobilized length. In addition, there is accumulation of intramuscular connective tissue of immobilized skeletal muscle, which results in a reduction of extensibility (Gracies 2005a). Another phenomenon that possibly increases resistance to passive movement in stroke survivors is “thixotropy”. The term thixotropy has been applied to substances, which can be changed from gel to solution after being stirred (Vattanasilp et al. 2000). Thixotropy at the ankle joint presented in both healthy individuals and stroke patients, however stroke patients did not exhibit an abnormally high response compared with the controls. This suggested that thixotropy may produce enough immediate resistance to limit movement in very weak stroke patients; however, it is not a substantial contributor to long term muscle stiffness (Vattanasilp et al. 2000).

A previous study reported that non-neural stiffness, and neural stiffness (spasticity), in upper limbs of stroke participants were larger than in healthy participants (Mirbagheri et al. 2007). The measurement of spasticity by passive movement (such as the modified AS) could measure the resistance to passive movement, but it is still difficult to determine whether the resistance occurs due to the tonic stretch reflex (neural) or soft tissue stiffness (non-neural) (Alibiglou et al. 2008; Yelnik et al. 2010). Therefore, it is necessary to distinguish non-neural stiffness from spasticity during passive movement.

Quantitative measurements of neural stiffness (spasticity) and non-neural stiffness can lead to more accurate characterisations of pathological conditions and outcome evaluations of interventions, potentially contributing to better rehabilitation programmes for patients with neurological disorders (Qiyu et al. 2011).

There are different methods to measure non-neural torque. Complex measurements of non-neural stiffness in previous research include measuring total torque (neural plus non-neural torque) during voluntary contraction and the measurement of non-neural torque during muscle contraction as elicited by electrical stimulation (Sinkjaer et al. 1993; Sinkjaer and Magnussen 1994); measuring perturbations at the joints and use of an advanced system to analyse neural and non-neural torque (Mirbagheri et al. 2007; Alibiglou et al. 2008) or measured stiffness of the joint after administered anaesthetic (Kamper et al. 2003). The measurement of non-neural torque at the wrist flexor by using slow passive movement was selected. Non-neural stiffness was calculated as the slope of a torque angle regression curve. It has been demonstrated that the stroke participants in the previous study by Turk et al. (2008). could not entirely avoid flexor or extensor activation during slow passive movement at the wrist. Therefore, the number of repetitious movements was increased and the average stiffness was calculated (Turk 2011).

2.2.3.2 Contracture

Contracture usually occurs when muscle is being maintained in a shortened position (Sheean 2001). The phenomenon leads to soft tissue contracture, which can be defined as i) physical shortening; and ii) reduction in extensibility of soft tissue, including muscles, tendons, ligaments, joint capsules, skin, vessels and nerves. The reduction of protein synthesis during the first few hours after the onset of immobilization can lead to those phenomena, and only intensifies in the days, weeks and months following stroke, particularly stroke patients who do not receive proper management (Yelnik et al. 2010). Spasticity and muscle weakness result in a decrease in the mobility of the affected limb (Pandyan et al. 2003; Ada et al. 2006; Sheean and McGuire 2009; Malhotra et al. 2011). These are additional mechanisms of the contracture, which lead to chronic aggravation of contractures (Gracies 2005a).

Contracture is defined by measuring the passive range of motion (PROM) (Pandyan et al. 2003); 30% or higher restriction the affected side compared with the unaffected side (Yip et al. 1996) or the unaffected side PROM minus the affected side PROM (Ada et al. 2006).

Kwah et al. (2012) investigated incidence of muscle contractures during the first six months after stroke (N=200). The contracture scale was used to measure joint range in upper and lower limb joints including at baseline (within 4 weeks) and 6 months. It has been seen that more than 50% of stroke patients developed at least one contracture at shoulders, elbows, forearms, wrists, fingers, thumbs, hips, knees or ankles. Wrist contracture was observed in 12% of their participants (Kwah et al. 2012).

2.3 Upper limb functional activity (ULFA)

This section reviews the recovery stage and compensation of ULFA following stroke. Measurements used for assessing ULFA in stroke patients are then described.

2.3.1 Recovery versus compensation of ULFA following stroke

Approximately 70% of people with stroke experienced limitations to ULFA (Nijland et al. 2010b; Kong et al. 2011). Following stroke, ULFA recovery appears to be slower than lower limb recovery (Kwah et al. 2013). One possible reason is that people with stroke received therapy with greater emphasis on improving their gait and mobility, so that they could achieve early ambulation and be discharged from hospital; an outcome that lead to a reduction in costly hospital fees (Levin et al. 2009). In addition, ULFA is complicated and involves various systems such as trunk coordination (Likhi et al. 2013) and multi-joint movements (Lang and Beebe 2007), which are difficult to improve within a short period of time. Clinically, the outcome of ULFA recovery mainly focuses on task accomplishment. This section reviews the number of studies that investigated improvement of ULFA, as assessed by clinical measurement that capture paretic arm use.

Au-Yeung and Hui-Chan (2009) conducted a longitudinal prospective study to investigate ULFA recovery after stroke (N=57). The baseline assessment was conducted within the first five days. The participants were followed up weekly in the first month and then at two and six months. The researchers reported that more than 80% of stroke patients had poor ULFA at their initial assessment (measured by Action Research Arm Test; ARAT scores <10). Clinical improvement was observed during the first four weeks. At 26 weeks, 32% of stroke participants regained full ULFA recovery. However, 47% of them continued to exhibit poor ULFA.

Kong and Lee (2013) also investigated ULFA recovery (measured by MAS, Upper Extremity Motor Index (UEMI) and modified Barthel Index (MBI) respectively) at 24 hours post-stroke and followed up at 3, 6 and 12 months. The results showed that 18%, 25.5% and 31.6% of 100 stroke participants gathered higher UEMI and MAS scores than baseline assessment at 3, 6 and 12 months, respectively. There were only 18% of stroke participants who gained full UEMI and MAS scores at 12 months. ULFA improvements significantly improved up to 3 months with smaller improvements at 6 and 12 months.

Kwah et al. (2013) evaluated ULFA by the MAS in 200 stroke participants. Baseline assessment was conducted within the first four weeks with a follow-up at 6 months. The results showed that, of the 51 participants who could not move a cup across the table by their paretic limb at the initial test, 21 (41%) achieved the upper limb task at six months. Of the 56 stroke survivors, who were unable to use their paretic limb feed themselves initially, 25 (45%) could feed themselves at six months. In summary, less than half of stroke participants recovered their ULFA at 6 months. Their result was consistent with a previous study by Nijland et al. (2010b), which found that 34% of 156 stroke participants had maximum ULFA scores as assessed by the ARAT, at six months.

A larger study conducted by Houwink et al. (2013) (N=222) measured ULFA with the Stroke Upper Limb Capacity Scale (SULCS). The SULCS was developed by the same team (Houwink et al. 2011). At baseline, 125 patients had no hand capacity (SULCS score, 0-3), 58 had basic hand capacity (SULCS score, 4-7), and 116 had advanced hand capacity (SULCS score, 8-10). At discharge, 59% of the

participants who initially had no hand capacity remained the same and 78% of the participants who had basic hand capacity now had advanced hand capacity.

These results suggested that people with stroke who have some movement of upper limb on admission are highly likely to regain their ULFA at discharge. Another study found 11% of stroke participants who presented with flaccidity of upper limb at admission (defined by the Fugl-Meyer Motor Scale; FM) exhibited complete ULFA at six months. Thirty-eight percent of those flaccid upper limb stroke participants made some ULFA recovery (ARAT \geq 10 points) (Kwakkel et al. 2003).

It should be noted that ULFA recovery rate could be due to the utilisation of compensation strategies (Kwakkel et al. 2004). Recovery is defined as restoration of normal movement kinematics and muscle activation patterns, whereas compensation is defined as the use of alternative degrees of freedom and/or muscles for accomplishing a task (Lum et al. 2009). For example, the anterior deltoid muscle was activated during forward reaching in healthy participants. In the paretic arm of stroke participants, the anterior deltoid and lateral deltoid were both activated during the same task. This finding indicates that people with stroke, who could not generate sufficient force by their typical agonist muscle, may necessitate the use of a compensatory muscle to accomplish the task (McCrea et al. 2005). Stroke survivors, who have motor impairment of their paretic limb used different patterns of joint recruitment with different scaling rules (Roby-Brami et al. 2003). Furthermore, ULFA improvement of the paretic arm in chronic stroke patients could occur without meaningful improvements of kinematic measures and motor recovery (Kitago et al. 2013). An understanding of motor impairment recovery therefore aid in distinguishing true recovery from compensation (Krakauer 2005; Krakauer et al. 2012). The investigation of underlying motor impairments of ULFA is necessary to measure whether ULFA improvements are developed by motor impairments recovery or by using compensation strategies.

2.3.2 Measurement of upper limb motor impairment and upper limb functional activity (ULFA) in people with stroke

This section discusses the issues related to the selection of outcome measures followed by a section detailing the selection of the upper limb impairment and ULFA measurements.

2.3.2.1 Issues related to the selection of outcome measures

One way to try to ensure that measurement error is minimised is to determine validity and reliability of the measurement. Knowing and understanding the terms and definitions of reliability and validity enable the author (WS) to undertake a critical review in terms of the quality of measurement. This section presents the types of reliability and validity, which have been reported typically in research.

The concept of validity refers to whether an instrument actually measures what it sets out to measure. Reliability refers to whether an instrument can be interpreted consistently across different situations. (Field 2009).

Hulley et al. (2013) suggested three ways to view and assess validity as follows:

1) Content validity refers to how well the assessment represents all aspects of the phenomena under study (Rowland and Gustafsson 2008; Hulley et al. 2013). For example, the wrist rig has high content validity to measure wrist motor control, since it measures muscle activity, accuracy and range of motion, spasticity, muscle weakness and stiffness, which are the main constructs of wrist motor control. Content validity that uses subjective judgment about whether the measurements appear reasonable is termed as 'face validity' (Hulley et al. 2013).

2) Construct validity examines how well a measurement confirms with theoretical constructs (Hulley et al. 2013). Salkind (2010) defined construct validity as an ability of a test or instrument to measure the distinct dimension (construct) they are intended to measure. For example, wrist motor control between stroke and healthy participants is theoretically different. The wrist rig

is able to distinguish wrist motor control between these two groups; the wrist rig has good construct validity (Turk 2011).

3) Criterion-related validity refers to the degree to which a new measurement correlates with well-accepted existing measures (Rowland and Gustafsson 2008; Hulley et al. 2013). There are four types of criterion-related validity.

- Predictive validity: an ability of measurement to predict performance on a criterion measure administered at a later time (Trochim 2006; Salkind 2010).
- Concurrent validity: the extent to which scores on a new measure are related to scores from a criterion measure administered at the same time (Salkind 2010).
- Convergent validity: a degree of similarity between two measures that they theoretically should be similar. High correlations would be evidence of convergent validity (Trochim 2006).
- Discriminant validity: in contrast with convergent validity, discriminant validity is the degree to which the measure diverges from other measure that theoretically should not be similar (Trochim 2006).

Furthermore, an evaluation of the validity of a research study or procedure is relevant to internal and external validity. Internal validity is associated with valid inference in the population studied (Benestad and Laake 2007). External validity is related to generalization; it is the degree to which the conclusions in a study would apply to other persons, objects or situations in other places and at other times (Trochim 2006).

Measurements also require testing for reliability. Generally, there are three classes of reliability, as follows (Polgar and Thomas 2008):

- 1) Inter-rater reliability, which refers to the consistency of observations between the observers
- 2) Test-retest reliability, which is the consistency of a measure when the same test is given to the same sample on two different occasions.
- 3) Internal consistency reliability, which refers to consistency of the results of different items within the measure.

Responsiveness, sensitivity and specificity are other criteria to examine measurement quality. Responsiveness is the ability of measurement to be responsive to actual changes, which occur over time. Sensitivity refers to the proportion of positives that are correctly identified. Specificity is the proportion of negatives that are correctly identified (Bowling 2005; Rowland and Gustafsson 2008). Assessment and consideration of possible floor and ceiling effects are also needed as they indicate limits to the range of detectable change beyond which no further improvement or deterioration can be noted (Salter et al. 2005).

2.3.2.2 Selection of outcome measurement of upper limb motor impairment

The Fugl-Meyer Motor Scale (FM), which was established by Fugl-Meyer et al. (1975), consists of 33 items for assessing upper limb motor deficit. The FM is the outcome measure at the ICF body function level, which is one of the most widely used in research (Lang et al. 2013; Murphy et al. 2015; Santisteban et al. 2016). It has demonstrated a high level of measurement quality and clinical utility. However, the administration is very lengthy and it may be challenging for some patients to tolerate the full assessment. Therefore, the 50-item version was shortened to 12 items (S-FM) (Hsieh et al. 2007) which made it rigorous, but also easily administered. The 12 items consisted of a 6-item upper limb subscale and a 6-item lower limb subscale. As we were focused on ULFA, therefore, only the upper limb subscale of S-FM was administered. The S-FM for upper extremity (S-FM-UE) are shoulder flexion 90° to 180°; grasp adduct thumb; elbow 90° pronation/ supination; elbow 90° wrist flexion/ extension; elbow extension and shoulder elevation. The psychometric properties of the FM and S-FM were therefore reviewed.

The concurrent validity of the S-FM was examined by investigating the correlation between S-FM and FM of 279 participants at 14, 30 and 90 days after their stroke. The predictive validity of the S-FM and FM were defined as the correlation between S-FM and FM at 14, 30 and 90 days and a combination between the BI and the Frenchay Activities Index (FAI) at 180 days. The S-FM had high concurrent validity ($r \geq 0.93$). The predictive validity of the S-FM was moderate ($r = 0.49$ to 0.59), which was similar to the FM ($r = 0.48$ to 0.53). The responsiveness (the ability of measurement to be responsive to actual changes)

of the S-FM and FM from 14 to 30 days and from 30 to 90 days was moderate (standardized response mean (SRM): 0.62 to 0.71 for the S-FM, and 0.60 to 0.67 for the FM) (Hsieh et al. 2007).

Validity and responsiveness of the FM and S-FM for upper limb (FM-UE and S-FM-UE) were investigated in 50 acute stroke participants. The assessments were conducted on admission (mean onset to admission=18 days) and discharge (mean rehabilitation stay=22 days). Both FM-UE and S-FM-UE showed a small response (effect size d 0.34 and 0.47, respectively) which indicated that it needed a large sample size to demonstrate a clinical change. However, the S-FM-UE was slightly more responsive than the FM-UE. Predictive validity of the FM-UE and S-FM-UE were defined as the correlation between them on admission and the BI at discharge. The S-FM-UE had a slightly higher predictive validity ($r_s=0.70$) than the FM-UE ($r_s=0.66$). The test-retest reliability of the FM-UE and S-FM-UE were tested in 60 chronic stroke participants in two assessment sessions. Both assessments had very satisfactory test-retest reliability (ICC 0.98 for FM-UE and ICC 0.93 for the S-FM-UE). The MDC of these two assessments were established as 7.2 for the FM-UE and 1.5 for the S-FM-UE. Neither of the assessments had notable floor- and ceiling effects (Hsueh et al. 2008). The S-FM-UE was selected to be used in our study because it showed good psychometric properties and obviously saved time compared to the FM-UE. Table 2.1 illustrates the measurement properties of the FM and the S-FM.

Table 2.1 Measurement properties of the FM and the S-FM

Criteria	Methodology of testing	Results
Predictive validity	<p>- Spearman rank correlation coefficient (r_s)* *the strengths of the relationship were classified as excellent ($r_s > 0.75$), good ($r_s = 0.5-0.75$), fair ($r_s = 0.25-0.5$), and low ($r_s < 0.25$) (Wu et al. 2011)</p>	<p>- The FM-UE was related to BI ($r_s = 0.66$) (Hsueh et al. 2008).</p> <p>- The S-FM-UE was related to BI ($r_s = 0.70$) (Hsueh et al. 2008).</p>
Concurrent validity	<p>- Spearman rank correlation coefficients</p> <p>- Pearson correlation coefficients</p>	<p>- The FM correlated with ARAT ($r_s = 0.73$ [0.58, 0.83] (Hsieh et al. 2009).</p> <p>- The FM correlated with WMFT ($r_s = 0.71$ [0.56, 0.82] (Hsieh et al. 2009).</p> <p>- The S-FM-UE correlated with FM ($r \geq 0.93$) (Hsieh et al. 2007).</p>
Inter-rater reliability	Intraclass correlation coefficient (ICC)	<p>- The FM-UE was ICC 0.97 (Sanford et al. 1993).</p> <p>- The S-FM has not yet been tested.</p>
Test-retest reliability	ICC	<p>- The FM-UE was 0.98 (Hsueh et al. 2008).</p> <p>- The S-FM-UE was 0.93 (Hsueh et al. 2008).</p>

Criteria	Methodology of testing	Results
Responsiveness	- effect size d was defined as mean change scores divided by the SD of the baseline score (effect size d greater than 0.8 is large, 0.5 to 0.8 is moderate, and 0.2 to 0.5 is small) (Hsueh et al. 2008)	- The FM-UE was 0.34 (Hsueh et al. 2008). - The S-FM-UE was 0.47 (Hsueh et al. 2008).
Floor and ceiling effects	The percentage of participants who achieved highest (ceiling effect) and lowest (floor effect) scores. Significant floor and ceiling effects were considered to be present if more than 20% of the patients fell outside the lower or upper bound, respectively (Salter et al. 2005; Nijland et al. 2010a)	- 4% and 4% of participants had lowest and highest scores of FM-UE at admission; 0 and 9% of participants had lowest and highest scores of FM-UE at discharge (Hsueh et al. 2008) - 9% and 1% of participants had lowest and highest scores of S-FM-UE at admission; 3 and 10% of participants had lowest and highest scores of FM-UE at discharge (Hsueh et al. 2008)
Minimal detectable change (MDC)	- assessed WMFT before and after treatment - the MDC, at 90% confidence interval (MDC_{90}) was calculated from the standard error of measurement to indicate a real change for individual patient	- The FM-UE was 7.2 (10.9% of maximum scores [66]) (Hsueh et al. 2008). - The S-FM-UE was 1.5 (12.2% of maximum scores[12]) (Hsueh et al. 2008).

2.3.2.3 Selection of outcome measurement of upper limb functional activity (ULFA)

A starting point for selecting the clinical outcome measure was to identify the measure, which clearly assesses the activity level of upper limbs, according to the ICF definition. The criteria that were considered to select appropriate outcome measurements were:

- the measure includes everyday tasks using whole arm reaching and hand manipulation of real life objects.
- the measure must be sensitive to differences in ULFA during two to 26 weeks.
- the measure can be completed within 30 minutes.
- the measure has been thoroughly evaluated for validity and reliability and also has no substantial floor and/ or ceiling effect.

The Nine-Hole-Peg-Test (NHPT) (Mathiowetz et al. 1985b), Action Research Arm Test (ARAT) (Lyle 1981), Arm Motor Ability Test (AMAT) (McCulloch et al. 1988), Box and Blocks Test (BBT) (Mathiowetz et al. 1985a), Chedoke Arm and Hand Activity Inventory (CAHAI) (Barreca et al. 2015), Jebsen Taylor Hand Function Test (Jebsen et al. 1969), Motor Activity Log (Taub et al. 1993), Stroke Rehabilitation Assessment of Movement-Mobility Subscale (STREAM) (Daley et al. 1999), Frenchay Arm Test (FAT) (Heller et al. 1987), Stroke Upper Limb Capacity Scale (SULCS) (Roorda et al. 2011) and Wolf Motor Function Test (WMFT) (Sullivan et al. 2013) have all been found to yield standardised measurements of ULFA.

Measurements that focus on assessment of manual dexterity (e.g. NHPT (Mathiowetz et al. 1985b) and BBT (Mathiowetz et al. 1985a)), and hand function (e.g. Jebsen Taylor Hand Function Test) have been excluded since they assess hand and finger movement rather than whole upper limb function. The ARAT (Lyle 1981) contains tasks using arm reaching and hand manipulations; however those tasks are not everyday tasks. In addition, the ARAT showed notable floor effects (Hsueh and Hsieh 2002). Taken together, the ARAT was excluded. The Frenchay Arm Test (Heller et al. 1987), the AMAT (O'Dell et al. 2011) and the CAHAI (Barreca et al. 2004) were excluded since they involve contributions from two arms and therefore do not focus on ability of paretic arm. The STREAM was excluded since there was large floor effects

and large ceiling effects for assessments at admission and at the time of discharge, respectively (Hsueh et al. 2006). The NHPT, and the FAT, also suffer from a 'floor effect', with more than 65% of cases scoring zero at the initial stage of stroke (less than 1 month) (Sunderland et al. 1989). The Motor Activity Log (Taub et al. 1993) was also excluded because a self-reported questionnaire is not consistent with the context of our study, which aim to investigate participants' ULFA objectively. In addition, the self-reported questionnaire may be limited by reliability and validity issues (Shephard 2003).

The Stroke Upper Limb Capacity Scale (SULCS) (Roorda et al. 2011) has recently been developed to assess activity level of ULFA according to the ICF. This assessment presented with good psychometric properties (Roorda et al. 2011) and good inter-rater reliability and concurrent validity (correlation with the ARAT and Rivermead Motor Assessment (RMA)) (Houwink et al. 2011). The tasks of assessment are everyday tasks. However, it has not been evaluated in stroke patients who are more than three months. Therefore, SULCS was not selected to be used.

An original version of WMFT consists of 21 items (Wolf et al. 1989) and the widely used version consists of 17 items (Morris et al. 2001) for 3 parts of this measurement: (1) timing, the speed at which functional tasks can be completed; (2) functional ability, the movement quality when completing the tasks; and (3) strength, the ability to lift against gravity. Two items of the widely used version are simple measures of strength, which is motor impairment. Although the WMFT consists of some tasks that could be considered at impairment level, it has everyday tasks using real life objects that assess the whole ULFA. The WMFT was assessed for the thoroughness with which its reliability, validity and responsiveness have been reported in the literature. The WMFT is the one from six measurements (FM, ARAT, BBT, CAHAI, WMFT and ABILHAND) that was recently reviewed to demonstrate high level of measurement quality and clinical utility. It is recommended for evaluation of ULFA after stroke (Murphy et al. 2015). Taken together, the WMFT was chosen to measure ULFA in our study.

An extensive review into WMFT has been conducted. The psychometric and administrative properties of the WMFT, the modified WMFT and the Streamlined WMFT (SWMFT) are presented in Table 2.1. Construct validity of the WMFT was

demonstrated as an ability to distinguish between stroke impaired and unimpaired participants ($p < 0.001$) (Wolf et al. 2001). Woodbury et al. (2010) suggested that the WMFT item structure implies that all items measure a single UE motor function construct (Woodbury et al. 2010). The WMFT is good to predict improvement of the Fugl-Meyer Motor Scale (FM) ($r_s = -0.68$ to -0.54 , $p < 0.02$) (Wolf et al. 2001) and the Stroke Impact Scale (SIS) ($r_s = 0.64$ and 0.56 , $p < 0.01$) (Wu et al. 2011). Moreover, the WMFT has excellent association with the other standard measurement (ARAT) (Nijland et al. 2010a). The WMFT has been found to be an outcome measure capable of discriminating the upper limb motor function of the individuals with stroke into different functional groups (Ang and Man 2006). The inter-rater reliability, test-retest reliability and internal consistency of the WMFT are excellent (Morris et al. 2001; Wolf et al. 2001; Nijland et al. 2010a). There was modification of the WMFT, which involved decreasing the functional ability scoring from 6 to 5-point scoring scale. The modified WMFT provided excellent concurrent validity (correlate with FM), inter-rater reliability and test-retest reliability for people with chronic mild to moderate UE hemiparesis (Whitall et al. 2006). Minimal detectable change (MDC) at 90% confidence interval (CI) of the WMFT was suggested to be 4.36 seconds for the performance time (WMFT time) and 0.37 points for the functional ability scale (WMFT FAS) by Lin et al. (2009). The study by Lin et al. (2009) also reported clinically important differences (CID) of the WMFT as 5 to 2 seconds on the WMFT time and from 0.2 to 0.4 points on the WMFT FAS. Lin et al. (2009) investigated MDC and CID in the WMFT version that contains 15 function-based tasks and 2 strength-based tasks. The maximum time allowed to complete an item is 120 seconds. A six point ordinal scale was used for functional ability scoring. Fifty-seven participants who were six months after stroke were recruited to receive 1 of the 3 treatments for 3 weeks. The WMFT was assessed before and after treatment. The MDC, at 90% CI was calculated from the standard error of measurement. The results of the study by Lin et al. (2009) have to be interpreted with caution because their study was not adequately powered. In addition, the CID results could apply to only participants who were getting better and not those getting worse.

Generally, the time taken to administer the WMFT ranges from 30-45 minutes. The WMFT was streamlined to reduce the burden of administration and provide the most relevant information about recovery potential (Bogard et al. 2009).

The SWMFT could be completed within 15 minutes. According to a study by Bogard et al. (2009), there are two versions of the SWMFT for use with sub-acute patients (SWMFT-S) (three to nine months) and chronic patients (SWMFT-C) (more than 12 months). The SWMFT-S consists of six tasks: hand to table, hand to box, reach and retrieve, lift can to mouth, lift pencil from table, and fold towel; these tasks evaluate performance time and the patient's functional ability scale. There are six levels of functional ability ranging from zero (does not attempt with involved arm) to five points (movement appears to be normal) (Bogard et al. 2009). Wu et al. (2011) investigated validity and responsiveness of the SWMFT in 64 stroke participants who were three to 10 months. The SWMFT was conducted in the participants before and after receiving three-week intervention programme. They observed that the SWMFT presented good predictive validity as it was associated with the FM and SIS at post-treatment ($r_s=0.68$ and 0.64 $p<0.01$). It appeared that the SWMFT exhibited slightly better correlation with the criterion measures than did the original scale (Wu et al. 2011). Concurrent validity of the SWMFT was good (correlation with the FM, and the SIS hand function ($r_s \geq 0.51$, $p < 0.01$)). There was comparable responsiveness of the SWMFT (post-treatment score of SWMFT was statistically significant different from pre-treatment score ($p<0.01$)) (Wu et al. 2011). However, only sub-acute participants were studied in their research. Future research needs to address the issue of applicability of the SWMFT in other stages of stroke. Subsequently, Chen et al. (2012) investigated test-retest reliability and internal consistency for SWMFT-S and SWMFT-C. Ninety-seven chronic and 75 sub-acute stroke participants with mild and moderate ULFA were recruited. The test-retest reliability for SWMFT-S was 0.89 and for SWMFT-C was 0.91. The internal consistency of SWMFT-S and SWMFT-C was 0.91 (Chen et al. 2012). Nevertheless, people with severe stroke are needed to be included in future research to assess the reliability in severe stroke participants. In addition, a longitudinal study has not been conducted to track changes of SWMFT within the participant over time.

Both WMFT and SWMFT are also have good validity and reliability. Nevertheless, our study was conducted with people who may have poorer tolerance to perform a series of tests (the wrist rig and ULFA tests). The SWMFT that takes shorter period of time to administer than the original version would be appropriate. Moreover, we studied stroke participants during the first 26

weeks; therefore, it was decided that the SWMFT-S was selected as an appropriate outcome measure.

Table 2.2 Measurement properties of the WMFT, modified WMFT and SWMFT

Criteria	Methodology of testing	Results
Construct validity	Wilcoxon signed rank (paired sample) test	- The Wolf Motor Function Test (WMFT) scores were different ($p<0.001$) between stroke and healthy groups (Wolf et al. 2001).
Content validity	confirmatory factor analysis (CFA)* * a statistic to test a relationship between observed variables and their underlying latent constructs exists	- The WMFT had a statistically significant relationship with overall improvement in the Extremity Constraint Induced Therapy Evaluation (EXCITE) trial, which demonstrated that the WMFT items measure a single construct (Woodbury et al. 2010).
Predictive validity	- the WMFT scores at baseline and the scores on the criterion measures at follow up were assessed by examining the association with Spearman rank correlation coefficient between (r_s)* *the strengths of the relationship were classified as excellent ($r_s >0.75$), good ($r_s =0.5-0.75$), fair ($r_s =0.25-0.5$), and low ($r_s <0.25$) (Wu et al. 2011)	- The WMFT was related to the FM (by two raters) ($r_s=-0.68$ to -0.54 , $p<0.02$) (Wolf et al. 2001). - The WMFT was associated with the FM and the SIS ($r_s=0.64$ and 0.56 $p<0.01$) (Wu et al. 2011). - The streamlined WMFT(SWMFT) was associated with FM and SIS ($r_s=0.68$ and 0.64 $p<0.01$) (Wu et al. 2011).

Criteria	Methodology of testing	Results
Concurrent validity	- Spearman rank correlation coefficients	<ul style="list-style-type: none"> - The WMFT FAS correlated with total score of the ARAT ($r_s = 0.86$, $p < 0.01$) (Nijland et al. 2010a). - The WMFT time score correlated with total score of the ARAT ($r_s = -0.89$, $p < 0.01$) (Nijland et al. 2010a). - The modified WMFT was related with FM ($r_s = 0.86$ to 0.89) (Whitall et al. 2006). - The SWMFT was related with the FM, and the SIS hand function ($r_s \geq 0.51$, $p < 0.01$) (Wu et al. 2011).
Discriminant validity	discriminant analysis	<ul style="list-style-type: none"> - The WMFT can classify 86.7% of original grouped cases into different levels of the Brunnstrom stages of recovery (Ang and Man 2006).
Inter-rater reliability	ICC	<ul style="list-style-type: none"> - The WMFT was ICC ≥ 0.95 (Wolf et al. 2001; Nijland et al. 2010a). - The WMFT time score was ICC ≥ 0.97 and of the WMFT FAS was ICC ≥ 0.88 (Morris et al. 2001).
Test-retest reliability	ICC	<ul style="list-style-type: none"> - The WMFT time score was ICC=0.90 and of the WMFT FAS was ICC=0.95 (Morris et al. 2001).

Criteria	Methodology of testing	Results
		<ul style="list-style-type: none"> - The modified WMFT was $ICC \geq 0.97$ (Whitall et al. 2006). - The SWMFT for use with sub-acute patients (SWMFT-S) was $ICC = 0.89$ and for use with chronic patients (SWMFT-C) was $ICC = 0.91$ (Chen et al. 2012).
Internal consistency reliability	Cronbach's α	<ul style="list-style-type: none"> - Cronbach α value of the WMFT was ≥ 0.92 (Morris et al. 2001; Wolf et al. 2001; Nijland et al. 2010a). - Cronbach α values of the SWMFT-S and the SWMFT-C were 0.91 (Chen et al. 2012)..
Responsiveness	<ul style="list-style-type: none"> - evaluated changes from pre-treatment to post-treatment - The Wilcoxon signed rank test was performed to determine any statistically significant differences in mean change score (MCS). 	<ul style="list-style-type: none"> - Pre-treatment and post-treatment score of the SWMFT was statistically significant differences ($p < 0.01$) (Wu et al. 2011).
Floor and ceiling effects	The cut-off points for WMFT were below 4 points and above 71 points. Significant floor and ceiling effects were considered to be present if more than 20% of the patients fell outside the lower or upper	<ul style="list-style-type: none"> - No significant floor and ceiling effects were found on the WMFT: approximately 17% of the patients scored beyond the upper 5% limits, 5% of patients scored below the lower 5% limits (Nijland et al. 2010a).

Criteria	Methodology of testing	Results
	bound, respectively (Salter et al. 2005; Nijland et al. 2010a).	
Minimal detectable change (MDC)	- assessed WMFT before and after treatment - the MDC, at 90% CI (MDC_{90}) was calculated from the standard error of measurement to indicate a real change for individual patient	- The MDC_{90} of the WMFT was 4.36 for the WMFT time and 0.37 for the WMFT FAS (Lin et al. 2009).
Clinically important differences (CID)	- anchor-based and distribution-based approaches were used to triangulate the values of minimal CID.	- The minimal CID ranged from 1.5 to 2 seconds on the WMFT time score and from 0.2 to 0.4 points on the WMFT FAS (Lin et al. 2009).

The SWMFT has two outcome measures (FAS and time scores). We anticipated a large number of low function stroke patients who used maximum time. This resulted in a ceiling effect for the time scores. The researcher decided, as with the other studies (Turk 2011; Subramanian et al. 2013), to report only the FAS scores.

2.4 Predictors of ULFA recovery

This section provides a literature review for predictors of ULFA recovery. Muscle weakness, which has been suggested as a strong predictor of ULFA, is discussed first. Following that, other motor impairments, which can potentially predict ULFA, are considered. Finally, prediction of ULFA based on the baseline ULFA is reviewed.

2.4.1 Muscle weakness as a predictor of ULFA recovery

Several researchers determined muscle weakness as a lack of ability to move (or lack of AROM); they found simple movement of proximal or distal parts of an affected upper limb to be a powerful predictor of ULFA recovery (Katrak et al. 1998; Beebe and Lang 2009; Nijland et al. 2010b). AROM of shoulder and middle finger segments were measured at one month could predict ULFA (measured by a battery of standardised clinical tests comprising grip strength, pinch strength, ARAT, Jebsen Taylor Hand Function Test, the Nine Hole Peg Test and the Stroke Impact Scale-Hand dimension) ($R^2=0.65$ and 0.06 respectively; $p<0.05$) (Beebe and Lang 2009). Similarly, Nijland et al. (2010b) reported that the outcome of ULFA at six months could be predicted by voluntary extension of fingers and abduction of shoulder on day two ($R^2=0.98$; $p<0.05$). In contrast, two studies found that upper limb voluntary movements do not adequately predict ULFA. Katrak et al. (1998) found that stroke patients who could shrug the hemiplegic shoulder at initial assessment (mean = 11 days, range 0-23 days) were more likely to show good recovery of hand movement (measured by the Hand Movement Scale) at 1, 2, and 3 months post stroke (R^2 ranged from 0.13 to 0.14; $p<0.5$, respectively). Prager and Lang (2012) found that the initial shoulder and wrist AROM explained only 28% of the variance in ULFA at three months.

The difference in results may be explained by the different severity levels of stroke participants in each study. A good prediction of ULFA through upper limb AROM was found only in patients who exhibited some AROM at the baseline assessment (Nijland et al. 2010b). Based on the same measurement, the prognostic information provided by AROM at one month (Beebe and Lang 2009) was substantially greater than at a few days (Prager and Lang 2012). Taken together, initial voluntary movement of the upper limb, which was assessed between two and four weeks, is a good predictor of ULFA recovery.

Muscle weakness, as measured by the Motricity Index (MI), has also been shown to be a strong predictor of ULFA recovery (Kwakkel et al. 2003; Au-Yeung and Hui-Chan 2009; Kong and Lee 2013). A study in 57 participants (within five days) found that upper limb MI scores at weeks one, two, three, four and two months, are statistically significant predictors of ULFA at six months (odds ratio ≥ 1.04 , 95% CI 1.02-1.07, $p=0.001$) (Au-Yeung and Hui-Chan 2009). This finding is consistent with studies involving more than 100 participants by Kwakkel et al. (2003) and Kong and Lee (2013). Kwakkel et al. (2003) suggested that upper limb MI scores at 7.3 ± 2.8 days statistically significantly predicted ARAT scores (odds ratio 28.33 95%CI 9.18 to 87.46, $p<0.001$). Kong and Lee (2013) found that ULFA recovery, as measured by the MAS score at 12 months, was predicted by upper limb MI scores at 7.8 ± 3.8 days (odds ratio 1.54, 95% CI 1.13 to 2.10).

The measurement of muscle weakness, by MVC, appears to be precise and easy to monitor, particularly with reference to any improvement. It has been used for assessing an improvement of muscle weakness for stroke patients in several studies (Renner et al. 2009; Harris and Eng 2010; Conrad and Kamper 2012). However, a small number of research studies examined the predictive power of ULFA through MVC. A previous study by Higgins et al. (2005) found that grip strength at the first week could not explain any portion of ULFA (measured by BBT) at five weeks. This finding is consistent with a previous study by Wagner et al. (2007c), which found that a composite upper limb muscle strength measure (shoulder, elbow, wrist flexor/extensor and grip strength measured by MVC) at the acute time-point (8.7 ± 3.6 days) explained a very small variance of ULFA (measured by ARAT) at the sub-acute time-point (108.7 ± 16.5 days) ($R^2=0.2$, $p \leq 0.01$).

The difference in results may be explained by the time course recovery of MVC. Evidence suggests that MVC is low at 2 weeks (Ada et al. 2006). The recovery rate of upper limb muscle weakness considerably increased for three months (Ada et al. 2006; Verheyden et al. 2008). The measurement of MVC at one-week following stroke appears to be too early to be able to distinguish the improvement in muscle weakness.

From the above findings, the degree of muscle weakness, either measured by simple movement or MVC, is a good predictor of ULFA recovery, especially for people who regained their ability to move at initial post stroke. Obviously, if the patient cannot move the upper limb at all or can only move minimally, it is reasonable to conclude that their ULFA was poor (Lang et al. 2013). There is a lack of studies investigating predictors of ULFA based on muscle weakness measured by simple movement at the wrist. In addition, an investigation of muscle weakness measured by MVC was also limited. Therefore, predictors of ULFA recovery through muscle weakness, as measured by MVC and AROM were currently investigated.

2.4.2 Other upper limb motor impairments as potential predictors of ULFA

Most of the motor impairments of stroke patients appear to exist in combination (Lang et al. 2013). Although, as suggested above, muscle weakness is a strong predictor of ULFA recovery (Katrak et al. 1998; Smania et al. 2007; Beebe and Lang 2009; Nijland et al. 2010b; Prager and Lang 2012), a crucial issue in upper limb assessments after stroke is how the presence of various other impairments contributes to loss of ULFA (Lang et al. 2013). Current evidence suggests that ULFA, following stroke, is related to various upper limb impairment not just muscle weakness.

Numerous studies have investigated the relationship between upper limb impairment and upper limb functional activity (ULFA). The findings suggest that various motor impairments contribute to ULFA limitation, such as loss of MCA (Canning et al. 2004; BurrIDGE et al. 2009; Turk 2011), muscle weakness (Chae et al. 2002b; Canning et al. 2004; Ada et al. 2006; BurrIDGE et al. 2009; Turk 2011), spasticity (Ada et al. 2006; Turk 2011), coactivation (Chae et al. 2002b; Turk 2011), and muscle contracture (Ada et al. 2006; Malhotra et al.

2011; Turk 2011). This section provides a review of the literature where the relationship between upper limb impairment and ULFA is discussed.

The method used for reviewing the literature on the relationship between upper limb impairment and upper ULFA included retrieving the literature and screening the relevant studies. The electronic search was performed via CINAHL and Medline on literature published between 1983 and 2013. The search strategy used the keywords in various combinations. There are criteria for screening that ensure studies are relevant to the topic under investigation. The keywords and criteria are described in Table 2.3. Relevant academic journal, books, and dissertations or theses related to, or informed by, the keywords were used as the references.

Table 2.3 Keywords and criteria for screening a relevant study

Keywords				Inclusion criteria	Exclusion criteria
stroke or cerebrovascular disease	AND	muscle weakness or muscle strength or motor control accuracy or dexterity or spasticity or coactivation or cocontraction or contracture	AND upper limb or upper extremity	studies that examined the associations between upper limb motor impairment, and ULFA	1. predictive study 2. studies about the effect of intervention on upper limb motor impairment 3. studies about the effect of intervention on ULFA 4. studies that measured motor control or dexterity by the clinical scale (such as Nine hole peg test, Action Research Arm test) 5. studies that measured spasticity by the clinical scale (original or modified Ashworth Scale, Tardieu scale) 6. studies that measured contracture without muscle activity monitoring

Figure 2.1 presents the flowchart used to identify studies for inclusion. A total of 5,978 articles was retrieved using the detailed search strategy. After screening the inclusion and exclusion criteria, there were 6 studies, which met inclusion. Furthermore, one thesis, which also met the criteria, was used as the reference. The summary information, strengths and weaknesses of selected papers is described in Table 2.3.

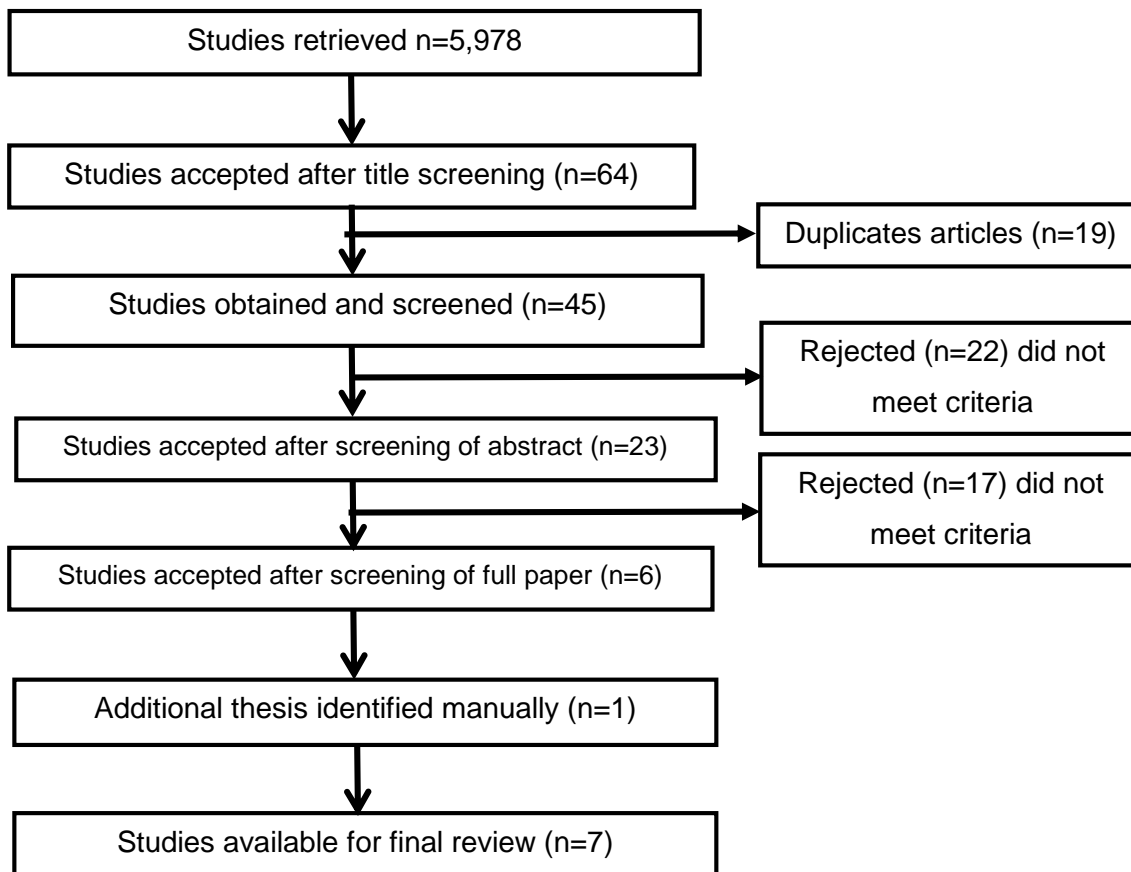


Figure 2.1 Flowchart used to identify studies

Table 2.4 Summary information, strengths and weaknesses of selected papers

Author (year)	Motor impairments	Study design	Joint	Sample size	Time from stroke	Key findings	Strengths of the study	Weaknesses of the study
Chae et al. (2002a)	delayed muscle onset timing	cross sectional	wrist	26	6 months	- delayed muscle onset timing was associated with ULFA	- compared muscle onset timing between paretic and non-paretic arm)	- a reliability of impairment measures was not reported
Chae et al. (2002b)	muscle weakness and coactivation	cross sectional	wrist	26	6 months	- muscle weakness and coactivation were associated with ULFA	- compared muscle weakness and coactivation between paretic and non-paretic arm)	- measurements of muscle weakness, muscle onset timing and coactivation were conducted at single assessment session - measured coactivation and muscle onset timing at wrist joint during isometric contraction, which may be less correlated with ULFA than isotonic contraction. - the study was not adequately powered
Canning et al. (2004)	muscle weakness, and MCA	longitudinal (27 weeks)	wrist	22	2 or 3 weeks	- muscle weakness and MCA were associated with ULFA	- longitudinal study design allowed evaluation of relationships between motor impairments	- the validity and reliability of impairment measures were not reported

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Author (year)	Motor impairments	Study design	Joint	Sample size	Time from stroke	Key findings	Strengths of the study	Weaknesses of the study
							and ULFA over time (6 months)	- measured only by sine tracking task, which may not best represent ULFA than discrete movement - the study was not adequately powered
Ada et al. (2006)	muscle weakness, spasticity and contracture	longitudinal (52 weeks)	elbow	27	2 weeks	- muscle weakness, spasticity, and contracture were associated with ULFA - muscle weakness was more associated with ULFA than spasticity and contracture	- longitudinal study design allowed evaluation of relationships between motor impairments and ULFA over time (1 year) - participants exhibited a wide range of activity level to provide as broad a representation of stroke	- the validity and reliability of impairment measures were not reported - the study was not adequately powered
Burridge et al. (2009)	muscle weakness, AROM, MCA, spasticity, coactivation and non-neural stiffness	cross sectional	wrist	17	1.1 to 13 years	- muscle weakness, MCA, and AROM were associated with ULFA	- construct validity to distinguish between stroke and healthy participants, within-day test-retest reliability, inter-rater agreement and MDC of the impairment measures have been reported (Turk et al. 2008)	- the study was not adequately powered

Author (year)	Motor impairments	Study design	Joint	Sample size	Time from stroke	Key findings	Strengths of the study	Weaknesses of the study
Malhotra et al. (2011)	spasticity and contracture	longitudinal (36 weeks)	wrist	30	3 weeks (range 1–5)	- ULFA may not be affected by spasticity - loss of ULFA may be the contributor to contracture	- longitudinal study design allowed evaluation of relationships between motor impairments and ULFA over time (6 months)	- the study was not adequately powered - the velocity used during stretching was uncontrolled, which may result in unreliable measure - measurements of spasticity and contracture only - the participants were homogenous, hence they were not fully representative of the stroke population
Turk (2011) [PhD thesis]	muscle weakness, AROM, MCA, spasticity, coactivation, contracture and non-neural stiffness	cross sectional	wrist	13 (acute); 13 (chronic)	0.7 to 4 months (acute); 12-91 months (chronic)	- muscle weakness, MCA, coactivation, contracture were associated with ULFA	- validity of motor impairments to distinguish between acute and chronic stroke and healthy participants were reported - between day test-retest reliability and minimal detectable change of motor impairments were reported for sine TI, step TI, path length, extension AROM,	- the study was not adequately powered - no test-retest reliability evaluation for spasticity and non-neural stiffness tests

Chapter 2

Author (year)	Motor impairments	Study design	Joint	Sample size	Time from stroke	Key findings	Strengths of the study	Weaknesses of the study
							extensor IF, extensor onset timing, sine CI, step CI and extension PROM	

Canning et al. (2004) found the contribution of elbow MCA (termed as “dexterity”, measured by tracking tasks) to ULFA (measured by modified MAS) was statistically significant at three and five week ($R^2=0.14$, $p<0.01$). In the chronic stage of stroke, wrist MCA was strongly correlated with ARAT scores ($r=0.710$, $p=0.003$) (Burridge et al. 2009). The tracking tasks, which were used to measure MCA in these previous two studies, were rhythmic movements. It is possible that rhythmic movements are less related to normal functional use of the arm. Discrete movements, which involve moving to the different points of displacement with variable rest periods in between, appears to be a closer approximation of the day-to-day activities of the upper limb. Turk (2011) examined MCA using sine tracking tasks (rhythmic movement to follow the target) and step tracking tasks (discrete movement to follow the target). The relationship between sine TI (note: greater index value is better) and the modified Wolf Motor Function Test (mWMFT) scores in the acute stroke group approached significance ($r=0.54$, $p=0.06$). A step TI (note: lower index value is better) was less related to mWMFT scores than a sine tracking task ($r=-0.37$, $p=0.21$). There was a very strong association between MCA and ULFA in the chronic group (sine tracking $r=0.863$, $p<0.001$; step tracking $r=-0.835$, $p<0.001$). Although there was no statistical relationship between the step TI and ULFA in the acute stroke group, a strong relationship was shown in the chronic group. This might be due to lack of homogeneity of the participants in these two stroke groups. The stroke participants in the chronic group had higher ULFA than the acute stroke group at baseline. In addition, there was only a small number of participants ($N=13$) (Turk 2011). A study with a homogeneous and a larger sample size may help to confirm this finding.

It has been observed that stroke patients present with delayed muscle initiation of their paretic side (Chae et al. 2002a; Wagner et al. 2007b; Seo et al. 2009; Hughes et al. 2010; Turk 2011). A statistical association between delayed wrist extensor muscle onset timing and mWMFT was found in the chronic stage of stroke ($r=-0.647$, $p=0.031$) but not in the acute stage ($r=-0.273$, $p=0.367$) (Turk 2011). The results of a study by Turk (2011) was consistent with a study by Chae et al. (2002a), which found a strong association between delayed wrist extensor muscle onset timing and ULFA measured by AMAT ($r\leq -0.74$, $p<0.01$) in chronic stroke participants. However, there is another study, which shows that changes in anterior deltoid and wrist

extensor muscle onset timing (note: greater index value is better) were correlated with the changes in reaching performance ($r=0.53$, 0.65 respectively; $p<0.05$) in the acute to sub-acute phase of stroke (from 9 to 109 days) (Wagner et al. 2007b). Therefore, there is some evidence that delayed muscle onset timing is associated with ULFA in both the acute and chronic phases, but further research is warranted.

The debate is still on-going about the association between spasticity and ULFA (Ada et al. 2006; Burridge et al. 2009; Malhotra et al. 2011; Turk 2011). This literature review excluded a study, which assessed spasticity using the original or modified Ashworth scale (AS, modified AS), since the usefulness of these assessments has been questioned. The modified AS showed low validity and reliability (Fleuren et al. 2010; Marciniak 2011). Spasticity, when measured by use of the neurophysiological measurement appears to be more precise than the modified AS, since the former can distinguish between neural or non-neural stiffness (Alibiglou et al. 2008). Previous studies have demonstrated that there was no relationship between spasticity and ULFA from the acute (Malhotra et al. 2011) to the chronic phase of stroke (Burridge et al. 2009; Malhotra et al. 2011). However, the study by Turk (2011) showed a strong association between SI (note: greater index value implies high stretch response) and the modified Wolf Motor Function Test (mWMFT) scores in the chronic stroke group ($r=-0.720$, $p=0.008$). It could be observed that there were differences in methods to quantify spasticity between the study by Turk (2011), Burridge et al. (2009) and Malhotra et al. (2011). Malhotra et al. (2011) measured spasticity by quantifying muscle activity during brisk stretch (within 1 second). However, this method was difficult to control velocity of passive wrist movement which may resulted in the unreliability of this method. Burridge et al. (2009) controlled frequency of passive wrist movement for measuring spasticity at 1.5 Hz. Nevertheless, this frequency of passive movement in a study by Burridge et al. (2009) may be unable to elicit stretch reflex. The study by Turk (2011) measured spasticity during passive movement at 1.5 Hz and 3.5 Hz, respectively and found that at 1.5 Hz could not differentiate between stroke and healthy participants. A one-year observational study by Ada et al. (2006) found the contribution of spasticity (measured by stretch-evoked EMG) to ULFA (measured by the Motor Assessment Scale) was statistically significant at 17 weeks ($R^2=0.10$, $p=0.04$). Randomised controlled trial studies suggested

that people with stroke who exhibited decreased spasticity presented improvement in ULFA (Sun et al. 2010; Wu et al. 2013). Wu et al. (2013) evaluated the efficacy of transcranial direct current stimulation (tDCS) on decreasing upper limb muscle tone after stroke. Ninety participants were randomly assigned into active tDCS group or sham tDCS group. The modified AS, FM, and BI were measured at admission, after treatment, and after follow-up. After 4 weeks of treatment, decreasing of modified AS scores at elbow and wrist have been found only in the active tDCS group and the decrease was maintained at 4 weeks follow-up. The FM and the BI scores were improved in both groups after treatment and at follow-up. Sun et al. (2010) investigated whether a combination of Botulinum toxin type A (BtxA) injection and modified constraint-induced movement therapy (mCIMT) improved spasticity and upper limb motor function more than BtxA plus conventional rehabilitation in chronic stroke patients with upper limb spasticity. Thirty-two participants were randomly assigned to receive BtxA plus mCIMT (combination group) or BtxA plus conventional rehabilitation (control group) for 2 hours/day, 3 days/week for 3 months. The MAS and Action Research Arm Test (ARAT) were evaluated before BtxA injection, at 4 weeks, 3 months, and 6 months post-injection. A Motor Activity Log (MAL) was evaluated before injection, at 3 months, and 6 months post-injection. Spasticity of all participants decreased at 4 weeks and 3 months assessments with no statistically significant difference between groups. The combination group showed significantly greater improvements in elbow, wrist, and finger spasticity ($p=0.019$, $p=0.019$, and $p<0.001$, respectively), MAL ($p<0.001$) and ARAT ($p<0.001$) than the control group at 6-month post-injection. However, the assessment for spasticity in these two studies was conducting using the modified AS, which exhibited insufficient validity and reliability. In addition, ULFA measurement in the study by Wu et al. (2013) assessed at impairment level rather than activity level according to the ICF. Therefore, it is interesting to debate whether spasticity correlates with ULFA and whether it predicts ULFA.

The degree of coactivation during an isometric test (note: negative value is indicating reciprocal activation; positive value is indicating coactivation) was statistically associated with the AMAT scores ($r=-0.72$ to -0.62 , $p<0.001$) of chronic stroke patients (Chae et al. 2002b). This finding is consistent with a study by Turk (2011), which provided a strong relationship between

coactivation (note: negative value is indicating reciprocal activation; positive value is indicating coactivation) and mWMFT scores (sine tracking coactivation $r=-0.786$, $p=0.001$, step tracking coactivation $r=-0.697$, $p=0.012$) in the chronic stroke group. Such an association was not found in the acute stroke group. Similarly with delayed muscle onset timing and spasticity, there is no study that has investigated prediction of ULFA based on the degree of coactivation.

Although muscle contracture is a secondary motor impairment, some studies suggested that it occurs at an early stage of stroke (Ada et al. 2006; Turk 2011). A combination of muscle weakness, spasticity and contracture was statistically significantly associated with ULFA during the first year following stroke (mean $R^2=0.50$, range=0.24 to 0.68, $p=0.001$ to 0.08) (Ada et al. 2006). A recent study also found a strong correlation between wrist flexor contracture and ULFA in acute stroke patients ($r=0.624$, $p=0.02$) (Turk 2011). In addition, wrist muscle contractures are more likely to develop in stroke patients who have not recovered ULFA (Malhotra et al. 2011).

Overall, the research conducted tests in one plane of movement e.g. at the elbow or the wrist joints, which are simple movements for stroke participants. Based on the above studies, MCA, delayed muscle onset timing, spasticity and coactivation, and muscle contracture, were found to be related, to greater or lesser degrees, to ULFA. The assessment tools used in previous studies (Chae et al. 2002a, b; Canning et al. 2004; Ada et al. 2006; Malhotra et al. 2011) could not measure all those motor impairments in a single assessment session. This may result in time-consuming and inefficient measurement, for example parameters may be measured by more than one tool. In particular, the time taken to complete a comprehensive assessment may make it impractical to assess the motor impairments of early sub-acute stroke patients, as they may not be able to tolerate undergoing numerous tests. The wrist rig overcomes this problem by measuring a wide range of wrist impairments in one streamlined assessment in a single assessment session (Turk et al. 2008; Turk 2011). In addition, validity and reliability of the wrist rig have been reported (Notley et al. 2007; Turk et al. 2008; Turk 2011). Therefore, it was decided, for pragmatic reasons, to use the wrist rig in our study. The relatively small number of participants recruited for a study by BurrIDGE et al. (2009) and Turk (2011) resulted in limited strength of the statistical findings. A larger sample is needed to confirm the results of these two studies cited immediately above. A

study to investigate predictors of ULFA based on motor impairments should be conducted for up to six months, which is the time that ULFA reached a plateau (Ada et al. 2006; Verheyden et al. 2008; Kong and Lee 2013).

2.5 Summary of findings

This section summarises the findings from the literature review, which lead to the research questions. Evidence from the literature suggests that multiple motor impairments contribute to the prediction of ULFA recovery. Baseline muscle weakness (Kwakkel et al. 2003; Au-Yeung and Hui-Chan 2009; Beebe and Lang 2009; Nijland et al. 2010b; Kong and Lee 2013) is a strong predictor of ULFA recovery. Spasticity, MCA, delayed muscle onset timing, muscle coactivation and muscle contracture have yet to be determined as predictors of ULFA.

A considerable number of measurements have been used to assess upper limb motor impairment. There is currently no study that utilises a tool to assess various motor impairments in a single assessment session. The information gathered from assessing such motor impairments may be used for predicting ULFA recovery.

Taken together, a question of whether baseline upper limb impairment can predict ULFA recovery in the long term has not been fully addressed. A longitudinal observational study in this area is warranted.

Different motor impairments occur at different stages of stroke, and the clinical and neurological status of patients may be stable at different time points and unstable at others. Therefore, in this research baseline assessments were conducted at the first two, four, eight and 12 weeks.

2.6 Research questions

The overall aim of the research is to increase our understanding of the way in which people recover from upper limb impairment and regain ULFA following stroke; in particular, the way in which impairments impact on the recovery of ULFA.

To achieve this aim the following specific research questions are proposed;

1. Is the redesigned wrist rig reliable?
2. What is MDC for AROM, flexor and extensor IF, sine and step TI, path length, extensor onset timing, sine CI, SI, PROM and MTI?
3. Are there differences in wrist impairments and ULFA between healthy, sub-acute and chronic stroke groups in the Thai population?
4. How do upper limb impairment (measured by S-FM-UE), ULFA (measured by the SWMFT-S) and wrist impairments (measured in the redesigned wrist rig) change during the first 26 weeks following stroke?
5. What is the relationship between ULFA at 26 weeks and wrist impairments at two, four, eight, 12 and 26 weeks?
6. Which, if any, of the following wrist impairments: range of motion (flexion to extension AROM), muscle weakness (flexor and extensor IF), MCA (sine and step TI, path length), delayed muscle onset timing (extensor onset timing), spasticity (SI; flexor spasticity), coactivation (sine CI), muscle contracture (PROM; flexor contracture) and non-neural stiffness (MTI; flexor stiffness) can predict ULFA at 26 weeks?

2.7 Research objectives

1. Evaluate the test-retest reliability of wrist motor impairment indices measured by the redesigned wrist rig
2. Calculate MDC for each wrist motor impairment index
3. Determine the construct validity (defined as ability to distinguish between healthy, sub-acute and chronic stroke groups) of the wrist motor impairment indices (AROM, flexor and extensor IF, sine and step TI, path length, muscle onset timing, SI, sine CI, PROM and MTI) generated by the redesigned wrist rig
4. Quantify upper limb impairment (measured by S-FM-UE), wrist impairments (measured in the redesigned wrist rig) and ULFA (measured by SWMFT-S) at two, four, eight, 12 and 26 weeks
5. Identify any relationships between ULFA at 26 weeks and wrist impairments at baseline (two, four, eight, 12 and 26 weeks)

6. Identify which, if any wrist impairments (at two, four, eight and 12 weeks) can predict ULFA at 26 weeks

2.8 Summary of Chapter 2

This chapter has provided a detailed literature review covering the field of upper limb impairment, upper limb functional activity and predictors of ULFA recovery. A summary of the findings from previous studies is presented. The identification of the gaps in knowledge, the research objectives and research questions are detailed.

The next chapter informs the development of the redesigned wrist rig, which was used as the main outcome measurement tool.

Chapter 3: Development of a redesigned wrist rig

The redesigned wrist rig was used to measure wrist motor impairments. This chapter details the development of the redesigned wrist rig including its modifications, measurement properties, safety testing, calibration and usability.

3.1 Modifications of the redesigned wrist rig

The wrist rig was modified from the Strathclyde wrist rig (Pandyan et al. 1997) based on biomechanical and neuromechanical principles (Burridge et al. 2009; Turk 2011) for measuring wrist impairments. The wrist rig consists of an instrumented armrest attached to a chair, with a potentiometer (angle sensor) and strain gauges (force sensors) combined with surface electromyography (sEMG) (Figure 3.1). The original wrist rig was first redesigned by Turk (2011) as follows. The target display was changed from the computer screen at eye level to arm level (front of the armrest). The hand positioning was designed to be supported by an air splint (an inflatable cuff within a U-shaped thermoplastic splint). The elbow restraint, forearm support and strapping were designed to prevent movement of elbow, upper arm and forearm. The slip clutch was incorporated in the pivot joint and the strain gauge was built on the slip clutch. In addition, the electronics and connections for signal acquisition were organized (Turk 2011).

The wrist rig was further redesigned to be used in our study. The electronic and mechanical elements of the wrist rig were similar to the previous version created by Turk (2011). Currently, there were physical changes of the redesigned wrist rig to make it friendly to be used in the hospital and able to be transported. The material is stronger and more robust than the older version. The rig can be fixed to a standard wheelchair and can be easily removed. The software is more user-friendly than the previous version's.

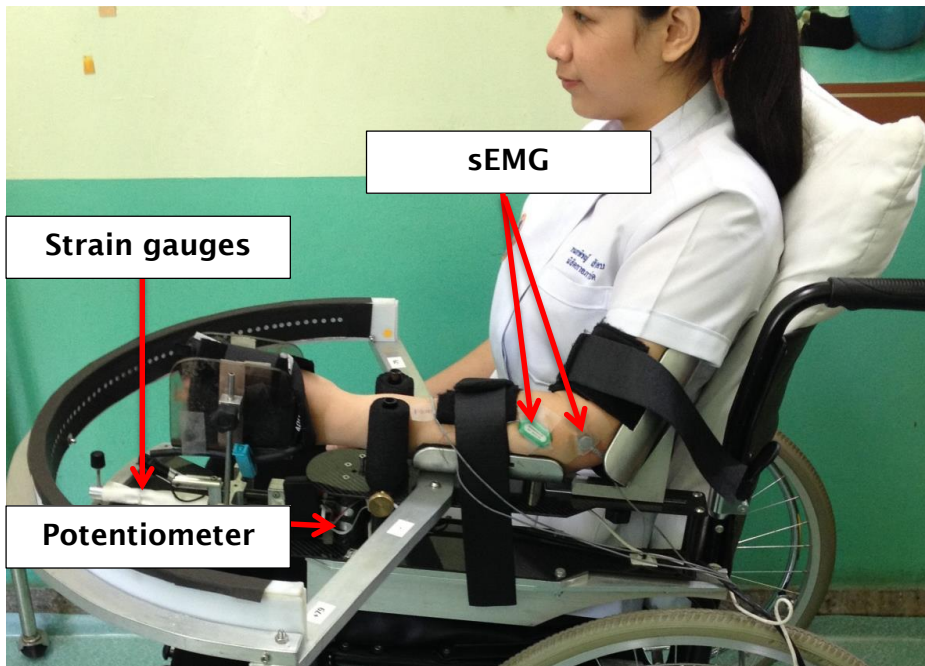


Figure 3.1 redesigned wrist-rig attached to a standard wheelchair

The target LEDs display of the redesigned wrist rig was modified from red (Turk 2011) to blue light and a red light laser pointer was placed above the lever arm (Figure 3.2). These modifications enable the participants to see the target more clearly than was possible with the previous version of the wrist rig.

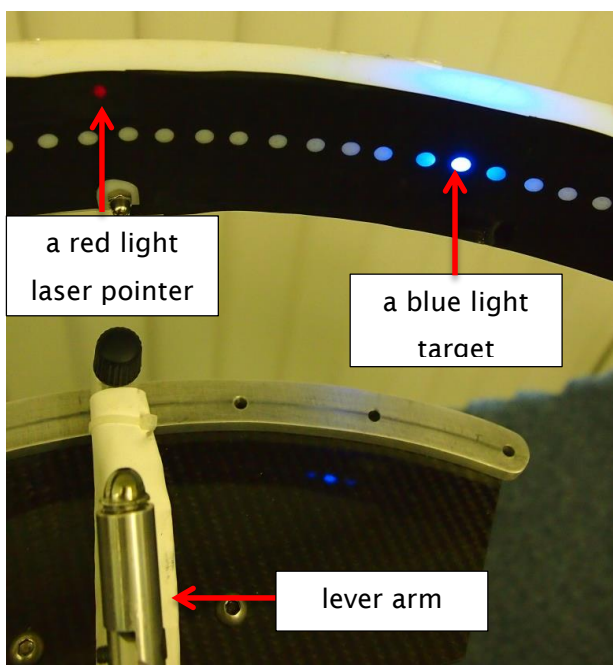


Figure 3.2A blue light target and a red laser pointer

3.2 Measurement properties of the wrist rig

The wrist rig was developed and tested for its measurement properties to ensure that it was valid and reliable to be used in previous research (Notley et al. 2007; Turk et al. 2008; Turk 2011). The measurement properties of the wrist rig are demonstrated in Table 3.1. Notley et al. (2007) investigated three different indices (root mean square error, cross correlation and signal-to-noise ratio) to quantify motor control accuracy (MCA) during sine tracking task. Ten chronic stroke participants and 12 age-matched healthy participants were recruited. The test was conducted three times: first by the assessor 1, then by the assessor 2 and then a second time by the assessor 1. Inter-rater reliability was assessed by Bland and Altman limits of agreement. Test-retest reliability was evaluated by the reliability coefficient (coefficient R). Concurrent validity was evaluated as the Pearson correlation coefficients between three indices and ULFA assessed by the Action Research Arm Test (ARAT). The Bland and Altman limits of agreement showed a good agreement between two assessors for all indices (good inter-rater reliability). The cross correlation demonstrated the greatest reliability coefficient (coefficient R of 91%) for test-retest reliability compared with root mean square error and signal-to-noise ratio methods. In addition, the cross correlation method was statistically significantly correlated with ARAT ($r=0.799$, $p=0.006$) (good concurrent validity). Therefore, the cross correlation method was determined as the method to quantify the MCA of wrist movement during sine tracking task.

Full assessments of the wrist rig impairment measures (sine TI, flexor modulation index (coactivation), wrist flexor and extensor IF, wrist flexion AROM, wrist extension AROM, SI and force angle index (non-neural stiffness)) were investigated for their reliability and validity and reported their MDC by Turk et al. (2008). They recruited 12 chronic stroke participants and 12 age-matched healthy participants. The paretic arm (impaired group) and dominant arm (unimpaired group) were tested in 3 sessions on the same day by 2 assessors. Test-retest reliability was examined by an intraclass correlation coefficient (ICC) and the Bland and Altman limits of agreement. Construct validity (defined as ability to distinguish between impaired and unimpaired groups) was determined by t-test. Test-retest reliability was excellent for all indices in the impaired group (ICC = 0.88-0.98). The Bland-Altman ranges

showed a good agreement between assessors (good inter-rater reliability). There were statistically significant differences between impaired and unimpaired groups for sine TI ($p=0.007$), wrist flexor IF ($p<0.001$), wrist extensor IF ($p<0.001$), wrist extension AROM ($p<0.001$) and SI ($p<0.001$). Hence, the wrist rig assessment had a good construct validity. The MDC for all indices were also reported.

Consequently, a step tracking task was developed to assess MCA. A correlation coefficient was selected to analyse coactivation during the sine and step tracking tasks. A correlation coefficient ranging between +1 and -1, with positive values indicating coactivation and negative values indicating reciprocal inhibition/activation. Construct validity of the negative impairment indices (sine and step TI, extension AROM, extensor IF and extensor onset timing), positive impairment indices (SI [spasticity] and sine and step CI); and secondary impairment indices (extension PROM and MTI [non-neural stiffness]) were evaluated in 26 stroke participants (13 sub-acute and 13 chronic) and 14 healthy participants (Turk 2011). All impairment indices were able to distinguish between impaired and unimpaired participants at the $p<0.05$ level of significance. The exceptions were made for the step CI and MTI ($p=0.558$ and 0.109 respectively). The step CI did not show any statistically significant differences between stroke and healthy groups. A possible explanation for this might be that healthy participants coactivated their muscle as a break during the step tracking task, in the same way as did the stroke participants. On the other hand, the sine CI showed clearer differences between the three study groups than the step CI. Therefore, we decided to assess only the sine CI. It was observed that the sub-acute stroke participants presented a significantly lower MTI than the healthy participants. Therefore, it is informative to investigate how these two indices change during the patients' recovery period from the sub-acute to the chronic phase.

Between-days test-retest reliability of the wrist rig was conducted in 17 stroke participants for negative impairment indices (sine and step tracking indices, extension AROM, extensor IF and extensor onset timing) and 13 stroke participants for positive (sine and step CI) and secondary (PROM) impairments. The Bland and Altman plots showed a good agreement between two days assessment except for the extension AROM and step CI. There was statistically significant difference between the first and the second day assessments for

extension AROM ($p < 0.05$), however the difference was small (4°) compared to the range of values (-52.3° to 51.2°). A statistically significant reduction in step CI from day 1 to day 2 ($p < 0.05$) suggested that stroke participants may use more reciprocal activation on the repeated day (Turk 2011), which is expected as a result of training (Prange et al. 2012). These findings further supported that the step CI had less reliable compared to the sine CI.

To summarise, the wrist rig impairment measures demonstrated good construct validity (ability to distinguish wrist impairments between stroke and healthy participants), excellent test retest reliability and repeatability (Turk et al. 2008; Turk 2011). However, test-retest reliability for the SI and MTI were not evaluated in the previous study by Turk (2011). In addition, construct validity, test-retest reliability of the wrist rig following its recent modifications had not been investigated. Therefore, reliability and matched pair studies of the redesigned wrist rig with adequate power was carried out as a part of this thesis. The MDC of the wrist motor impairment indices measured in the redesigned wrist rig were also investigated to provide the real change of each index during the 26 weeks recovery period of stroke participants (Chapter 6).

Table 3.1 Measurement properties of the wrist rig

Criteria Author (year)	Sample size	Validity	Reliability	Agreement between assessors	Minimal detectable change (MDC)
Notley et al. (2007)	10 chronic stroke participants and 12 healthy participants of similar age with stroke participants	- concurrent validity of 3 indices (root mean square error, cross correlation and signal-to-noise ratio) to quantify MCA during sine tracking task were investigated by calculating the correlation between indices and ULFA (assessed by ARAT) - cross correlation and signal-to-noise ratio were statistical significant correlated with ARAT ($r=0.799$, $p=0.006$ and $r=0.829$, $p=0.003$, respectively)	- a test-retest reliability was evaluated by coefficient R and 95% measurement ranges - cross correlation demonstrated greatest reliability coefficient (coefficient R of 91%)	- the Bland-Altman ranges showed no bias between assessors	not reported
Turk et al. (2008)	12 chronic stroke participants and 12 healthy participants of similar age with stroke participants	- there was statistically significant difference for sine TI ($p=0.007$), wrist flexor IF (IF)($p<0.000$), wrist extensor IF ($p<0.001$, wrist extension AROM ($p<0.001$) and SI ($p<0.001$) between impaired and unimpaired participants, thus representing good construct validity	- test-retest reliability was excellent for sine TI, flexor modulation index (coactivation), wrist flexor IF, wrist extensor IF, wrist flexion AROM, wrist extension AROM, SI and force angle index (non-neural stiffness) in the impaired group (ICC = 0.88-0.98)	- the Bland-Altman ranges showed no bias between assessors	- MDC of each motor impairments in the impaired group has been reported for sine TI (± 58 deegree ²), flexor modulation index (± 0.397), wrist flexor IF (± 21.73 Nm), wrist extensor IF (± 7.6 Nm), wrist flexion AROM (± 18.9 degrees), wrist extension AROM (± 27.0 degrees), SI (± 2.28) and force angle index (± 0.03)
Turk (2011) [PhD thesis]	13 acute and 13 chronic stroke	- construct validity was defined as ability to distinguish between stroke and healthy participants	- the Bland and Altman plots showed no evidence for a trend in difference between assessments for	not reported	- MDC of each motor impairments has been reported for sine TI (± 35.32 degree ²), step TI (± 1.88 degrees), path

Criteria Author (year)	Sample size	Validity	Reliability	Agreement between assessors	Minimal detectable change (MDC)
	participants and 14 healthy participants	- there were statistically significant differences of motor impairments between stroke and healthy participants (sine TI ($p<0.001$), step TI ($p<0.001$), path length ($p<0.001$), wrist extension AROM ($p<0.001$), wrist extensor IF ($p<0.001$), wrist extensor onset timing ($p<0.001$), sine CI ($=0.024$), SI ($p<0.001$) and wrist extension PROM ($p<0.001$))	sine TI, step TI, path length, extension AROM, extensor IF, extensor onset timing, sine CI and extension PROM - step CI showed trend toward less coactivation on day 2 assessment		length (± 0.014 degrees/sample), extension AROM (± 14.1 degrees), extensor IF (± 1.1 Nm), extensor onset timing (± 0.37 seconds), sine CI (correlation coefficient ± 0.61), step CI (correlation coefficient ± 0.34) and extension PROM (± 13.4 degrees)

3.3 Safety testing

The first version of the wrist rig system had met the required medical safety standard in place since 2010 (standard BS EN 60601-1). The control unit and power supply of the redesigned wrist rig have been recently tested and passed before data collection commenced for this research. Therefore, it can be concluded the wrist rig is safe to use with human subjects.

3.4 Calibrations of the wrist rig

Angle (potentiometer) and torque (strain gauge) were calibrated to ensure that the rig system and output data were valid and reliable. The calibration coefficients for each output (angle and torque) were calculated and input into a customised Excel spread sheet (Table 3.1). The Excel spread sheet was read by the specially designed Matlab® wrist rig software when processing signals and illustrating signals on graphs in appropriate units of measurement (degrees; Nm; mV). Angle and torque calibrations were carried out before data collection in the pilot study 1 and were re-calibrated every 2 days. Following that, the wrist rig was calibrated each time that it was transported to a new place or every 2 weeks if it had not been moved.

3.4.1 Potentiometer (angle)

Calibration of angles was undertaken by making marks with a single blue light on a black display curve, which represented actual angle values. The angles to the left were positive angles and to the right were negative angles. The zero degrees point was set at the midline. Potentiometer voltage outputs were recorded when the lever arm was moved to different angles (in steps of 10 degrees from -79 to 79 degrees). Linear regression was generated between the known angles and measured voltages (Figure 3.3) and the gradient and offset values calculated (Table 3.2).

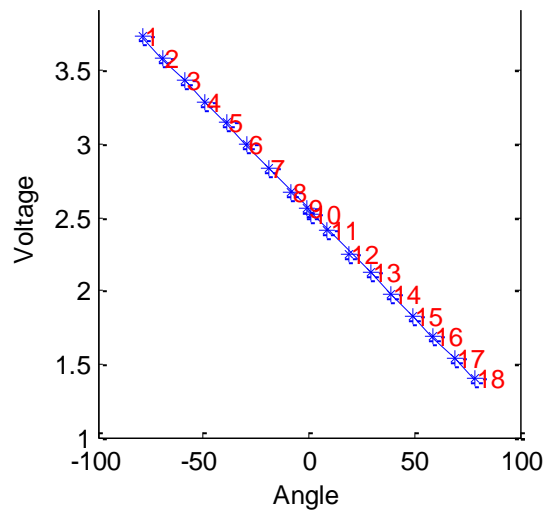


Figure 3.3 Results from calibration of potentiometer. The horizontal axis shows the true angles, and the vertical axis shows the measured voltages.

3.4.2 Strain gauge (torque)

The strain gauge was calibrated by recording voltage when different weights (1500, 1000, 500, 0, -500, -1000, and -1,500 grams respectively) were hanging from the end of the lever arm on a string over a free-running pulley system, with a 90° angle (perpendicular) to the lever arm and the weights pulling both to the left (positive direction) and to the right (negative direction). Known weight and measured voltages were generated the linear regression line (Figure 3.4). The gradient and offset values were calculated (Table 3.2).

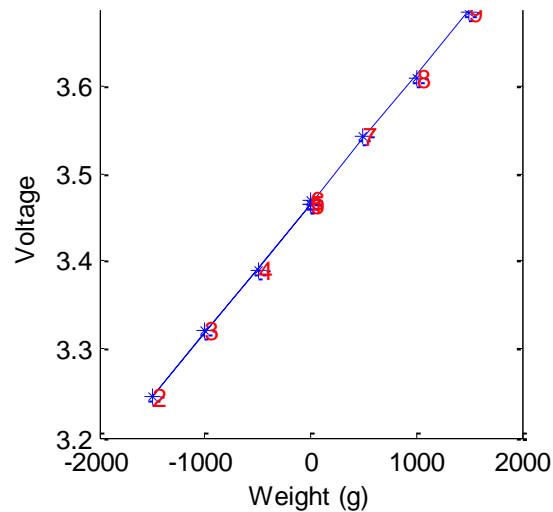


Figure 3.4 Results from calibration of strain gauge. The horizontal axis shows the true weights, and the vertical axis shows the measured voltages.

Initially, torque calibration coefficients were found to be unstable.

Subsequently, the modification of the wrist rig was made by moving the amplifier closer to the strain gauge (Figure 3.5) to prevent any unwanted drift of the voltage. Following that, the signals remained stable, with no drift over time in gain and offset.

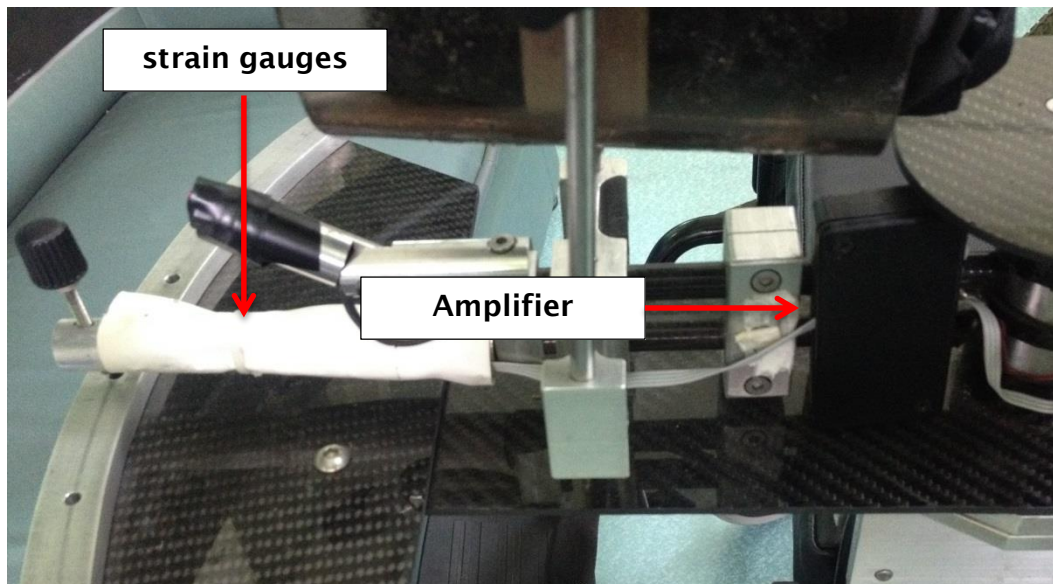


Figure 3.5 The amplifier placement on the redesigned wrist rig

Table 3.2 The gradient and offset values of angle and lever torque calibrations

Outputs	gain	Added offset
Angle	-67.8955	174.3784
Lever torque	5.3472	-18.353

3.5 Usability of the redesigned wrist rig

The initial usability of the redesigned wrist rig system was evaluated, through comments from an informal group of colleagues, to investigate whether it was fully ready to be used in this research. The following check list was evaluated and modifications were made if needed.

- The order of the wrist rig tests
- The visibility of blue light target and red laser pointer
- The accuracy of force and angle measurement
- EMG signal
- The usability of the wrist rig when it was attached to a standard wheelchair

These preliminary tests also enabled the author (WS) to become familiar with, and competent in carrying out the test protocol.

3.6 Summary of Chapter 3

This chapter has demonstrated the development of the redesigned wrist rig, particularly its modifications and measurement properties; the redesigned wrist rig being used as the main outcome measurement tool. Safety testing, calibration and usability of the redesigned wrist rig have been detailed.

The next chapter provides details of research methodology of four studies in this PhD thesis: pilot studies, reliability study, matched pair study and longitudinal study.

Chapter 4: Methodology

4.1 Introduction

The pilot (Chapter 5), reliability (Chapter 6), matched paired (Chapter 7) and longitudinal (Chapter 8) studies were conducted to address the overall aim of this PhD thesis (to increase our understanding of the way in which people recover from upper limb impairment and regain ULFA following stroke; in particular, the way in which impairments impact on the recovery of ULFA). This chapter details study design, sites and recruitment of participants, study samples for each study. In addition, selection criteria, screening assessments, confounding factors, outcome measures, training to conduct the tests, statistical analysis, ethical consideration and data management and storage are then demonstrated. The research questions, objectives and methodology, which related to each study, are described specifically in their own Chapter.

4.2 Study design

4.2.1 Pilot studies

To test the feasibility of the protocol of the longitudinal study including the wrist rig test, SWMFT-S and clinical assessment tests, a cross-sectional study design is applied for pilot study 1 and 2. Six healthy volunteers of different nationalities and three British chronic stroke participants were recruited to the pilot study 1. Three Thai chronic and eight Thai sub-acute stroke participants (4 at 2-week, 2 at 4-week and 2 at 8-week) were recruited to the pilot study 2.

4.2.2 Reliability study

To measure reliability of the redesigned wrist rig, a between-days test re-test was conducted in 14 8-week post-stroke participants.

4.2.3 Matched pair study

A cross-sectional study comparing wrist movement characteristics in a convenience sample of participants from Thailand was conducted. Three

samples of participants were tested: 25 sub-acute stroke participants (two weeks), the same pool of 25 chronic stroke patients (26 weeks) and 25 healthy participants who were match-paired for age, gender, height and weight were conducted.

4.2.4 Longitudinal study

A longitudinal observational design in which 52 participants (see section 4.4.4 for more details of the sample size calculation) were assessed at two weeks. Follow up assessments were conducted at four, eight, 12 and 26 weeks.

4.3 Sites and recruitment of participants

4.3.1 Pilot study 1

Pilot study 1 was conducted at the Faculty of Health Sciences (Building 45) in the University of Southampton (UoS), United Kingdom. Convenience samples of healthy participants were recruited from posters (Appendix B) placed around the Faculty of Health Sciences (Building 45), University of Southampton, after obtaining ethics approval.

People with chronic stroke (>26 weeks) were recruited from the School of Health Sciences research participant database. Interested volunteers received an invitation letter (Appendix D) and a participant information sheet (Appendices E and F) by e-mail or mail. Those who have had read the information sheet and wished to take part were given convenient appointments for the data collection to take place.

4.3.2 Pilot study 2

Pilot study 2 was conducted at the Department of Physiotherapy, Buddhachinaraj Hospital, Thailand with participants who were recruited from the inpatient and outpatient pools.

The treating physiotherapists assisted the author (WS) to identify the eligible participants based on the selection criteria. Following that, the stroke

participants were invited to take part by showing a poster of this study (Appendix G) and describing the study's objectives.

Consequently, an appointment was arranged with interested volunteers to explain the study to them in greater detail. The interested volunteers were given an invitation letter (Appendix H) and a participant information sheet (PIS) (Appendix I). They were given five days to discuss with their general practitioner, families or caregivers regarding participation. They could contact the author (WS) via telephone, as stated in the PIS, to ask any questions before making a final commitment to take part. Those who had read the participant information sheet and wished to volunteer were given convenient appointments for the data collection to take place.

4.3.3 Reliability

A sub-set of 14 participants from the longitudinal study, who were at eight weeks, were recruited for the reliability study. Participants were selected and invited to take part based on their ability to tolerate a second testing session. Attempts were made to ensure that they were representative of different age, sex and motor deficit groups.

4.3.4 Matched pair study

Twenty-five healthy participants were recruited from Elderly Club of Buddhachinaraj Hospital, Phitsanulok, Thailand. The author (WS) described the objective and protocol of this study in the monthly meeting of the club. Interested volunteers received the invitation letter and the PIS at the meeting. Those who read the information sheet and wished to take part contacted the author (WS) by phone and were given convenient appointments for the data collection to take place.

The wrist impairments data from 25 chronic stroke participants who already participated in a longitudinal study and were assessed for all indices (active and passive tests) at 2 and 26 weeks were used.

4.3.5 Longitudinal study

The longitudinal study was conducted at the Department of Physiotherapy, Buddhachinaraj Hospital, Thailand with participants who were recruited from the inpatient pools same as the pilot study 2. In addition, partly of the follow up assessments were conducted at the Department of Physiotherapy, Community Hospital including Bang rakam, Bang Krathum, Nakhon Thai, Phrom Piram and Wang Thong Hospital where are nearby participants' houses.

4.4 Study samples

The flow of participants in the various studies is illustrated in Figure 1.3.

4.4.1 Pilot studies

A sample size for the pilot studies 1 and 2 was determined by convenience sampling. A small group of healthy, sub-acute and chronic stroke participants (six of each group) were recruited.

4.4.2 Reliability study

The sample size was determined using G*Power 3 (Prajapati et al. 2010). The estimation was based on the test-retest reliability of the sine TI (ICC=0.66), which was the smallest correlation in unimpaired people (Turk et al. 2008). Twelve participants were required to achieve 80% power in a 2-sided 5% test. To allow for dropout, non-compliance and anticipated smaller between-group differences for other impairment measures, 14 participants were recruited for the reliability study.

4.4.3 Matched pair study

A large number of wrist motor impairment indices (negative wrist impairments: AROM, flexor and extensor IF, sine and step TI and extensor onset timing; positive wrist impairments: sine CI and SI; and secondary wrist impairments: PROM and MTI) were examined. It was therefore difficult to decide which primary outcome measure to use for estimating sample size for this matched pair study. In previous research by (Turk (2011)), a power calculation was made

based on the difference between chronic stroke and healthy participants for one impairment measure. Taking the step CI as an example of the impairment measure (mean differences = 0.30, standard deviation of differences = 0.47), it was calculated that, to detect a difference between groups, 19 participants per group were required to achieve an 80% power in a 2-sided 5% test. This sample size also enable detection of any difference between healthy and chronic groups for wrist extensor IF, wrist extensor AROM and PROM, sine and step TI, sine and step CI and SI. The difference between healthy and chronic groups for MTI was not investigated at this stage because a large sample size of 338 participants would be required for the study. To allow for dropout, non-compliance and anticipated smaller between group differences for other impairment measures, 25 age-matched healthy participants were recruited.

4.4.4 Longitudinal study

A reasonable ratio of cases to predictors can be determined by a formula suggested by Allen et al. (2014).

$$N = 50 + 8(k) \text{ (k is the number of predictors)}$$

Eleven predictors were investigated; therefore, the ideal sample size should be 138 participants. Unfortunately, it was challenging to recruit this target sample size within the constraints of this PhD research programme's timeline and resources (one year of data collection). For a feasibility study, sample sizes between 24 and 50 have been recommended by Sim and Lewis (2012) and Julious (2005) to estimate a standard deviation, which can be used in a sample size calculation for the future full scale trial. Therefore, the sample size was determined as 40. In total, 45 participants were recruited to allow for dropout. Timing expected for this longitudinal study was six months for recruitment and another six months for follow up assessments.

4.5 Selection criteria

4.5.1 Healthy participants

Healthy participants in the pilot study 1 and the matched pair study were selected if they were aged of 18 or over and were without any

neuromusculoskeletal condition that might impair movement of their dominant arm and/or had visual deficiencies that were not corrected by contact lenses or glasses.

4.5.2 Stroke participants

People with chronic stroke (>26 weeks) and people with sub-acute stroke were recruited to the study if they met the following criteria. Stroke patients who were at two, four and eight weeks were recruited to the pilot studies 2. The participants with eight weeks were engaged the reliability study. Only the stroke participants at 2 weeks continued the follow up assessments in the main (longitudinal) study.

1. participants who had been clinically diagnosed with stroke as confirmed by CT, MRI or clinical examination
2. present with upper limb movement deficit defined as a score of less than 12 (highest score) on the upper limb sub-section of the S-FM-UE.
3. aged 18 years or over
4. able to tolerate the whole study protocol, which may last for one hour
5. had sufficient language and cognitive ability to understand the purpose of the study
6. had no other medical problems affecting upper limb movement
7. informed written consent (Appendix N)

Exclusion criteria

1. skin allergy to alcohol wipes, sEMG electrode, and sticky tape
2. had previous stroke affecting the same side unless they have made full recovery (defined as a modified Rankin scale score of 0 (mRS))

4.6 Screening assessments

Before taking part in the study, the following tools were used to screen stroke participants to ensure they satisfied the selection criteria. The assessments are described in the following sub-sections.

4.6.1 Short form of the Fugl-Meyer Motor Scale

The S-FM-UE was used to screen eligibility of stroke patients to participate in our study. The six items of the S-FM-UE is scored on a 3-point scale from 0 to 2. The total score of the S-FM-UE ranges from 0 to 12.

Only people with stroke who had the S-FM-UE scores of less than 12, represented motor deficits of ULFA, were recruited.

4.6.2 Premorbid functioning factors

The premorbid functioning status of the stroke participants was evaluated by using the mRS (Appendix P). The mRS provides an ordinal grading scale from zero (no symptoms) to five (severe disability). A grading of six refers to death (van Swieten et al. 1988). The mRS is a well-defined scale that describes the range of global disability and has established validity for assessing recovery from stroke (Banks and Marotta 2007). Only people with stroke who had no symptoms before their recent stroke were included.

4.7 Confounding factors

There were possible confounding factors in the longitudinal study that were not controlled. The following factors were recorded by reviewing patients' charts or interviewing them prior to data collection on the same day as the initial assessment (Appendix O).

Possible confounding factors identified are:

1. Age
2. Gender
3. Hemiplegic side (dominant or non-dominant hand affected)

4. Type of stroke (ischemic or haemorrhagic stroke)
5. Wrist joint proprioception (assessed by the Nottingham Sensory Assessment)
6. The programme record for treatment intervention for upper limb during rehabilitation, gathered from the upper limb treatment recording form (Appendix Q)

4.8 Outcome measures

4.8.1 Upper limb functional activity (ULFA)

ULFA of the affected arm in the stroke participants and dominant arm in the healthy participants was assessed by the SWMFT-S before testing with the wrist rig. The instructions for the administration of the SWMFT-S were extracted from the Wolf motor function test manual (Taub et al. 2011).

4.8.2 Wrist impairments

The redesigned wrist rig was used to measure wrist impairments of participants. The dominant side of each healthy participant was assessed, while the hemiparesis side of stroke participants was tested. Before each assessment session, the wrist rig system was set up and the input sensors were checked to ensure that they could generate the signals.

The testing procedures of the wrist rig, as described by Turk (2011) were summarised and adjusted. They are outlined in the following sub-sections.

4.8.2.1 EMG protocol

Participants were seated comfortably in the wheelchair. The skin of the forearm was cleaned with an alcohol wipe. Surface EMG electrodes (Biologic snap electrodes, Biosense Med Ltd) were applied to the skin. The flexor (flexor carpi radialis (FCR)) sEMG electrode was positioned on a line from the medial epicondyle of the elbow to the FCR tendon at the wrist, seven to nine centimetres distal to the medial epicondyle (Leis and Trapani 2000). The extensor (extensor carpi radialis longus) sEMG electrode was positioned on a line from the lateral epicondyle of the elbow to the second metacarpal, five to

seven centimetres distal to the lateral epicondyle (Leis and Trapani 2000) (Figure 4.1). A reference electrode was placed over the lateral epicondyles of the elbow. The electrodes were held in firm contact with the skin by using tape. The EMG signal quality was checked visually in every subject by testing for clear evidence of EMG response to voluntary muscle contractions of wrist flexor and extensor muscles.

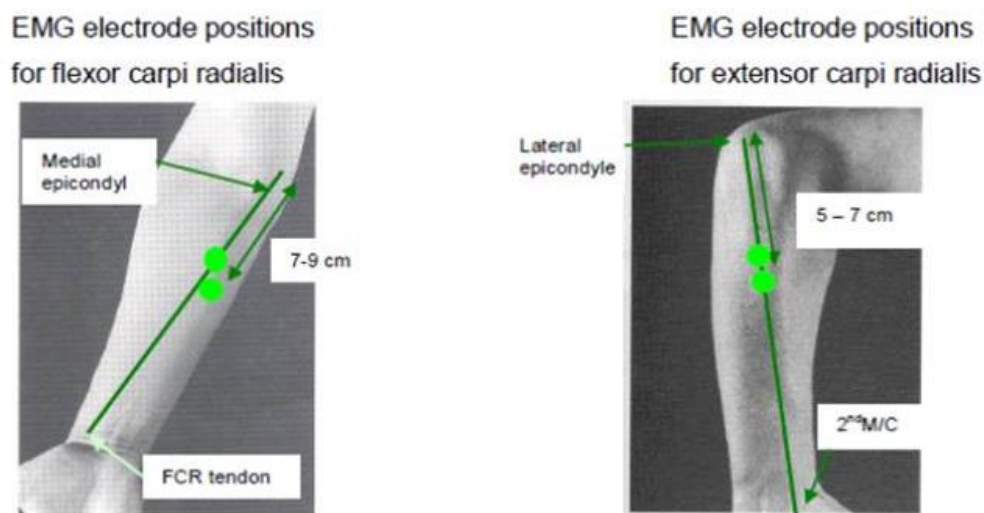


Figure 4.1 Position of the wrist flexor and extensor sEMG electrodes (Leis and Trapani 2000)

4.8.2.2 Positioning of participants

The hemiplegic arm to be tested was placed on the armrest and the forearm support was adjusted to the correct height. With the joint axis of the wrist positioned over the pivot point, fingers were fully relaxed in flexion in the air splint. The forearm was strapped to the armrest and the upper arm was strapped to an elbow restraint positioned behind the elbow so that the arm was held in place firmly but comfortably (Figure 4.2).

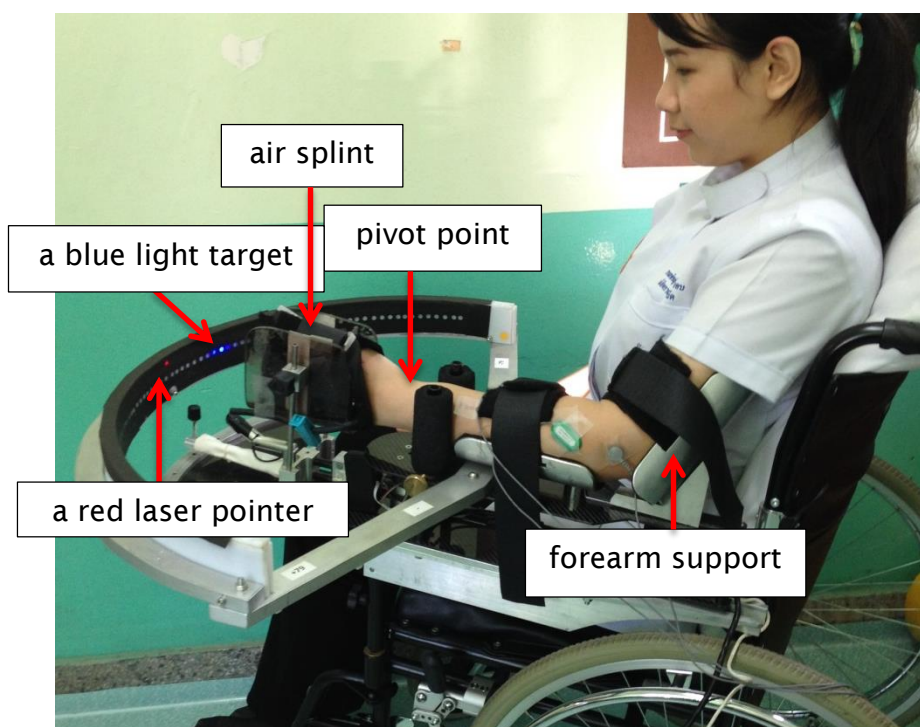


Figure 4.2 The position of the participant in the wrist rig

4.8.2.3 Wrist rig testing procedure

The following tests were performed in the rig (Turk 2011). The following variables were measured.

- ❖ Active range of motion (AROM): The participants performed three maximal active extension to flexion movements, from which the active mid-point was calculated.
- ❖ Passive range of motion (PROM): Three maximal passive extension to flexion movements were conducted by the author (WS). The end of the passive extension range is defined as the point where resistance from tissues increases either to movement limitation or where further movement is difficult but remains pain-free.
- ❖ Maximal voluntary isometric contraction (MVC) of wrist extensor at 20° flexion: Three 5-second contractions with a 10 seconds rest interval were performed by the participants.
- ❖ Stretch response test: Passive sinusoidal movements of $\pm 5^\circ$ displacement around the active mid-point at 3.5Hz speed were conducted by the author (WS) for 40 seconds.

- ❖ Torque/angle test: The author (WS) administered six repetitions of passive ramp and hold at 5 °/s through full passive ROM.
- ❖ Active tracking tasks: The participants were asked to move their wrist (red laser pointer) to follow a blue light target (Figure 4.2) during the following tasks.
 - Sinusoidal tracking task between $\pm 20^\circ$ of participants' active mid-range at 0.5Hz speed for 80 seconds
 - Step tracking task with random displacement of the target from 5 ° to 40 ° and random two to four seconds rest intervals between movements of the target for 90 seconds

Prior to the final performance, participants practise each tracking task until they reached their maximal performance (two to five practise sessions depending on the participant's ability and their rate of learning).

4.8.2.4 Derivation of impairment indices

Eight wrist impairments (negative impairments: range of movement, muscle weakness, MCA, delayed muscle onset timing; positive impairments: spasticity and muscle coactivation; secondary impairments: contracture and non-neural stiffness) were measured by the wrist rig. These eight motor impairments were categorised by 11 indices (*negative impairments*: AROM, flexor and extensor IF, sine and step TI, path length, muscle onset timing; *positive impairments*: SI and sine CI; *secondary impairments*: PROM and MTI). The impairment measurements, and signals needed for measurement, were described as follows.

- Range of movement

Previously, both the active and passive wrist extension had been quantified from 'zero' (where the hand is aligned in a neutral position to the forearm in a straight line) (Turk 2011). However, it was confusing because sometimes there were negative degrees. Therefore, maximum active and passive ranges of motion were quantified i.e. the range from maximal flexion to maximal extension.

- Muscle weakness

Wrist flexor and extensor muscle weakness were measured as the maximum voluntary IF. The lever arm torque (Nm) was calculated as muscle weakness (Turk 2011).

- Tracking indices
 - ❖ Step TI (mean absolute error and path length)

The total mean absolute error (MAE) between wrist movement (flexion and extension) and a target (between 5 to 65 seconds of testing duration) was used to assess step tracking accuracy.

$$TI_{step} (MAE) = \frac{1}{N} \sum_{i=0}^{N-1} |w_i - t_i|$$

N is the total number of samples in the two signals. The w_i is the wrist angle at sample i and t_i is the corresponding target. The summation, that was selected for analysis, is taken over N samples in the recording.

Path length is defined as the extent of corrective sub-movements at the target's end-point. The path length was measured in units of 'degrees per sample' (using the decimated sampling rate of 200 Hz) and the sum was taken over the entire sample in the target phase (Turk 2011). However, the unit 'degrees per sample' could not be used for comparison with the other studies, which used a different sampling rate (i.e. 500 Hz). Therefore, the path length is given by the sum of the distances travelled (in degrees) between samples within one second. It is the average speed (in degrees per second), when only the absolute value (magnitude) of the movement is taken into account, as follows:

$$Path\ length = \frac{1}{(N-1)} \sum_{i=1}^{N-1} |w_i - w_{i-1}| \times f_s$$

Figure 4.3 illustrates the period of time which was used to quantify path length.

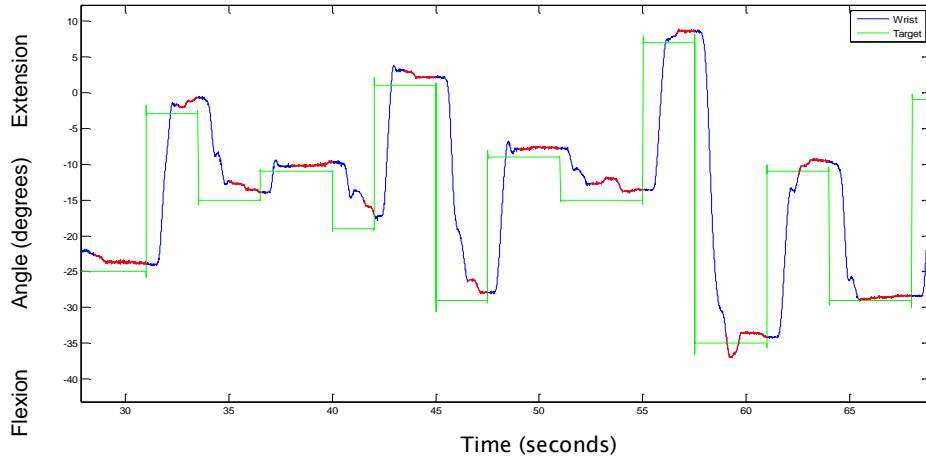


Figure 4.3 Duration to calculate path length. Green line refer to the target movement, the blue line refer to the wrist movement. The red line indicate duration length, which calculate path length.

❖ Sine TI

Cross correlation between the target and wrist movement (flexion and extension) (between 5 to 55 seconds of testing duration), which has not been normalised to the range ± 1 , has been calculated as *TI_{sin}*. It is sufficiently sensitive to detect the difference of amplitude, and shape of movement curve, between wrist and the target (Turk 2011).

$$TI_{sin} = \max \left\{ \frac{1}{N} \sum_{i=\tau}^{N-1} w_i t_{(i+\tau)} \right\}$$

The w_i is the wrist angle at sample i and t_i is the corresponding target, τ is a delay, which varies over a range of ± 1.2 s (i.e. a little over half a cycle for the 0.5 Hz sinusoidal target), N is the length of the discrete signals (in samples). For 50 seconds of recording this corresponds to be $50 \times 2000 = 100,000$ samples.

- Sine CI

A correlation analysis method for the step CI was undertaken during sine tracking task (between 5 to 55 seconds of testing duration). The correlation coefficient between wrist flexor EMG and wrist extensor EMG was performed when extensor EMG is increasing during sine tracking movement (Turk 2011).

- Extensor onset timing

Wrist extensor onset timing was defined as the interval between the target moving and the detected extensor EMG activation onset, where ‘onset’ was 4 standard deviations above resting local baseline, recorded for 1 second immediately prior to each target displacement during the step tracking task (Turk 2011).

- Stretch index (SI)

The SI was measured during fast passive sinusoidal displacement (following a blue light target on the white display) at $3.5 \text{ Hz} \pm 5 \text{ degrees}$ around the subject’s AROM midpoint. The SI was quantified as the median ratio of the flexor EMG area during wrist extension divided by the local baseline flexor EMG area (taken over an interval of 0.1 second prior to the extension movement).

$$SI(\text{area: LBL}) = \text{median}\left(\frac{\text{postEMG}_{fe}(m)}{\text{preEMG}_{fe}(m)}\right)$$

Where $\text{preEMG}_{fe}(m)$ is the mean EMG area of the flexor over an interval of 0.1 s prior to extension on the m^{th} cycle (i.e. the local baseline), and $\text{postEMG}_{fe}(m)$ is the equivalent during that extension.

In total, there are 54 cycles of wrist flexion to extension movement within 40 seconds. The extension cycles, where displacement was more than $\pm 5^\circ$ of the target extension peak and/or more than $\pm 10^\circ$ of the target flexion peak, were excluded to ensure that the analysis was conducted on cycles that were as accurate to the target displacement and frequency as possible (Turk 2011).

- Mean torque index (MTI)

The MTI was used to measure non-neural stiffness. It was considered as the torque around the joint applied by soft tissues during slow passive movement. The passive movement ramp and hold stretch tests were moved at $5^\circ/\text{s}$ for six cycles. Wrist flexor activity (voluntary or stretch reflex) may increase wrist flexor stiffness and extensor activity (participant assisting the movement) may reduce wrist flexor stiffness. Therefore, prior to calculation, cycles of passive wrist extension with flexor and/ or extensor EMG envelope amplitudes above a set threshold were excluded. The threshold was three standard deviations from the baseline flexor or extensor, which was recorded for 1 second immediately prior to each target displacement EMG. Hence, this ensured that the cycles of movement, which were exaggerated by voluntary contraction or stretch reflex,

were not calculated as the non-neural stiffness. The gradients of the torque and angle curves were plotted. The MTI was calculated as the centre torque value of the 50° regression line (Turk 2011).

4.8.2.5 Missing data

The wrist rig tests comprise active (AROM, MVC and sine and step tracking tasks) and passive (PROM, stretch response and torque/angle) tests.

Participants with very poor ULFA were unable to perform active tests, most often at the first assessment. These low-functioning participants were not excluded to ensure participants with a wide range of ability levels were included in the study. The active tests that were not conducted were therefore classified as missing data.

Despite attempts to check all data and on occasions repeat data collection there were some examples of poor quality signals or artefacts of EMG data that could not be analysed. These data were excluded from the analysis and also classified as missing data.

4.9 Training to conduct the tests

This section describes the training process for conducting the SWMFT-S, S-FM-UE and the wrist rig tests by the author (WS).

4.9.1 Streamlined Wolf Motor Function Test for use with sub-acute (SWMFT-S) and Short form of the Fugl-Meyer motor scale (S-FM-UE)

The training to administer the SWMFT-S was based on reviewing the video recording of twelve stroke participants performing the test with a physiotherapist, (Dr Seng Kwee Wee), who was experienced in administering and scoring the SWMFT-S and the S-FM-UE. The S-FM-UE administration was trained by observing Dr Wee assessing five stroke participants. Differences in scoring were highlighted and guided by Dr Wee, until the author (WS) was proficient in scoring each task performance accurately and consistently.

4.9.2 The wrist rig tests

The wrist rig tests training included how to carry out the test protocol and the data analysis to derive the impairment measure indices. The author (WS) was trained in using the redesigned wrist rig system with healthy participants before the pilot studies. The method to derive impairments indices was taught by the author's PhD supervisor, Dr. Ruth Turk.

4.10 Statistical analysis

All data analysis was performed using the IBM SPSS, version 22 software. A p -value of 0.05 was accepted as statistically significant.

Data for all studies (pilot, reliability, matched pair and longitudinal studies) was tested for normal distribution using the Kolmogorov-Smirnov and Shapiro-Wilks tests. Histograms with normal distribution curves overlaid, were examined for all data. Parametric tests were employed if data were normally distributed. If not, non-parametric tests were used for analysis.

Statistical analysis, which related to each study, are described in each chapter.

4.11 Ethical consideration

4.11.1 Ethical approval

Ethical approval for pilot study 1 was given by the Faculty of Health Sciences Ethics Committee, University of Southampton, UK (ETHICS ID: 8747). Ethical approval for pilot study 2, reliability, matched pair and the main studies was given by the Faculty of Health Sciences Ethics Committee, University of Southampton, UK (ETHICS ID: 16653) and the Ethics Committee of the Buddhachinaraj Hospital, Phitsanulok, Thailand (ETHICS ID: 35/57) (Appendix A).

4.11.2 Informed consent

The study protocol and the participant information sheet (PIS) (Appendices E and F) were explained to potential participants. People who were willing to

participate were asked to sign a consent form (Appendix N) to show their agreement to take part and that they understood what was involved.

The participants were free to withdraw at any time, without giving a reason. Such a decision in no way affected the standard of care that they received.

4.11.3 Participant confidentiality and data anonymity

Only the author (WS) and her PhD supervisors (Professor Jane BurrIDGE and Dr Ruth Turk) from the University of Southampton have access to the personal data set. All the information collected about participants during the study were kept strictly confidential and were not shared with any personnel who was not involved in this project.

Participants' names and addresses were removed from any report forms so they were not and could not be recognised from it. A unique number that connected their data to them was used to identify the participants.

Participants' personal details were kept separately from the research records in a locked cabinet in the Faculty of Health Sciences, UoS, for the pilot study 1 and in the Department of Physiotherapy (Buddhachinaraj Hospital, Phitsanulok, Thailand) for the pilot study 2.

4.12 Data management and storage

Data was collected in electronic and paper forms. The signals recorded during the wrist rig tests were automatically saved as Matlab files on the laptop computer. After checking and pre-processing the signal data, indices were derived from the signals, and were saved in Excel spread sheets on the University of Southampton's password-protected laptop computer. All data on the computerised data sheets were coded without using participants' names in order to ensure anonymity. Data collected on case record forms were also coded to ensure confidentiality. Data from the Excel spreadsheets were transferred to SPSS for statistical analysis.

4.13 Summary of Chapter 4

This chapter has presented the research methodology of four studies in this PhD research: pilot studies, reliability study, matched pair study and longitudinal study. The research methodology which are research questions, aim and objectives of study, study design, sites and recruitment of participants, ethical consideration, study sample, selection criteria, screening assessments, confounding factors, outcome measures, training to conduct the tests, statistical analysis and data management and storage.

The next chapter details the pilot study 1 and 2, which investigated feasibility of the redesigned wrist rig and the SWMFT-S tests to be used in sub-acute stroke participants.

Chapter 5: Pilot studies

5.1 Introduction

The pilot studies 1 and 2 tested the feasibility of the protocol including the wrist rig test, SWMFT-S and clinical assessment tests in terms of a) the time taken to conduct the tests; and b) the participants' views on the procedure. Six healthy volunteers of different nationalities and three British chronic stroke participants were recruited in the pilot study 1. Three Thai chronic and eight Thai sub-acute stroke participants (4 at 2-week, 2 at 4-week and 2 at 8-week) were recruited in the pilot study 2. The results from these pilot studies enabled the author (WS) to make refinements to the protocol before proceeding to conduct the tests with sub-acute stroke participants.

5.2 Research questions

The pilot study 1 and 2 are conducted to address the following research questions.

'Are the wrist rig tests and the Streamlined Wolf Motor Function Test for use with sub-acute patients (SWMFT-S) feasible to be used in sub-acute stroke groups?'

5.3 Objectives

1. To quantify time taken to conduct the whole assessment session for healthy, sub-acute and chronic stroke groups.
2. To explore the quality of data (impairment indices), which were collected from the pilot studies 1 and 2 (healthy, chronic and sub-acute stroke groups) and report data graphically.
3. To explore the participants' views about the equipment (comfort and ease of use) and testing procedures.

5.4 Methodology

Testing procedures and data analysis for the pilot studies are presented in this section.

5.4.1 Testing procedures

5.4.1.1 Pilot study 1

The demographic data (age, gender) and hand dominance (Edinburgh Handedness Inventory-short form (Veale 2014) of the healthy participants and chronic stroke participants were gathered via questioning before the assessment. The hemiplegic side and type of stroke (ischemic or haemorrhagic) were gathered via questioning the stroke participants. Subsequently, the SWMFT-S (Appendix S) and the wrist rig test (Appendix T) were administered. Finally, participants were given structured interviews about their perceptions of the whole assessment experience (Appendix U). Figures 5.1 and 5.2 illustrate the flow chart of pilot study 1.

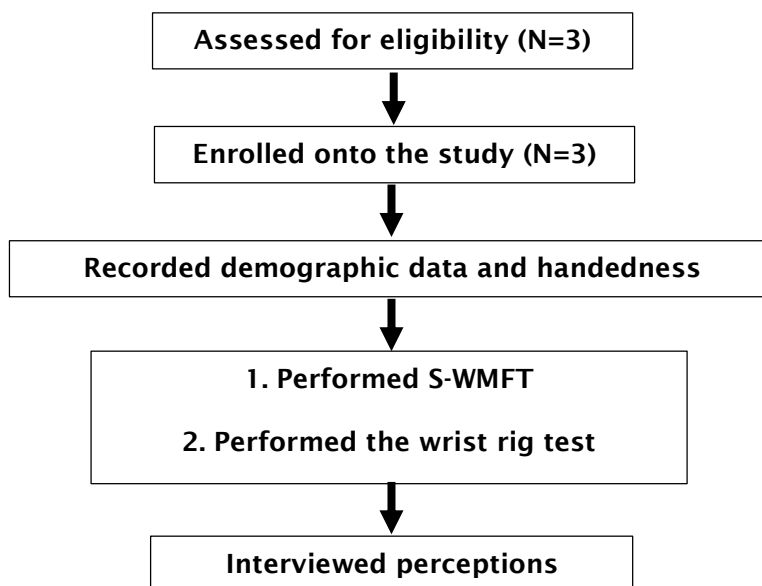


Figure 5.1 Flow diagram for healthy participants in the pilot study 1

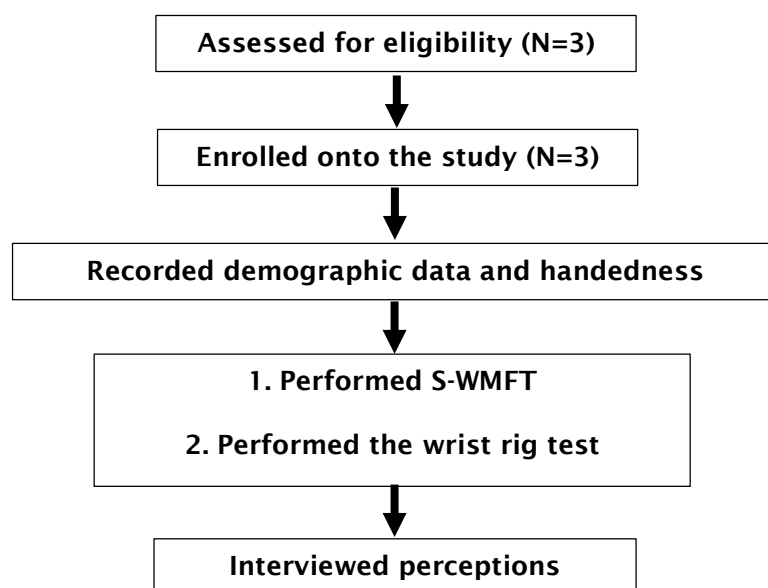


Figure 5.2 Flow diagram for chronic stroke participants in the pilot study 1

Figure 5.3 details the testing schedule for stroke participants in pilot study 1. This schedule also be applied for the pilot study 2.

Screening test (S-FM) and record demographic data (5 minutes)	Break (5 minutes)	S-WMFT (15 minutes)	Break (5 minutes)	Set up, practise and complete the wrist rig test (20 minutes)
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Figure 5.3 The testing schedule for participants in pilot study 1 and 2

5.4.1.2 Pilot study 2

The demographic data of the participants in pilot study 2 was recorded from each patient's chart, through questioning and via clinical assessments.

Subsequently, the SWMFT-S (Appendix S), the wrist rig tests (Appendix T) and structured interviews were carried out (Appendix U).

Three chronic stroke participants were assessed once, as per pilot study 1.

Four sub-acute stroke participants at 2-weeks post stroke from the pilot study 2 were eligible and gave consent to participate in the longitudinal study.

Therefore, they continued with subsequent assessments, as in the longitudinal study process (see Chapter 8 for more details). Figure 5.4 presents the flow diagram of the sub-acute stroke participants in pilot study 2.

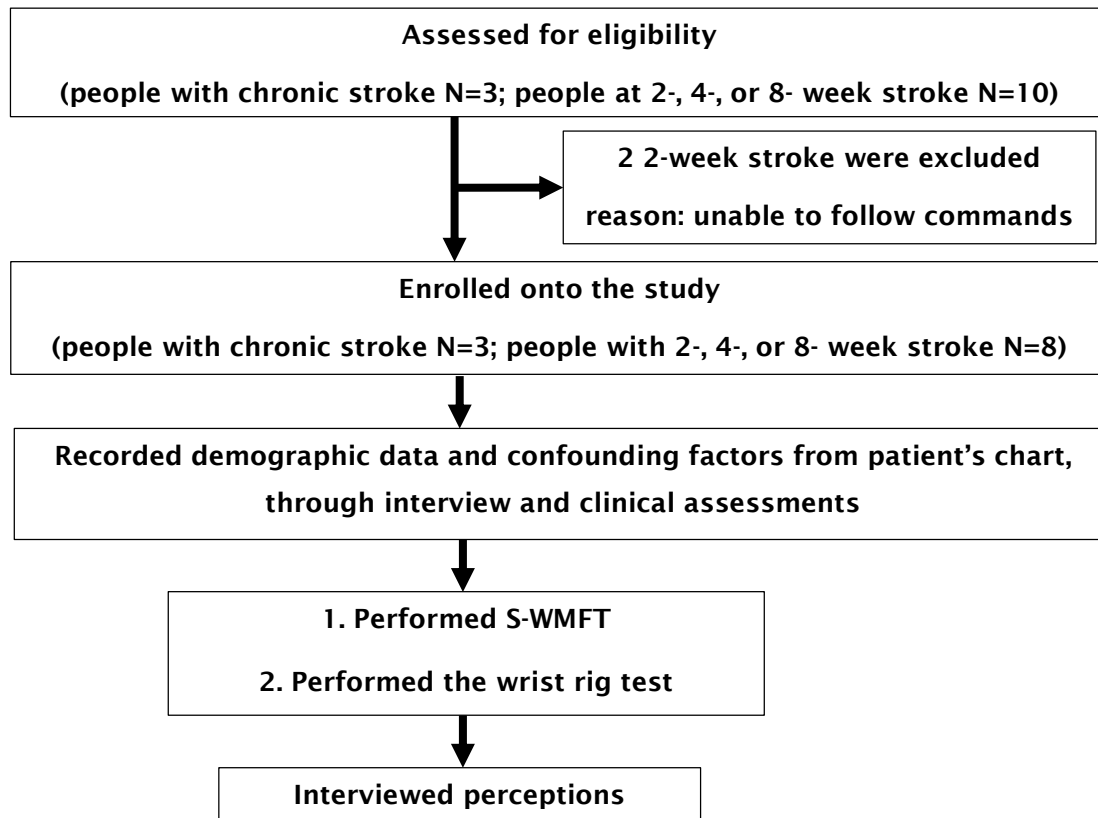


Figure 5.4 Flow diagram for sub-acute stroke participants in the pilot study 2

5.4.2 Statistical analysis

Participants' age were presented as mean and standard deviation. The median (interquartile range) are used to present clinical data (spasticity and upper limb impairment) of the participants since they were non-normally distributed.

Data from the wrist rig tests were presented descriptively and graphically compared between sub-acute, chronic stroke and healthy groups.

5.5 Results

5.5.1 Participants characteristics

Six healthy participants and three chronic stroke participants were recruited into the pilot study 1. It was planned to recruited only three chronic stroke participants and six sub-acute stroke participants from Buddhachinaraj Hospital, Thailand for the pilot study 2. However, two participants at week two were unable to perform the required active tests. Participants, who were at 2-

week and were able to be assessed on the active wrist rig tests, were recruited. Eventually, eight sub-acute stroke participants were recruited for the pilot study 2. Participants' characteristics are shown in Tables 5.1.

Table 5.1 Characteristics of study participants in the pilot studies (N=20)

	Healthy (N=6)	Chronic (N=6)	Sub-Acute (N=8)
Age (years): mean (SD) [min-max]	28 (3) [24-33]	66 (15) [42-81]	55 (16) [18-68]
Gender	3 male 3 female	3 male 3 female	3 male 5 female
Side assessed	1 left 5 right	1 left 5 right	2 left 6 right
Hand dominance	1 left 5 right	0 left 6 right	1 left 7 right
Time from stroke (Months): mean (SD) [min- max]	N/A	44 (47) [11-132]	1 (0.7) [0.5-2]
Type of stroke	N/A	7 ischemic 1 haemorrhagic	7 ischemic 1 haemorrhagic
Upper limb motor impairments-S-FM-UE (0-12): Median (IQR) [min-max]	N/A	8 (5.50, 10.50) [4-12]	6 (0.75, 10.50) [0-11]
Upper limb functional activity-SWMFT-S FAS (0-5): Median (IQR) [min-max]	N/A	2.83 (1.75, 4.70) [1-4.83]	2.17 (0.29, 4.08) [0-4.33]
Upper limb functional activity-SWMFT-time score (0-120): Median (IQR) [min- max]	N/A	15.24 (2.22, 75.87) [1.51-120.00]	54.17 (4.04, 115.63) [2.11-120.00]

5.5.2 Time taken to conduct the whole assessment session

The time taken to conduct the whole assessment session was measured for each participant. The timing commenced when the participant arrived in the laboratory and stopped when the participant finished the structured interview session. It was observed that time spent for the first healthy participant was approximately 2 hours. However, for the subsequent four healthy participants, the whole assessment was completed within 40 minutes as the author (WS) became more familiar with the research procedure. The three chronic stroke participants completed the whole assessment within 1 hour.

The time taken to assess the sub-acute stroke participants was longer than was needed for the healthy or chronic stroke participants. Two sub-acute stroke participants could not complete the whole test within the same day (#17 and #18). They spent 1 hour on the first day undergoing the SWMFT-S and practising the procedures for wrist rig testing. Following that, they completed the wrist rig tests on the following day. However, there were two participants who completed the whole test within 30 minutes, as they were unable to be assessed on the SWMFT-S and active wrist rig tests (#14 and #15). The sub-acute stroke participants, who presented with high ULFA, finished the whole test within one hour (#13 and #20).

5.5.3 Impairment indices

This section reports the indices of healthy, chronic stroke and sub-acute stroke groups. The impairment indices of each group are presented as the mean and standard deviation (SD) and 95% CI. Dot plots are used to illustrate the variation of individual data in each group.

5.5.3.1 Negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

The median (IQR) and range of values for negative impairments of sub-acute stroke for the negative impairment indices of each group are presented in table 5.2. The median AROM, flexor and extensor IF, sine and step TI were greater in the healthy group, as compared to members of the chronic and sub-acute stroke groups (*note*: greater index value is better). The step TI, path length and extensor onset timing were lower in the healthy group as compared to the stroke groups (*note*: lower index value is better).

Table 5.2 Median (IQR) and range of values for negative impairments of sub-acute stroke (N=6), chronic stroke (N=6) and healthy groups (N=6).

Wrist motor impairment indices	Median (IQR) [range of values]		
	Sub-acute (N=8)	Chronic (N=6)	Healthy (N=6)
AROM (degrees)	52.52 (11.70, 147.76) [46.79-155.79]	100.64 (22.54, 133.72) [4.54-134.27]	153.53 (146.15, 156.17) [142.56-158.81]
Flexor IF (Nm)	2.12 (0.18, 5.26) [0.00-9.11]	4.07 (2.80, 6.81) [2.08-13.70]	9.32 (3.79, 15.88) [2.68-17.51]
Extensor IF (Nm)	0.56 (0.09, 3.17) [0.34-3.48]	1.65 (0.23, 4.51) [2.08-13.70]	6.06 (3.09, 10.12) [2.50-12.74]
Sine tracking index (cross correlation) (degree ²)	102.53 (12.48, 239.96) [0.89-337.28]	154.11 (5.11, 242.92) [1.21-312.88]	215.03 (182.83, 223.33) [143.62-225.33]
Step tracking index (MAE) (degrees)	6.74 (5.05, 16.19) [4.55-17.09]	7.54 (6.03, 14.59) [5.33-14.80]	4.63 (3.56, 5.16) [2.55-5.28]
Path length (degrees/second)	9.60 (6.82, 12.54) [4.75-17.30]	6.20 (3.06, 11.33) [1.75-15.28]	1.41 (1.33, 1.96) [1.32-3.34]
Extensor onset timing (seconds)	0.40 (0.26, 0.77) [0.24-0.81]	0.65 (0.53, 0.79) [0.42-0.80]	0.23 (0.19, 0.26) [0.18-0.28]

The dot plots illustrate the individual negative impairment data of each participant (Figures 5.5 a-g). Blue dots represent the males and pink dots represent the females. There are 6 participants in each group, because two participants from the sub-acute stroke group (one was 2 and one was 4 weeks) were unable to be assessed by the active wrist rig test.

The majority of the negative impairments showed greater variability across stroke participants than with the healthy participants. In general, the spread of values of flexor and extensor IF in the healthy group can be explained by

gender differences, as illustrated in Figure 4.7b-c. All male participants from the healthy group demonstrated greater extensor IF than female participants.

The majority of stroke participants in both groups had higher step TI, path length and extensor onset timing (*note*: lower index value is better) than healthy participants (Figures 5.5e-g).

Figure 5.5 a) AROM

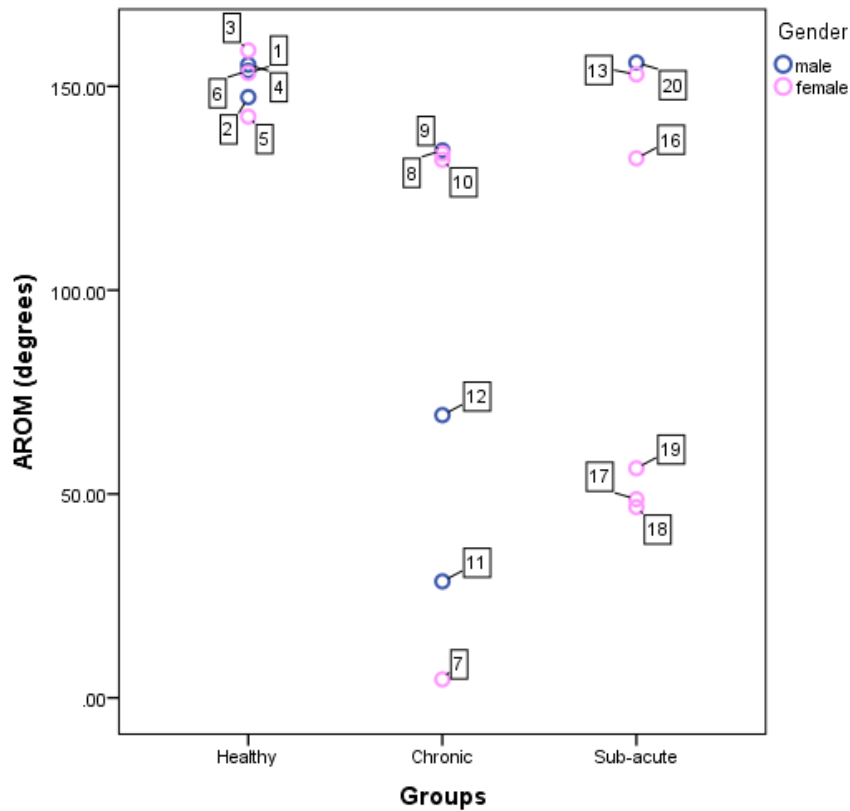


Figure 5.5 b) Flexor IF

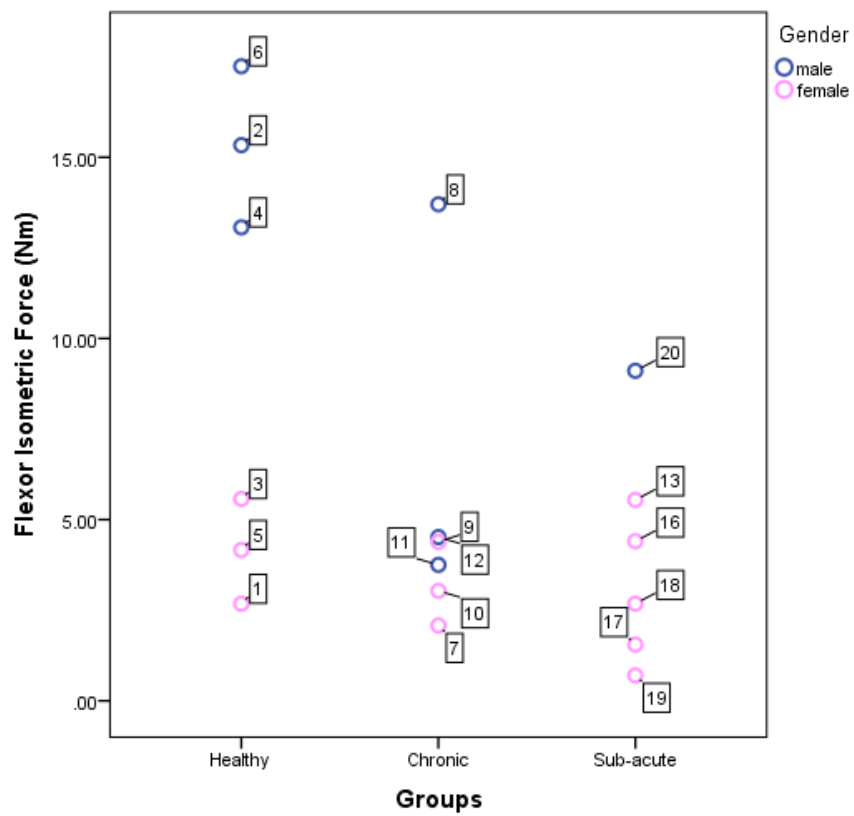


Figure 5.5 c) Extensor IF

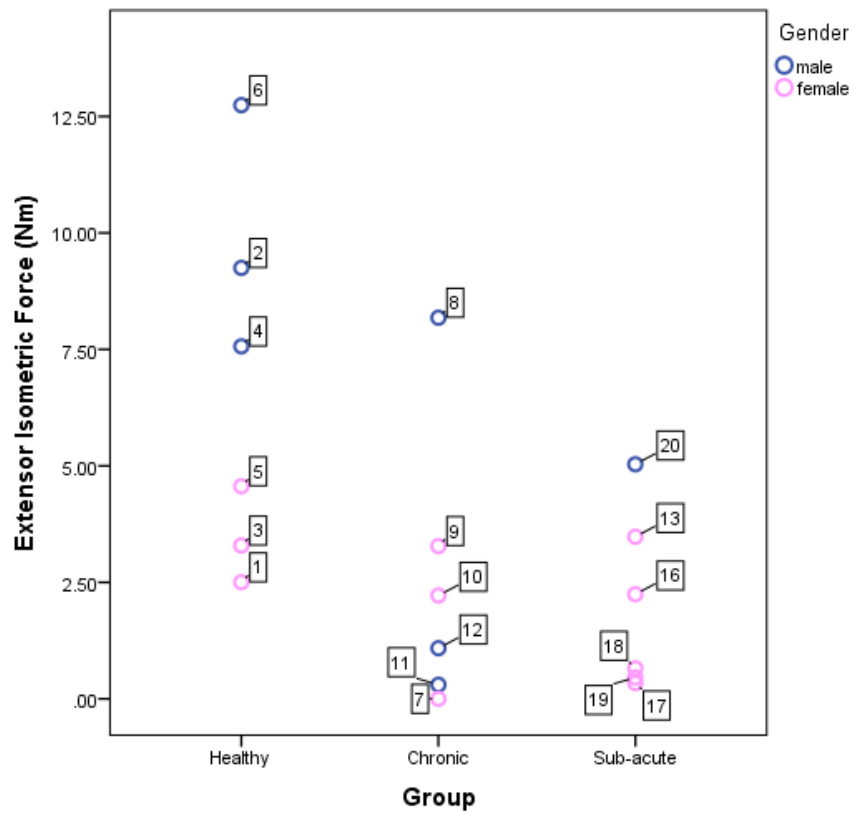


Figure 5.5 d) Sine TI (cross correlation)

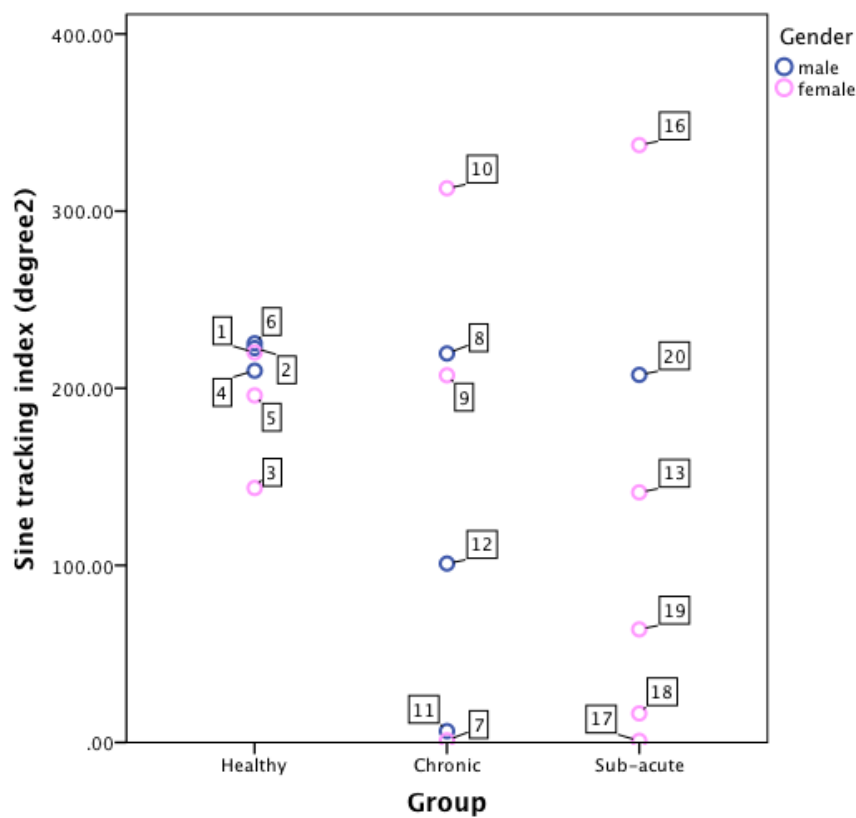


Figure 5.5 e) Step TI (MAE)

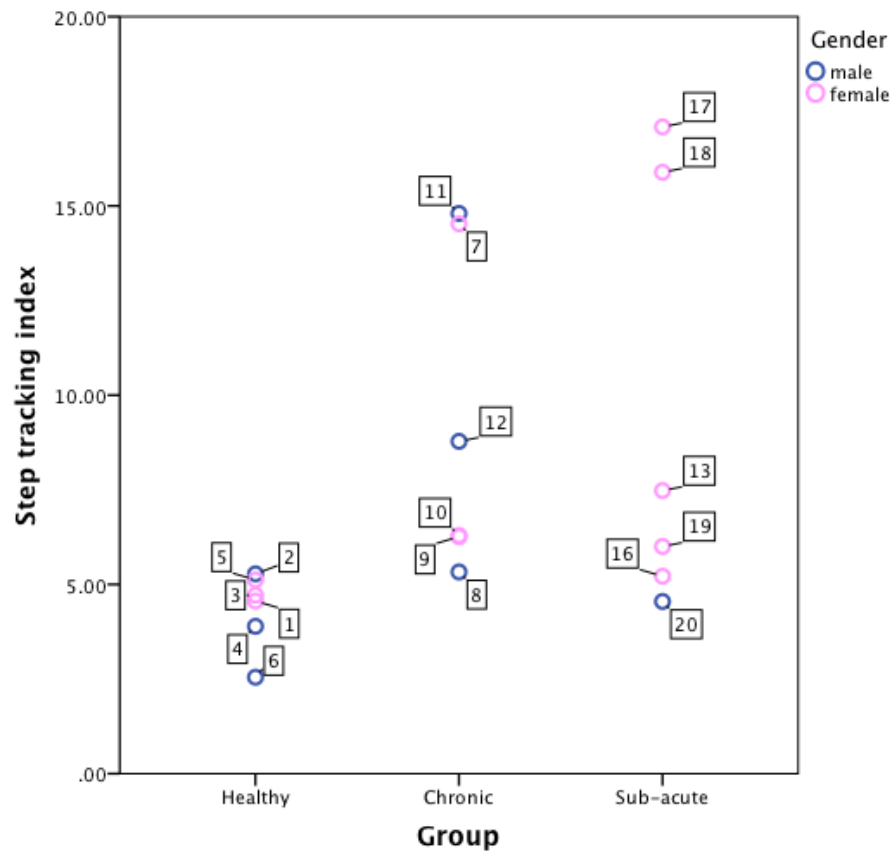


Figure 5.5 f) Extensor onset timing

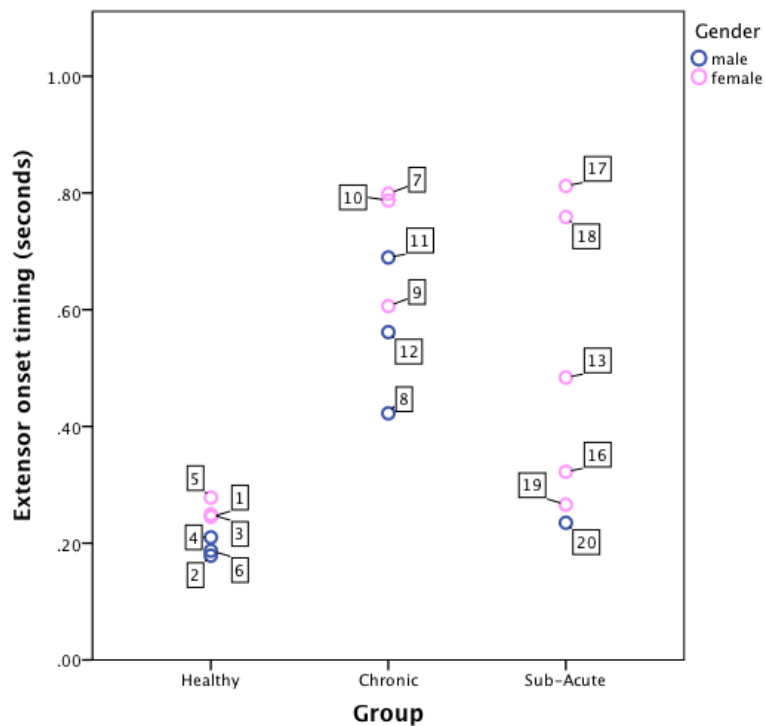


Figure 5.5 g) Path length

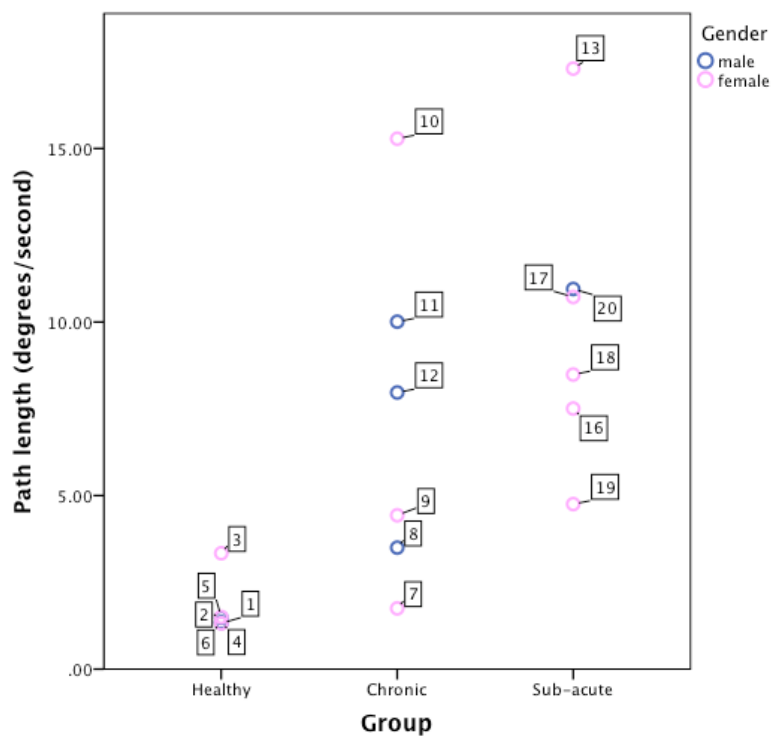


Figure 5.5(a-g) Dot plots for the negative impairment indices illustrating differences between participants in the healthy and chronic stroke groups (blue dot represents male; pink dot represents female)

Examples of participants' sinusoidal and step tracking performance are illustrated in Figure 5.6a-c and 5.7a-c, respectively.

Figure 5.6 a) Healthy # 5

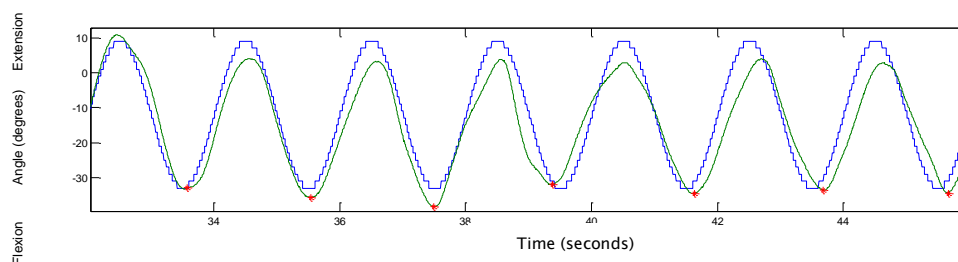


Figure 5.6 b) Chronic stroke # 10

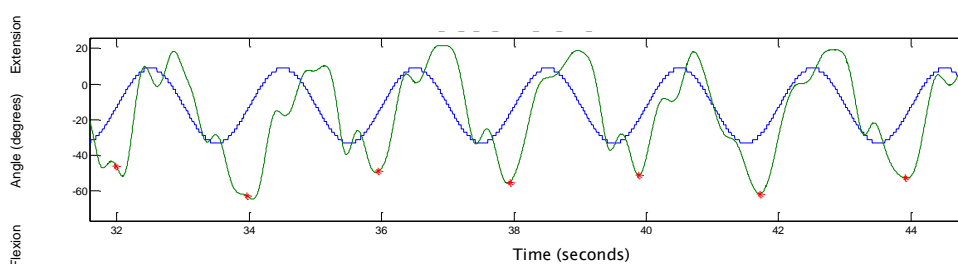


Figure 5.6 c) Sub-acute stroke # 17

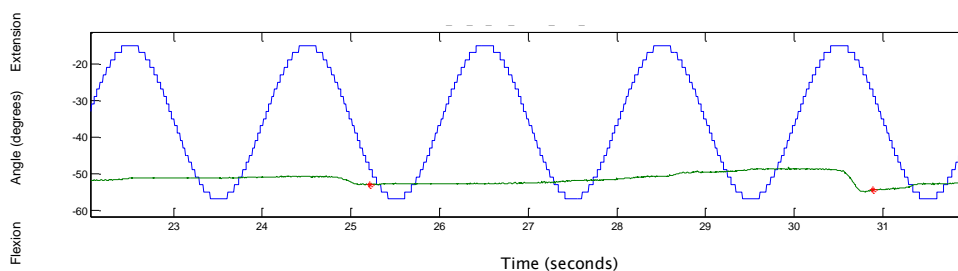


Figure 5.6(a-c) Examples of sinusoidal tracking performance at $0.5 \text{ Hz} \pm 20^\circ$ around the midpoint of the participant's AROM, showing target (blue line) and wrist movement (green line)

The chronic # 10 was able to track the target however, the movement was not smooth. The sub-acute stroke # 17 was unable to follow a target, as compared with the performances of healthy # 5 and the chronic # 10.

Figure 5.7 a) Healthy # 5

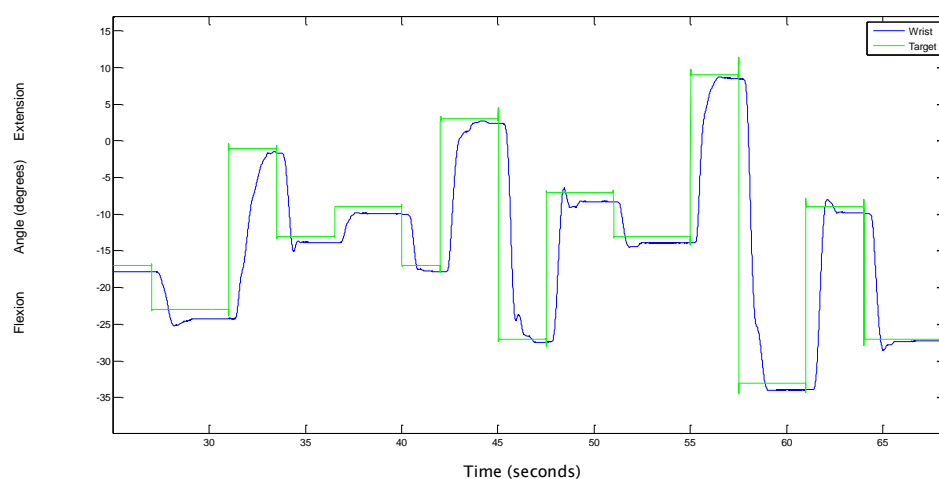


Figure 5.7 b) Chronic stroke # 10

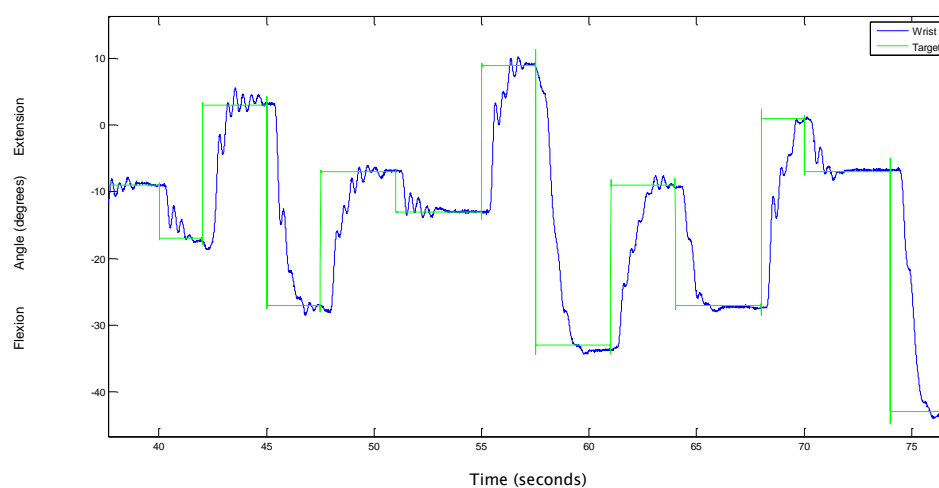


Figure 5.7 c) Sub-acute stroke # 17

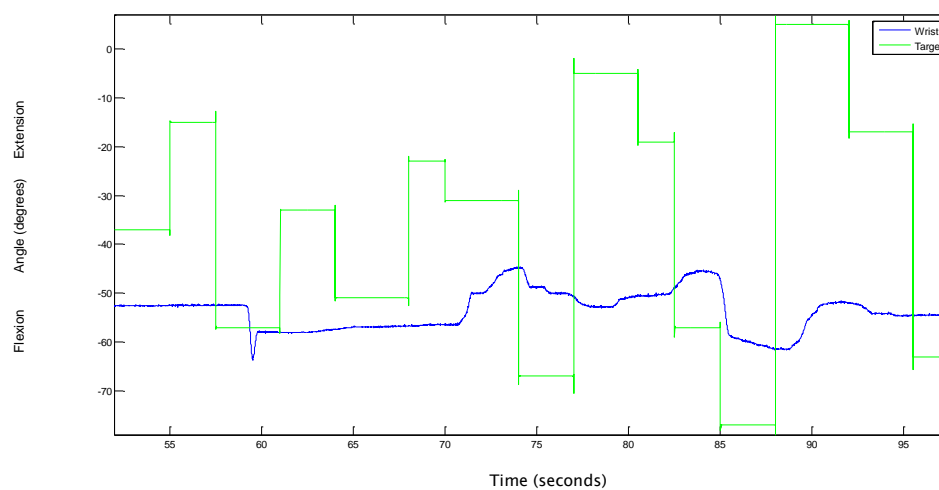


Figure 5.7(a-c) Examples of step tracking performance showing target (green line) and wrist movement (blue line)

It was observed that the chronic stroke # 10 could not execute movements smoothly. The sub-acute stroke # 17 missed a target, only being able to follow the flexion target.

According to the dot plots for the sine TI, there were outlier values from # 10 and #16 in the stroke groups (see Figures 5.5d). Their data were explored individually and it was found that their amplitude of movement was greater than the target amplitude, and the cross correlation calculation takes this into account (Figure 5.8 a-b).

Figure 5.8 a) Sub-acute stroke # 16

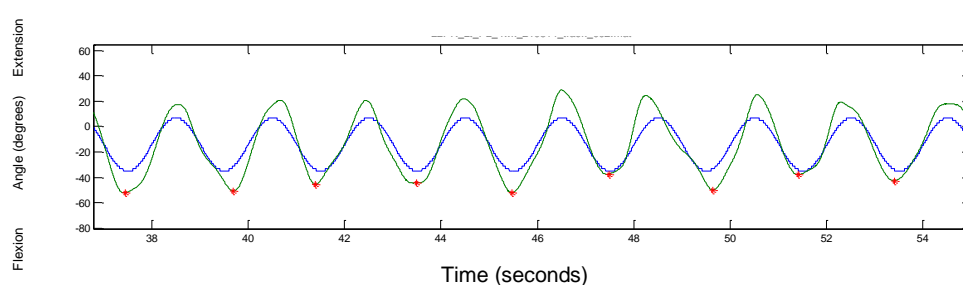


Figure 5.8 b) Healthy # 5

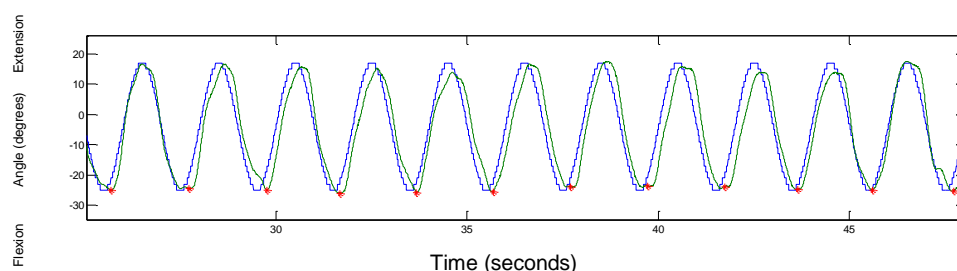


Figure 5.8(a-b) Example of participant's sine tracking movement (green line) and target movement (blue line) 5.8a) stroke # 16 who moved further than the target 5.8b) healthy # 5

5.5.3.2 Positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

The mean differences and 95% CI for positive impairments between the three groups are reported in Table 5.3. The medians of sine CI were negative value in all groups. The chronic stroke group presented highest third quartile sine CI compared to the two groups (note: negative value is indicating reciprocal activation; positive value is indicating coactivation). The third quartile SI of stroke groups were greater than for the healthy group (*note: greater index value implies high stretch response*).

Table 5.3 Median (IQR) and range of values for positive impairments in sub-acute stroke (N=8), chronic stroke (N=6) and healthy groups (N=6)

Wrist motor impairment indices	Median (IQR) [range of values]		
	Sub-acute (N=8)	Chronic (N=6)	Healthy (N=6)
Sine coactivation index	-0.16 (-0.27,-0.03) [-0.32-0.15]	-0.02 (-0.30, 0.36) [-0.34-0.37]	-0.17 (-0.47, 0.13) [-0.65-0.35]
Stretch index (3.5 Hz) (ratio SR: LBL)	1.01 (0.98, 1.14) [0.95-1.20]	1.00 (0.98, 1.07) [0.96-1.27]	1.00 (0.97, 1.01) [0.94-1.01]

SR-Stretch response; LBL-Local baseline

The dot plots demonstrated the individual data for each participant. The blue dots and pink dots represented the male and female participants, respectively (Figure 5.9 a-b). There were six participants in each group. The number of participants who had positive sine CI in the chronic stroke group was higher than the other two groups.

Figure 5.9 a) Sine CI

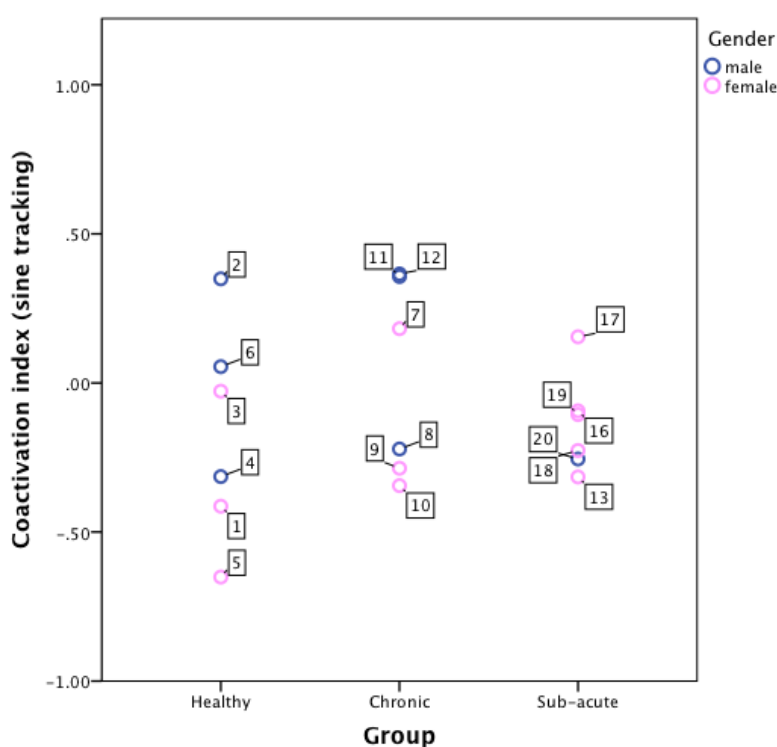


Figure 5.9 b) SI

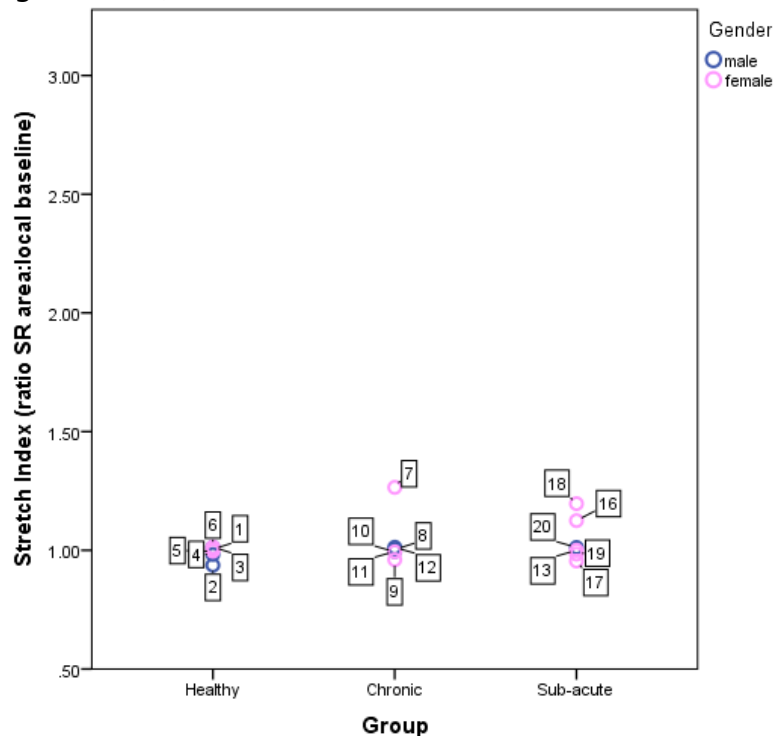


Figure 5.9(a-b) Dot plots for the positive impairment indices illustrating differences between participants in healthy and chronic stroke groups (blue dot represents male; pink dot represents female)

The majority of participants in all groups showed similar stretch indices. The # 7, #18 and #16 presented greater stretch index compared to other participants.

Examples of correlation between flexor and extensor EMG when extensor EMG was increasing, which indicated coactivation or reciprocal activation during sine tracking task in healthy and stroke participants, are illustrated in Figures 5.10 a-b.

Figure 5.10 a) Healthy # 5

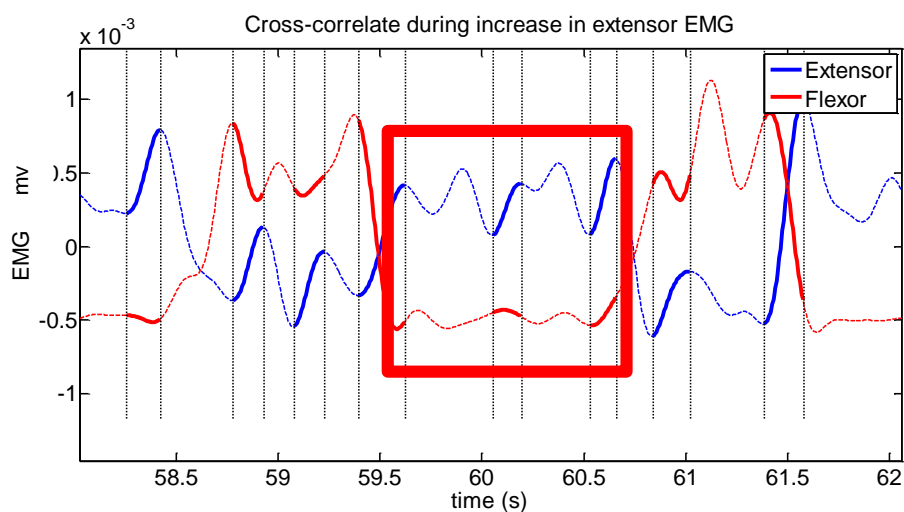


Figure 5.10 b) Chronic stroke # 7

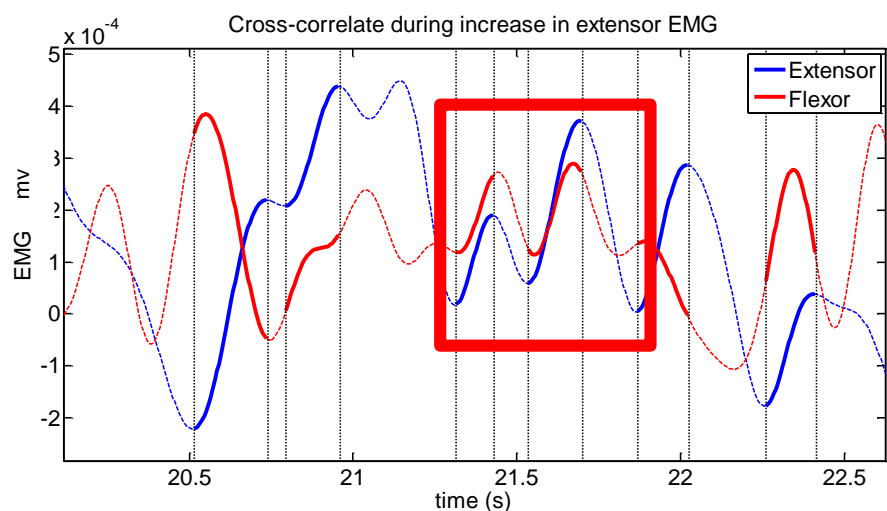


Figure 5.10 (a-b) Two examples (data in red boxes) of cross correlation during increase in extensor a) reciprocal activation and b) coactivation

It can be seen from the figure 5.10a that the extensor EMG was increasing when flexor EMG was decreasing (reciprocal activation) in the healthy # 5. In contrast, flexor EMG was increasing when extensor EMG was increasing in the chronic # 7 (coactivation) (Figure 5.10b).

5.5.3.3 Secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

Table 5.4 presents the mean differences and 95% CI for secondary impairments between the three groups. The healthy and sub-acute stroke groups exhibited a wider median PROM than members of the chronic stroke group. The average of MTI in the stroke groups was lower than in the healthy group.

Table 5.4 Mean (Standard deviation) and range of values for secondary impairments in sub-acute stroke (N=8), chronic stroke (N=6) and healthy groups (N=6)

Wrist motor impairment indices	Median (IQR) [range of values]		
	Sub-acute (N=8)	Chronic (N=6)	Healthy (N=6)
PROM (Degrees)	161.12 (158.66, 163.71) [145.94-164.50]	149.08 (130.36, 165.19) [89.98-167.15]	162.16 (158.17, 166.08) [152.37-167.34]
Mean torque index (Nm)	0.50 (0.29, 0.65) [0.18-0.69]	0.46 (0.32, 0.64) [0.28-0.83]	0.63 (0.45, 0.91) [0.43-0.96]

Individual data of each participant was presented by dot plots: blue dots represent males; pink dots represent females (Figure 5.11 a-b).

Figure 5.11 a) PROM

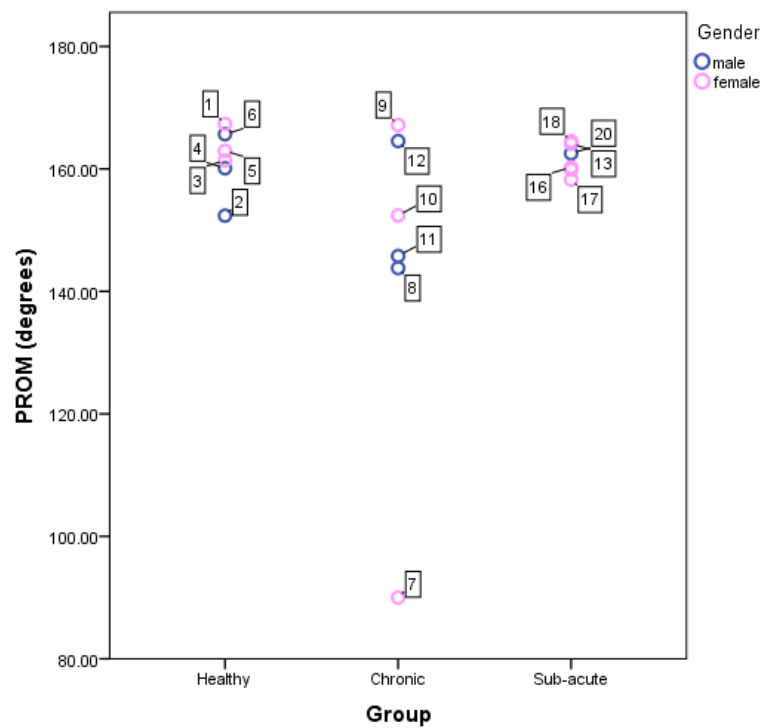


Figure 5.11 b) MTI

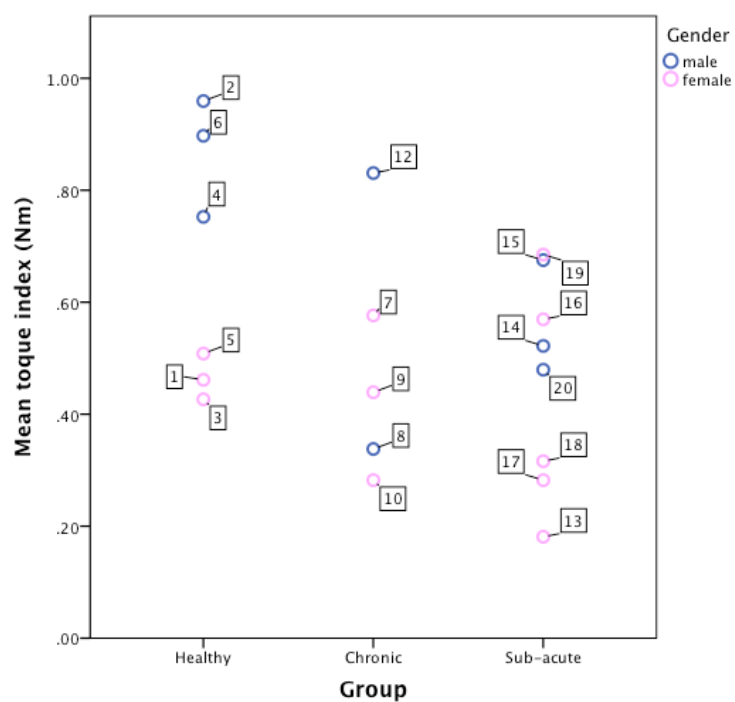


Figure 5.11 (a-b) Dot plots for the secondary impairment indices illustrating differences between participants in healthy and chronic stroke groups (blue dot represents male; pink dot represents female)

The majority of sub-acute stroke participants had a similar wrist PROM to that of healthy participants. Chronic stroke participants presented greater limitation of PROM than healthy and sub-acute stroke participants. There was considerable variation of MTI in the chronic stroke group, as compared to the healthy and sub-acute stroke groups. The variation of MTI in these three groups can be partly explained by differences in gender. Male participants exhibit greater MTI compared to female participants.

5.5.4 Participants' views about the wrist rig (comfort and ease of use) and the testing procedures

All participants took part in structured interviews about their experiences of using the wrist rig and its testing procedures. Issues of concern were noted and modifications were made prior to the longitudinal study. The majority of participants felt that the protocol was interesting and did not take too long to complete.

One participant experienced fatigue in their arms at the end of assessment. Another two participants, who were large in stature, felt uncomfortable in the wheelchair. All three healthy participants said that the wrist rig test was easy to perform, whereas the two chronic and another two sub-acute stroke participants (#11, #12, #18 and #19; all of whom had S-FM-UE scores= 6) mentioned that it was difficult to concentrate on the light on the white curvature screen. Three sub-acute stroke participants (#17, #18 and #19; one of whom had a S-FM-UE score =3 while the other two had S-FM-UE scores =6) experienced difficulties in contracting their wrist muscles.

5.5.5 Usability of the redesigned wrist rig

Usability of the redesigned wrist rig and software were evaluated during each assessment session and modified for further assessment. Issues encountered during usability test, before the pilot studies, and the modifications, which were made, are presented in Table 5.5. The modifications to the wrist rig and the software were carried out by Dr. David Simpson (ISVR Engineer) with the assistance of ISVR technicians.

Table 5.5 Issues encountered during a usability test before the pilot studies and modifications made

Subjects	Usability issues	Modifications
Force sensor	The force sensor was found to be inaccurate during calibration.	The amplifier was moved closer to the strain gauge to prevent drift of the voltages.
Wheelchair	The participants felt uncomfortable during the wrist rig testing because the backrest and seat did not provide firm support.	A cushion was inserted to improve the sitting posture of the participants.
Display target	The participants could not see a laser red light and a blue light target clearly. The red light was not bright enough on a white curve. The blue light was diffuse, which caused parallax. Therefore, the participants could not move to follow a real target.	A narrow black strip of paper with tiny holes was pasted on the white curved screen to improve contrast against the blue and red lights (Figure 5.12).



Figure 5.12 Black paper on a white curve of the redesigned wrist rig

There were more modifications made on the wrist rig system following the pilot studies with the healthy participants. Table 5.6 presents the issues that arose in pilot study 1 for healthy participants.

Table 5.6 Issues encountered during a pilot study 1 for healthy participants and modifications made

Subjects	Usability issues	Modifications
Sine tracking task	Duration of sine tracking task was too long. As a result, the participants complained of loss of concentration with looking at the lights for a long time.	Reduced testing duration of the sine tracking task from 240 seconds to 80 seconds. Rest break intervals must be provided during the tasks.
Target display	The red light superimposed on the blue light at the end of the curved screen, thus making it challenging to observe the red light.	Adjusted the red light to be higher than the blue light along the curved screen.

The procedure for data collection in pilot study 2 was further improved after the completion of pilot study 1 with 3 chronic stroke participants in the UK. The modifications made are presented in Table 5.7.

Table 5.7 Issues encountered during a pilot study 1 for chronic stroke participants and modifications made

Subjects	Usability issues	Modifications
Hand position	The participants who had severe spasticity could not place their hand in the air splint.	Passive stretch at the participants fingers into extension and placed their hand in the air splint in a flexed position, which is considered as a neutral starting position for that participant.
EMG	There were some instances when an EMG signal was not detected because of poor skin contact. In addition, movement of the reference electrode so that it	Use stronger elastic tape to secure the sEMG electrode to the participant's skin. The reference electrode was placed at the lateral

Subjects	Usability issues	Modifications
	touched the rig resulted in noise in the EMG signal.	epicondyle, which decreases the chance of the reference electrode coming in contact with any part of the redesigned wrist rig.
Rest period before starting torque/angle test	The rest period of 5 seconds before the commencement of the torque/angle test was too brief to ensure muscle relaxation, resulting in activity prior to commencing the passive movement and potentially a larger than expected stretch response.	Rest period of the torque/angle test was increased to 10 seconds.

Finally, modification was further made to be suitable for testing in the sub-acute stroke participants (Table 5.8).

Table 5.8 Issue encountered during pilot study 2 for sub-acute stroke participants and modifications made

Subjects	Usability issues	Modifications
Participants' endurance	Two participants were unable to be assessed by the SWMFT-S and the wrist rig test completely on the same day.	The participants who had low endurance were assessed by the SWMFT-S followed by the wrist rig on the day after.

5.6 Discussion

5.6.1 Time taken to conduct the whole assessment session

The average time to complete a whole assessment session (including clinical assessments, SWMFT-S and the wrist rig tests) was about 1 hour. The assessment period seemed appropriate for early acute stroke participant since, although easily fatigued, majority of participants managed to complete their

test sessions. It was noted that the assessment session had to be conducted before their routine physiotherapy programme as any treatment was likely to have an effect on motor impairments measured. Assessment duration for the participants who were able to ambulate independently was shorter than for the participants who were totally dependent because those in the latter group required some time for their transfer.

5.6.2 Impairments indices

5.6.2.1 Negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

Muscle weakness: AROM and wrist flexor and extensor IF in both the acute and chronic stroke participants were generally lower than healthy participants (Figure 5.5 b-c). These results are in accordance with previous research, which established that stroke patients commonly suffered muscle weakness in their affected side (Ada et al. 1996; Andrews and Bohannon 2000; Andrews and Bohannon 2003; Kamper et al. 2006; Conrad and Kamper 2012). Muscle weakness in the sub-acute stroke group appeared to be less than the chronic stroke group; results were similar to the previous study by Turk (2011).

Motor control accuracy: The MCA was determined as sine TI, step TI and path length. The participants in the sub-acute and chronic stroke groups demonstrated poorer MCA than the healthy group. Current evidence suggests that loss of MCA is found in stroke patients (Ada et al. 1996; Canning et al. 2000; Canning et al. 2004; Turk et al. 2008; Turk 2011). We quantified the sine TI during rhythmic movement using the cross correlation method as was done in the study by Turk (2011). Turk (2011) found that the sine TI of the healthy group was greater than the acute and chronic stroke groups and, therefore, a greater score was 'better'. However, we found two stroke participants who had sine TI greater than healthy participants (Figure 5.4d). This might be because the method of analysis of the sine TI was not valid. On the other hand, the step TI was lower in the healthy group than in the stroke groups. This might be due to the fact that the method used to quantify the step TI was based on the error of movement during the step tracking task. Obviously, the stroke participants had greater errors of movement than the healthy participants. Therefore, the MAE method was planned to assess the

sine TI in a similar way to the step TI. The reliability and validity of sine TI (MAE) are discussed in Chapter 6 and Chapter 7, respectively. The path length was very small in the healthy group, whereas it was wide in both stroke groups; a finding replicating that of Turk (2011).

Muscle onset timing: The healthy group demonstrated lower wrist extensor onset timing than the stroke groups (note: lower index value is better). These findings are consistent with other studies that found slow initiation of muscle contraction in people with stroke (Dewald et al. 1999; Chae et al. 2002a).

5.6.2.2 Positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

Spasticity: Although the median score for SI was similar between the three study groups, there were three stroke participants who presented a greater SI (high sensitive stretch reflex) than the healthy participants. This finding appears to be consistent with a study by Turk (2011), which analysed the SI by the same method as was employed in our study, and which found that the SI in both stroke groups was higher than the healthy group.

Muscle coactivation: The majority of healthy participants demonstrated a negative sine CI (indicating reciprocal activation). The number of participants who presented a positive CI (coactivation) in the stroke group (N=3 in chronic group and N=1 in sub-acute group) was higher than the healthy group (N=2). This finding further supported the premise that people with stroke exhibited abnormal muscle coactivation (Prange et al. 2012; Ohn et al. 2013)

5.6.2.3 Secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

Non-neural stiffness: The MTI in the healthy group was greater than both stroke groups. We found similar trends of MTI as in a previous study by Turk (2011).

Contracture: All participants in the healthy and sub-acute stroke groups demonstrated no limitation of the wrist movement. Development of contracture usually occurs when muscle is being maintained in a shortened position for a long period (Sheean 2001). This may explain by the participants

who had just lost their active movement (sub-acute stroke participants) had no contracture.

Overall, the method to quantify impairment indices could provide a similar trend of impairment indices compared to previous studies (Chae et al. 2002b, a; Ada et al. 2006; Burridge et al. 2009; Malhotra et al. 2011; Turk 2011). However, because all these studies have been conducted with western populations, it may be incomparable with the Thai population. Therefore, the range of values for each impairment index in the Thai impaired and non-impaired participants were investigated in a matched pair study (Chapter 7). The construct validity (ability to distinguish between impaired and unimpaired) of the redesigned wrist was examined in the matched pair study. The redesigned wrist rig shows high content validity to measure wrist motor control, since it measures muscle activity, accuracy and range of movement, spasticity, muscle weakness and stiffness, which are the main constructs of wrist motor control. These pilot studies were the ways employed by the author (WS) to assess the longitudinal study's feasibility. Statistical analysis was not employed at this stage.

5.6.3 Participants' views about the wrist rig (comfort and ease of use) and the testing procedures

The administration of the wrist rig test could exacerbate fatigue of the participants' arms. Normal fatigue can be defined as 'a state of general tiredness that is a result of overexertion, which can be recovered by rest' (De Groot et al. 2003). The participants who presented with fatigue recovered and then continued with the remainder of the test within the same day. Rest break intervals were provided during the whole testing session.

There were two UK participants who were large in stature and felt uncomfortable in the wheelchair. This problem was solved by adjusting the wheelchair for them. All Thai participants were able to fit into the wheelchair.

Four stroke participants (#11, #12, #18 and #19) in the pilot studies mentioned that it was difficult to concentrate on the blue light target on the white curvature screen during the tracking tasks (designed to measure MCA (MCA)). All of them had moderate motor deficit. Basically, low performance of

the tracking tasks occurred either because of their poor MCA or their mental saturation. Rest break intervals between tracking tasks were provided. Furthermore, the participants who were too tired to complete the whole assessment session could be tested again on another day. Hence, this ensured that their low MCA was not affected by fatigue.

5.7 Conclusions

The wrist rig tests together with the SWMFT-S were feasible for use with patients at the early stage in terms of the time needed for assessment and the comfort of the participants. Methods of analysis for wrist motor impairment indices generated similar trends of indices when compared with the previous study (Turk 2011). The construct validity of those indices was further addressed (Chapter 7).

5.8 Summary of Chapter 5

This chapter has presented the research questions, objectives, research methodology, results, discussion and conclusions of the pilot studies 1 and 2.

The next chapter details the reliability study, which investigated test-retest reliability and MDC of the wrist motor impairment indices generated by the redesigned wrist rig, including introduction, research questions, objectives, methodology, results, discussion and conclusions.

Chapter 6: Reliability study

6.1 Introduction

Following recent modifications of the redesigned wrist rig, a test-retest reliability study of the redesigned wrist has not been conducted. Although a between-days test-retest reliability of the wrist rig was conducted in a study by Turk (2011), the SI and MTI have not been evaluated. In addition, MDC of each wrist motor impairment is needed to report the benchmark values for defining true change of the motor impairments in the longitudinal study (Chapter 8).

This chapter presents the details of a reliability study including research questions, methodology, results, discussion and conclusions, which accounts for part of the longitudinal study.

6.2 Research questions

1. Is the redesigned wrist rig reliable?
2. What is MDC for AROM, flexor and extensor IF, sine and step TI, path length, extensor onset timing, sine CI, SI, PROM and MTI?

6.3 Objectives

1. To investigate reliability of the redesigned wrist rig tests.
2. To investigate the repeatability coefficient or MDC of each motor impairment measured by the redesigned wrist rig

6.4 Methodology

Testing procedures and data analysis for the reliability study are presented in this section.

6.4.1 Testing procedures

The participants, who were eligible to participate in this study, undertook the wrist rig tests (see section 4.8.2.3 for more detail) twice at their eight weeks

post-stroke assessment, within an interval of three to five days, with considerations to rule out practise effect and any possible spontaneous recovery of upper limb (Chen et al. 2009). An assumption was made that no clinically relevant changes in wrist impairments of the participants had occurred.

6.4.2 Statistical analysis

6.4.2.1 Descriptive statistics

The median (interquartile range) are used to present all characteristic and clinical (wrist joint proprioception, spasticity and upper limb impairment) data of the participants since they were non-normally distributed.

6.4.2.2 Reliability of wrist motor impairment indices

The intra-class correlation (ICC) was used to assess the reliability of wrist motor impairment indices. However, the ICC cannot indicate the magnitude of disagreement between measurements. In addition, the ICC is the ratio of true score variance (between-subjects variance) to true score variance plus error. If the true score variance is sufficiently large, reliability will always appear high. The 95% limits of agreement Bland and Altman plot have powerful visual representation of the degree of agreement. It's easy to see range of differences in measurements and to identify bias and outliers (Rankin and Stokes 1998). Therefore, the Bland Altman method was also used to evaluate the between-days agreement for the impairment measurement indices.

The MDC was calculated as $\pm 1.96\sqrt{2} \times \text{SEM}^*$ and gives a 95% range about the true change that might be expected from measurement error alone. Changes larger than the value of the MDC could be considered to be due to a real change in underlying values, rather than random variations (Beckerman et al. 2001).

* Standard error of measurement (SEM) = $\sqrt{((\text{total variance})(1 - \text{ICC}))}$ (Beckerman et al. 2001)

6.5 Results

6.5.1 Participants characteristics

The characteristic data of 14 sub-acute participants (eight weeks post-stroke) in the reliability sub-group is presented in Table 6.1. The participants exhibited moderate to mild upper limb impairment (S-FM-UE score range 6-12).

Table 6.1 Characteristics data of the participants in the reliability sub-group (N=14)

	sub-acute participants (8 weeks post-stroke) (N=14)
Age (years): mean (SD)	58 (15)
[min-max]	[18-77]
Gender	5 male
	9 female
Side assessed	5 left
	9 right
Wrist flexor spasticity-modified AS: Median (IQR)	0 (0, 0)
[min-max]	[0-1]
Wrist joint position sense -Proprioception- Nottingham Sensory Assessment	14 normal
Upper limb motor impairment-S-FM-UE (0-12):	9 (8, 11)
Median (IQR) [min-max]	[6-12]

6.5.2 Between-days test-retest reliability of impairment indices measured by using a redesigned wrist rig

6.5.2.1 Negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

The means (SD) of negative motor impairment indices for day 1 and 2 and ICCs, for between-days test-retest reliability are presented in Table 6.2. The ICCs of each negative motor impairment index was higher than 0.80.

The mean difference, limits of agreement and MDC for each index are reported in Table 6.3. The mean difference and limits of agreement for each index were small compared to its range of values.

The Bland and Altman plots for between-days test-retest reliability for each negative motor impairment index are illustrated (Figure 6.1 a-g). There was no evidence of a trend in the differences between two days assessment. There was a person who showed outliers of difference between two days for wrist flexor and extensor IF, sine and step TI, path length and muscle onset timing (Figure 6.1 b-g).

Table 6.2 Means (SD) and ICCs for between-days test-retest reliability of negative motor impairment indices (N=14)

Wrist motor impairment indices	Mean (SD)		ICC (95%CI)	<i>p</i>
	day 1	day 2		
AROM (degrees)	145.1 (11.5)	146.6 (12.5)	0.89 (0.70, 0.96)	0.000*
Flexor IF (Nm)	3.64 (1.84)	3.93 (2.12)	0.94 (0.80-0.98)	0.000*
Extensor IF (Nm)	2.67 (1.61)	2.82 (1.52)	0.99 (0.94, 1.00)	0.000*
Sine TI (MAE) (degrees)	8.18 (67.78)	8.64 (66.46)	0.97 (0.91, 0.99)	0.000*
Step TI (MAE) (degrees)	6.19 (2.29)	6.45 (2.58)	0.96 (0.88, 0.99)	0.000*
Extensor onset timing (seconds)	0.43 (0.22)	0.44 (0.24)	0.96 (0.88, 0.99)	0.000*
Path length (degrees/second)	8.50 (4.07)	8.16 (4.05)	0.92 (0.78, 0.97)	0.000*

AROM- active range of motion; IF-isometric force; MAE-mean absolute error; * $p \leq 0.001$

Table 6.3 Between-days reliability for the negative motor impairments indices showing the range of values, mean difference between day 1-day 2 (95%CI), limits of agreement and MDC (N=14)

Wrist motor impairment indices	Range of values	Between-days reliability		
		Mean difference (95%CI)	Limits of agreement	MDC
AROM (degrees)	126.3-169.8	-1.44 [-4.7, 1.8]	(-12.4, 9.5)	±11.56
Flexor IF (Nm)	1.45-8.08	-0.30 (-0.06, 0.44)	(-2.24, 1.64)	±1.31
Extensor IF (Nm)	0.92-3.33	-0.15 [-0.28, 0.01]	(-0.59, 0.29)	±0.43
Sine TI (MAE) (degrees)	2.95-25.69	-0.45 [-1.22, 0.32]	(-3.08, 2.18)	±2.62
Step TI (MAE) (degrees)	4.0-13.2	-0.25 [-0.64, 0.13]	(-1.56, 1.05)	±2.10
Path length (degrees/second)	1.35-16.13	0.34 [-0.59, 1.27]	(-2.82, 3.51)	±3.29
Extensor onset timing (seconds)	0.2-0.9	-0.01 [-0.04, 0.03]	(-0.14, 0.12)	±0.13

AROM- active range of motion; IF-isometric force; TI-tracking index; MAE-mean absolute error

Figure 6.1 a) AROM

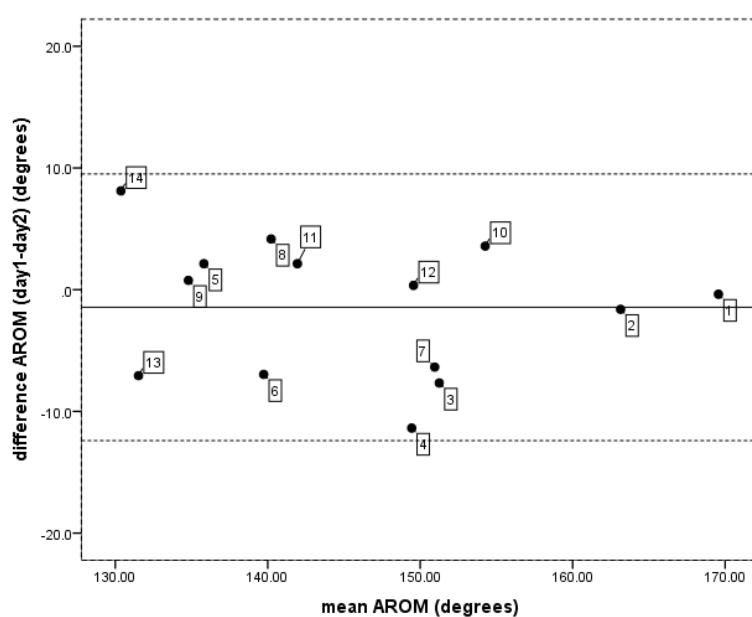


Figure 6.1 b) Flexor IF

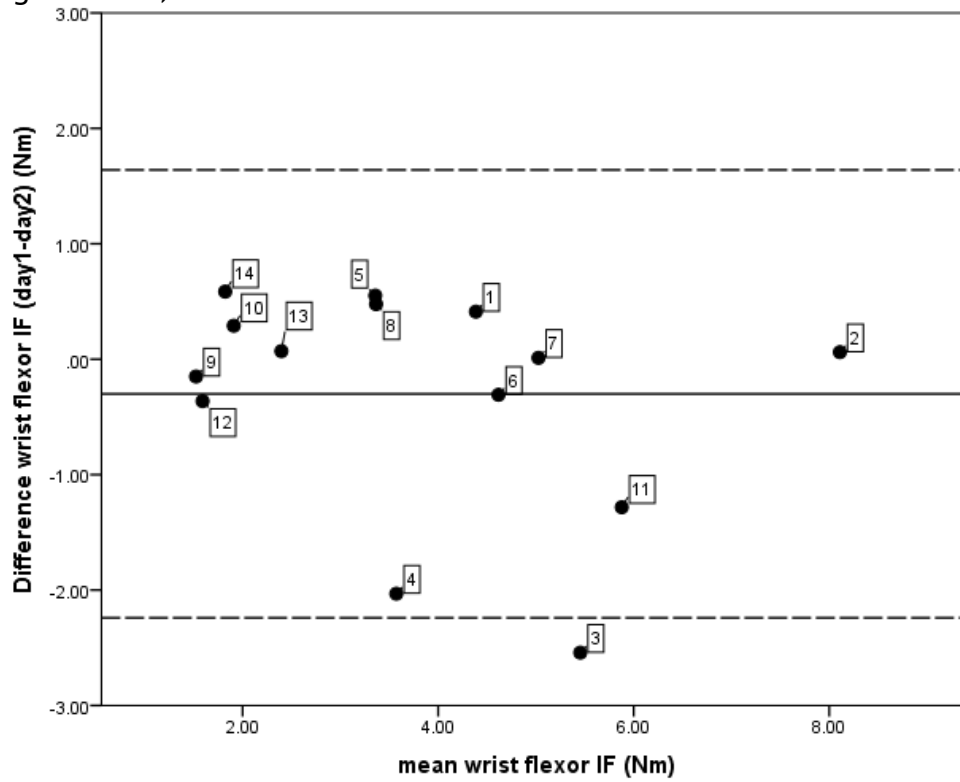


Figure 6.1 c) Extensor IF

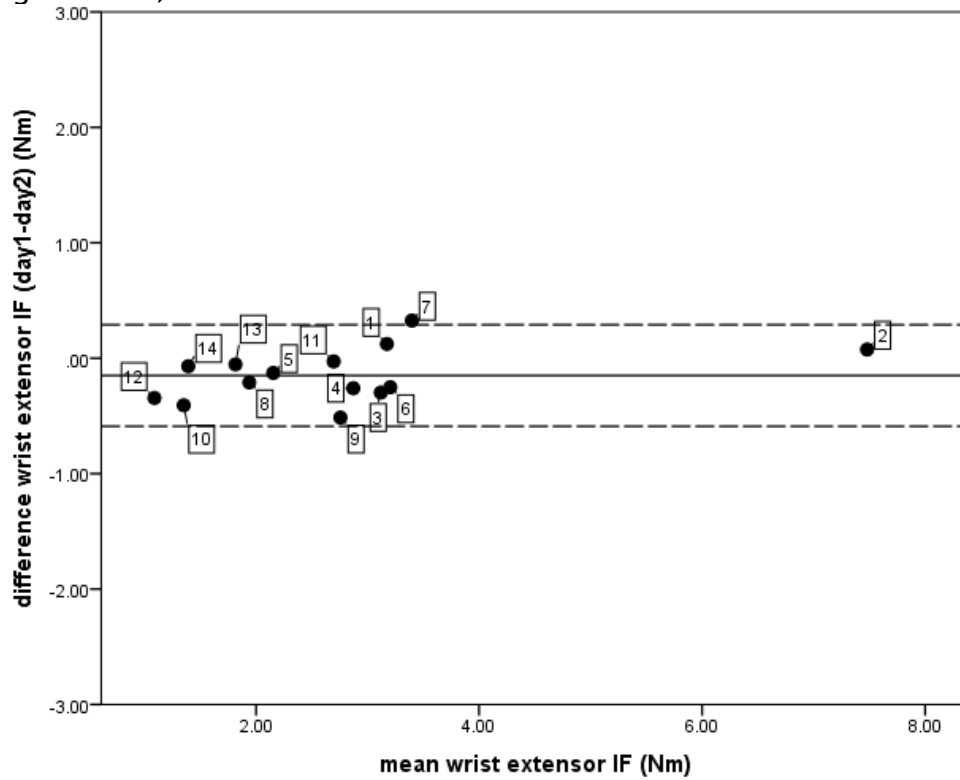


Figure 6.1 d) Sine TI (MAE)

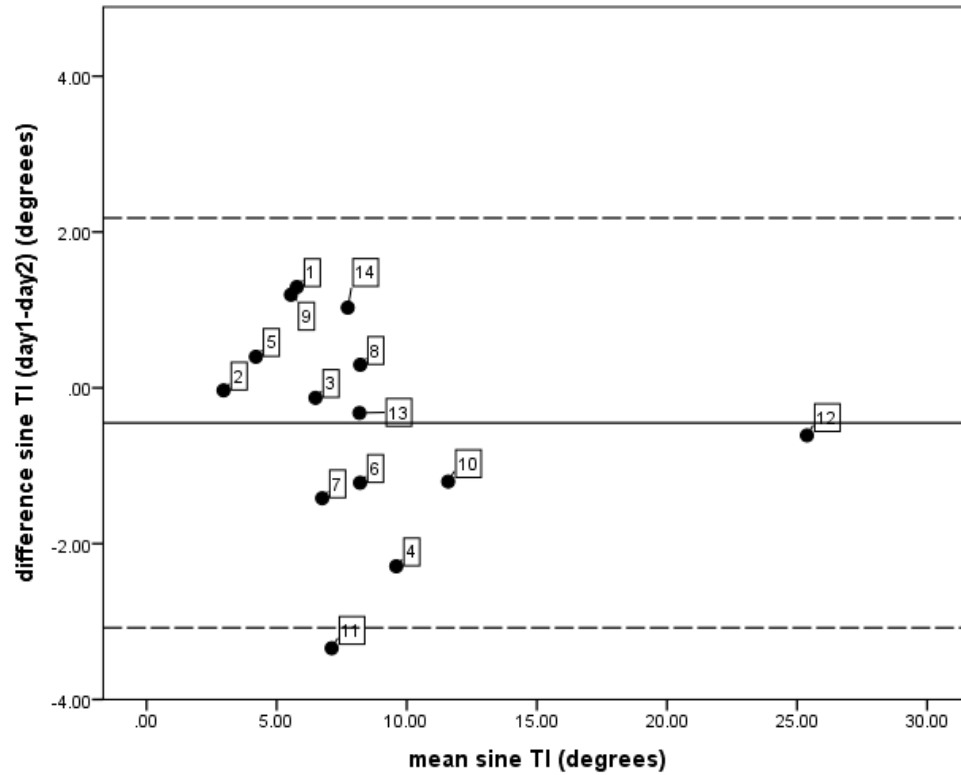


Figure 6.1 e) Step TI (MAE)

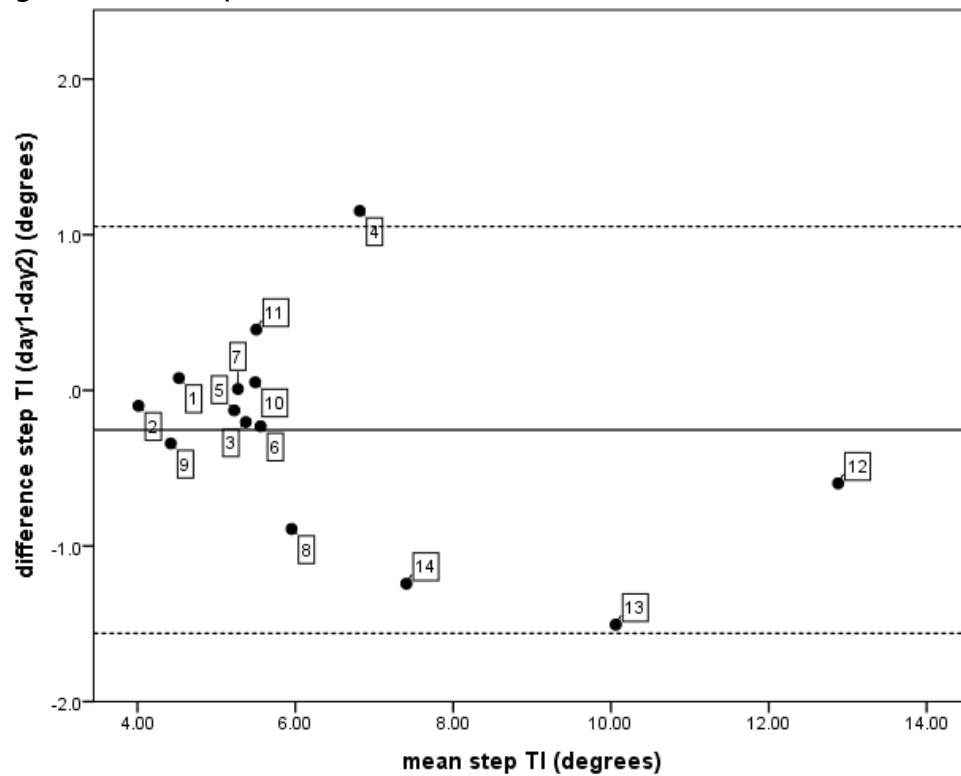


Figure 6.1 f) Path length

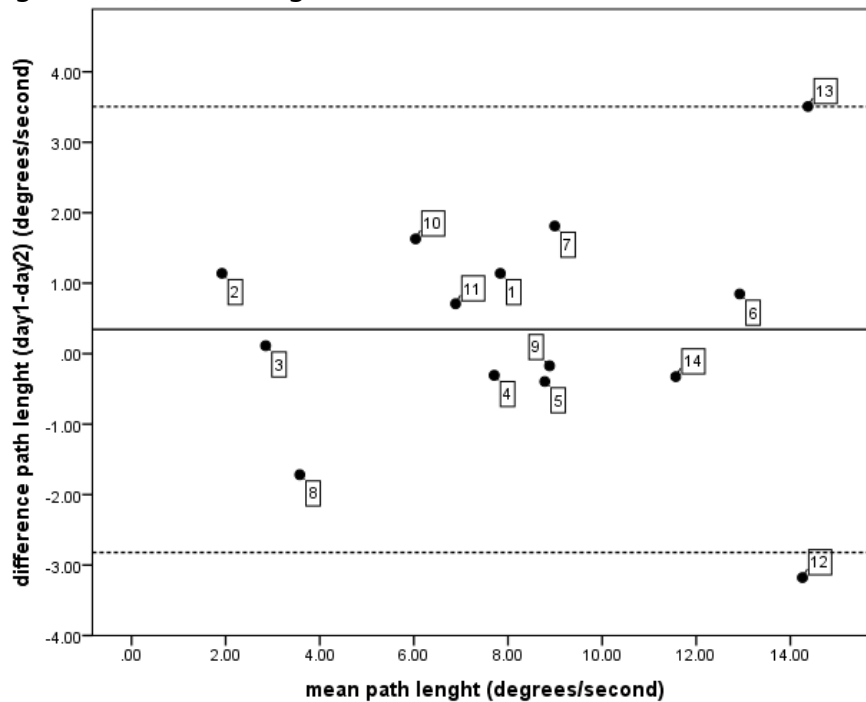


Figure 6.1 g) muscle onset timing

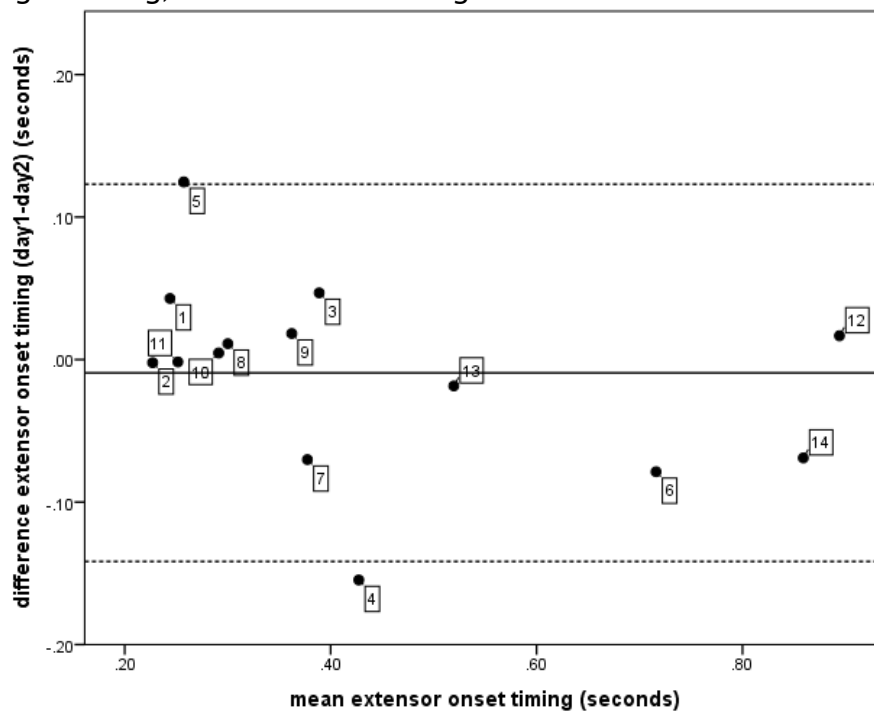


Figure 6.1(a-g) Bland Altman plots for between-days test-retest reliability for 14 sub-acute participants in the reliability sub-group, showing mean difference (bold line) and limits of agreement (dashed line) of negative impairments (AROM, wrist flexor and extensor IF, sine and step TI (MAE), path length and extensor onset timing)

6.5.2.2 Positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

Table 6.4 shows the means (SD) of positive motor impairment indices and ICCs for between-days test-retest reliability. The ICCs of the positive motor impairment indices were higher than 0.80.

Table 6.5 presents mean difference, limits of agreement and MDC for each positive motor impairment index. As with the negative motor impairment indices, the mean difference, limits of agreement for each index were small compared to its range of values.

The Bland and Altman plots for between-days test-retest reliability for positive motor impairment indices are illustrated (Figure 6.2 a-b). Similar to the negative motor impairment indices, there was no trace of a trend in the means between-day difference for all indices. An outlier was found for the SI in one person (Figure 6.2 b).

Table 6.4 Means (SD) and ICCs for between-days test-retest reliability of positive motor impairment indices (N=14)

Wrist motor impairment indices	Mean (SD)		ICC (95%CI)	<i>p</i>
	day 1	day 2		
Sine CI (correlation coefficient)	-0.39 (0.22)	-0.41 (0.19)	0.87 (0.65, 0.96)	0.000*
SI (3.5 Hz) (ratio SR: LBL)	1.11 (0.19)	1.14 (0.18)	0.91 (0.75, 0.97)	0.000*

SR-Stretch response; LBL-Local baseline* $p \leq 0.001$

Table 6.5 Between-days test-retest reliability for the positive motor impairments indices showing the range of values, mean difference between day 1-day 2 (95%CI), limits of agreement and MDC (N=14)

Wrist motor impairment indices	Range of values	Between-days reliability		
		Mean difference (95%CI)	Limits of agreement	MDC
Sine CI	-0.71-0.1	0.02 [-0.04, 0.08]	(-0.19, 0.23)	± 0.21
SI (3.5 Hz) (ratio SR: LBL)	0.98-1.71	-0.03 [-0.07, 0.01]	(-0.18, 0.11)	± 0.16

SR-Stretch response; LBL-Local baseline

Figure 6.2 a) Sine CI

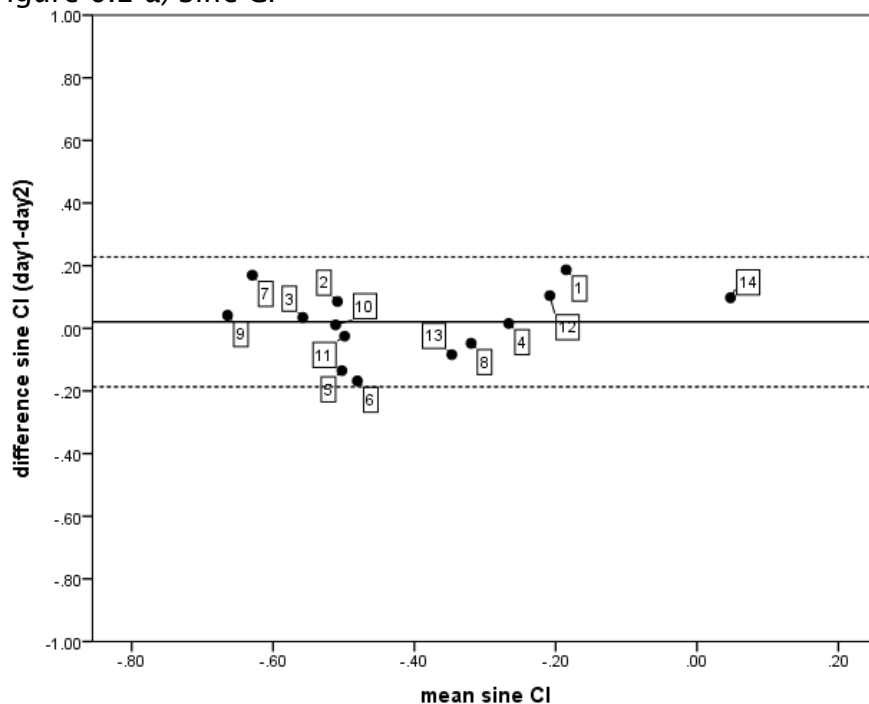


Figure 6.2 b) SI

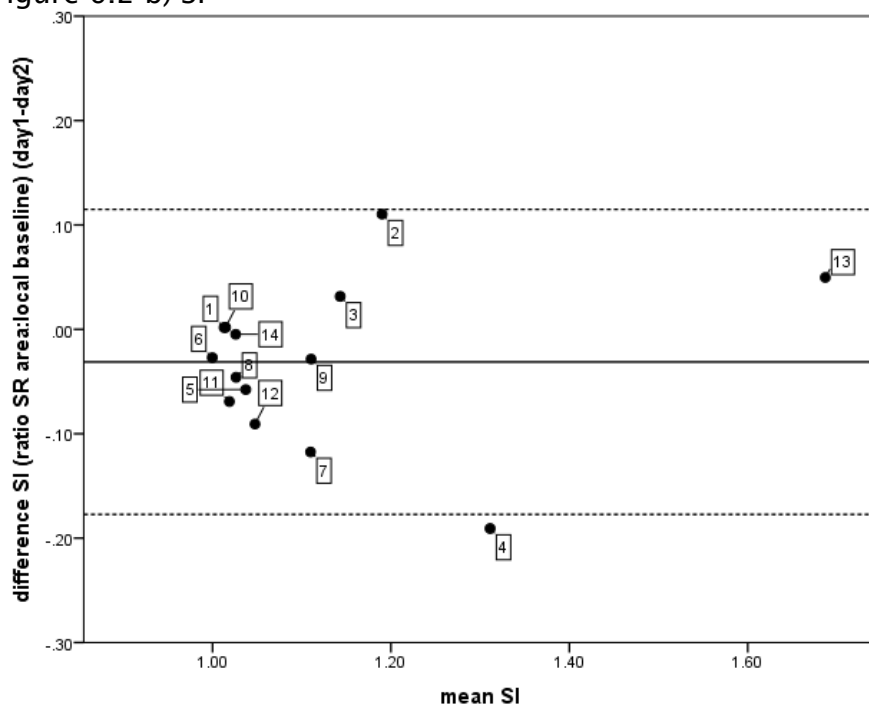


Figure 6.2(a-b) Bland Altman plots for between-days test retest reliability for 14 sub-acute participants in the reliability sub-group, showing mean difference (bold line) and limits of agreement (dashed): positive impairments – sine CI, SI

6.5.2.3 Secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

The means (SD) of secondary motor impairment indices and ICCs for between-days test-retest reliability are presented in Table 6.6. The ICCs for the PROM was the lowest compared to another wrist motor impairment indices.

Table 6.7 presents mean difference, limits of agreement and MDC for the negative motor impairment indices. The mean difference, limits of agreement for PROM was extremely small compared with its ranges of values.

Figure 6.3 (a-b) illustrates the Bland and Altman plots for between-days test-retest reliability for secondary motor impairment index. There was no trace of a trend in the means difference between-days for all indices. An outlier was found in one participant for the MTI (Figure 6.3 b).

Table 6.6 Means (SD) and ICCs for between-days test-retest reliability of secondary motor impairment indices (N=14)

Wrist motor impairment indices	Mean (SD)		ICC (95%CI)	<i>p</i>
	day 1	day 2		
PROM (degrees)	171.6 (1.3)	171.6 (1.3)	0.78 (0.43, 0.92)	0.000*
MTI (Nm)	0.27 (0.11)	0.26 (0.12)	0.90 (0.73, 0.97)	0.000*

PROM-Passive range of motion; Nm-Newton metre* $p \leq 0.001$

Table 6.7 Between-days test-retest reliability for the secondary motor impairments indices showing the range of values, mean difference between day 1-day 2 (95%CI), limits of agreement and MDC (N=14)

Wrist motor impairment indices	Range of values	Between-days reliability		
		Mean difference (95%CI)	Limits of agreement	MDC
PROM (degrees)	167.88-173.39	0.05 [-0.45, 0.56]	(-1.67, 1.78)	± 1.83
MTI (Nm)	0.06-0.43	0.01 [-0.02, 0.03]	(-0.10, 0.11)	± 0.11

PROM-Passive range of motion; Nm-Newton metre

Figure 6.3 a) PROM

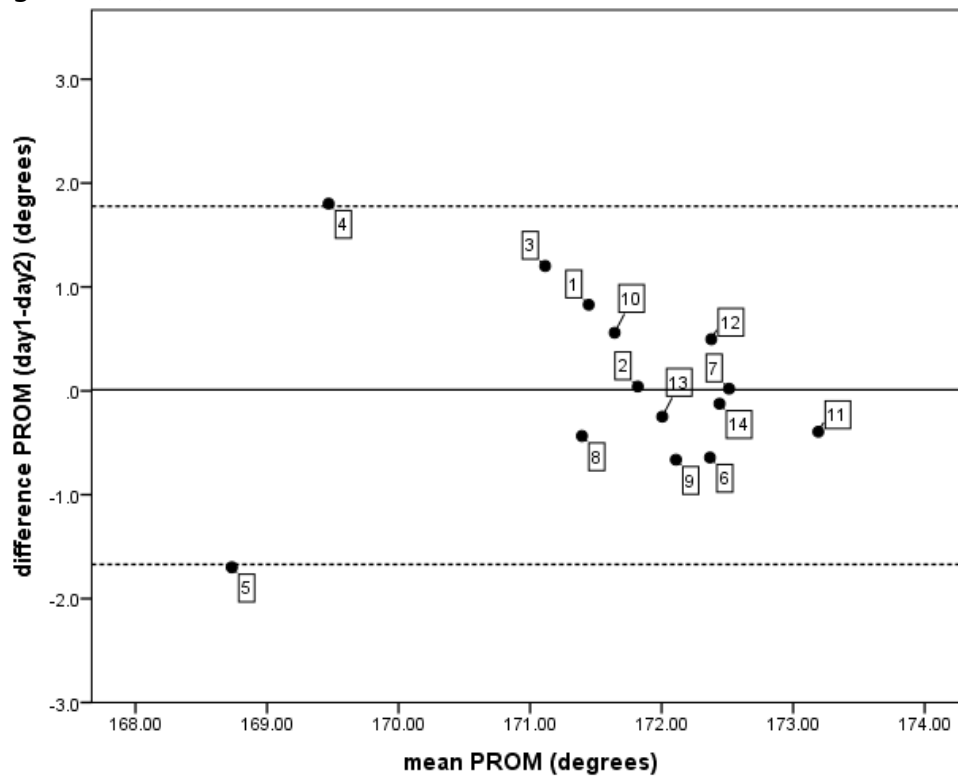


Figure 6.3 b) MTI

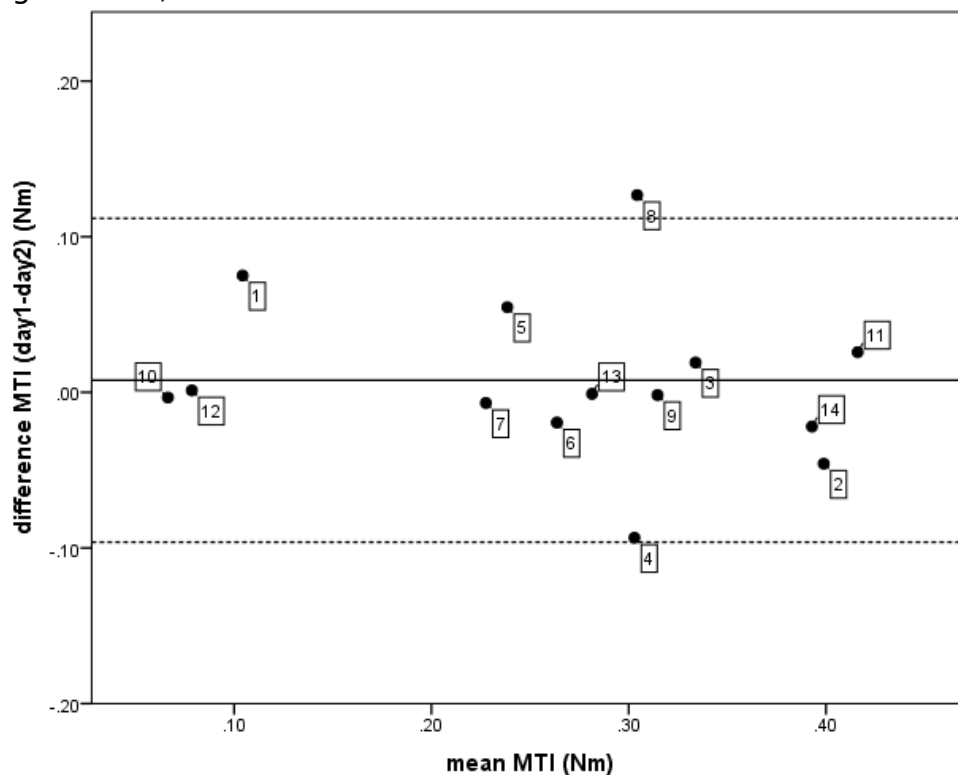


Figure 6.3(a-b) Bland Altman plots for between-days test retest reliability for 14 sub-acute participants in the reliability sub-group, showing mean difference (bold line) and limits of agreement (dashed): secondary impairments – PROM and MTI

6.6 Summary of results

The ICC for the between-days test-retest reliability for the measurement indices from the wrist rig tests, were greater than 0.8 (0.87 to 0.99). The only exception was the ICC for PROM, which was slightly less at 0.78. However, the PROM demonstrated a remarkably small mean difference between the two days assessments.

The MDC of AROM, flexor IF, extensor IF, sine TI, step TI, path length and extensor onset timing were $\pm 11.56^\circ$, ± 1.31 Nm, ± 0.43 Nm, $\pm 2.62^\circ$, $\pm 2.10^\circ$, ± 3.29 degrees/second and ± 0.13 seconds, respectively. For positive impairments, the MDC of sine CI was ± 0.21 and the SI was ± 0.16 . The MDC of the PROM and MTI, which are secondary impairments, were $\pm 1.83^\circ$ and ± 0.11 Nm, respectively. The MDC values represent the minimum amount of change needed to show a true change in a measure that is not due to measurement error alone.

6.7 Discussion

We evaluated the between-days test-retest reliability of wrist motor impairment indices generated by the redesigned wrist rig and established the MDC of those indices. The results showed that the redesigned wrist rig demonstrated good to excellent reliability (ICC 0.78-0.99). The MDC of each wrist motor impairment index, as measured by the redesigned wrist rig was suggested as benchmark values.

The between-days test-retest reliability of the wrist motor impairment indices was conducted in people with sub-acute stroke (eight weeks). There are five factors which might affect the results of the level of agreement: spontaneous recovery, the learning effect, participants' fatigue, error of the rater and surface electromyography (sEMG) placement. The data collection procedure was carefully planned to minimise the effect of those five factors. A period of between-days assessments was determined, similar to that of the previous study by Chen et al. (2009), who also investigated the test-retest reliability of upper limb impairment and ULFA assessments in patients with acute stroke (onset less than 26 weeks). Chen et al. (2009) suggested administering between-days assessments, three to five days apart, to minimise the effects of

spontaneous recovery and learning effect. In the same way, we conducted the wrist rig tests with the same participants within a 3-day period. Prior to the actual data collection, participants were allowed to practise performing the test until they reached their maximal performance (3 to 5 practise sessions depending on the participant's ability and their rate of learning). All data sets were analysed to select the best performance as their score. A rest break was provided during the assessment period. This would ensure that the data collected was not affected by fatigue. The researcher (WS) had been trained to conduct the test before commencement of data collection and was the only rater for all assessments, which ruled out any variability between raters. Another factor which may result in poor agreement between two assessment sessions was inconsistency of the sEMG electrodes placement. If the sEMG electrodes were not exactly placed at the same area, the signals that were gathered may differ. Therefore, the sEMG electrodes were placed according to the standard guidelines (European recommendations for surface ElectroMyoGraphy: results of the SENIAM project) (Hermens et al. 1999). In addition, ensuring good quality of contact between the electrode and the skin was vital, and so the skin of the forearm was rubbed with an alcohol wipe. The sEMG electrodes were placed firmly in contact with the skin using tape. Both precise electrode positioning and skin preparation could minimise potential signal errors or differences between sessions.

The ICC was used to assess the between-days test-retest reliability of wrist motor impairment indices. It was found that the ICCs were almost perfect (ICC 0.81-1.00) for all indices, suggesting excellent reliability. The only exception was the PROM, which demonstrated good ICC (ICC 0.78) (Landis and Koch 1977). The range of value of PROM from the two days assessment was relatively narrow (167.88°-173.39°). One limitation of the ICC is that it takes into account the spread of the values. Hence, a narrow spread of values in one group will result in a smaller ICC than another group with a wider spread of values, even though the mean difference between the 2 assessments is the same for both groups (Rankin and Stokes 1998). Therefore, the ICC for PROM need to be interpreted with caution.

There was only one person who showed an outlier for the flexor(# 3) and extensor IF (# 7), sine and step TI, path length, muscle onset timing, SI and MTI. This can be caused by several factors, such as the participants' activities

or mental status before the assessment session. Those factors were difficult to control. Although there were outliers for many motor impairment indices, the ICC of those indices was excellent (ICC 0.90-0.99) and the mean difference and limits of agreement for each index were small compared to its range of values. These findings support the conclusion that those motor impairment indices are very stable measures.

In our pilot studies (Chapter 5), stroke patients who had poor MCA and moved beyond the target movement had sine TI (quantified by the cross correlation method) as high, if not higher, than the healthy participants. This might be due to the cross correlation method taking into account the magnitude of the participants' movement. Therefore, in this reliability study it was decided to quantify step TI with the mean absolute error (MAE), which is the average magnitude of the errors of movements, which was used to quantify step TI. The results showed that sine TI (MAE) was a reliable measure. The construct validity of sine TI (MAE) is discussed in the next chapter (Chapter 7).

The limits of agreement for the sine CI was small (-0.19, 0.23) compared to its range of values (-0.71 to 0.1). The sine CI, which was analysed by the same method in a previous study by Turk (2011), showed limits of agreement (-0.60, 0.69) which were wider than ours, although there was also a much wider spread of their values (-0.54 to 0.73). The narrow spread of the sine CI values might be due to the fact that our study recruited the participants at the same period post-stroke (eight weeks), whereas Turk (2011) recruited stroke participants at any time point post-stroke, which may have resulted in differences in their sine CI values (negative to positive values). In addition, the number of stroke participants with coactivation in the study by Turk (2011) was higher than in our study. It seems possible that people with coactivation have more variability and less stability of muscle activation than people with reciprocal activation.

The MDC for passive tests (SI, PROM and MTI) were not established in the previous study by Turk (2011). Hence, we are the first to suggest the benchmark values for these indices that were then used for our longitudinal study and could be used in future research involving a similar wrist rig.

6.8 Conclusions

1. The redesigned wrist rig demonstrated good to excellent reliability.
2. The MDC of each motor impairment index, as measured by the redesigned wrist rig, are suggested as benchmark values.

6.9 Summary of Chapter 6

This chapter has provided details of the reliability of the redesigned wrist rig. The results showed that wrist motor impairment indices generated by the redesigned wrist rig were stable measures. We established the MDC of each motor impairment index that was used as benchmark values for the longitudinal study (Chapter 8).

The next chapter presents the introduction, research question, objectives, methodology, results, discussion and conclusions of the matched pair study, which evaluated construct validity of the wrist impairments indices generated by the redesigned wrist rig, and established non-impaired ranges for each index in Thai population.

Chapter 7: Matched pair study

7.1 Introduction

To date, the redesigned wrist rig has been used for research with a sample of Thai stroke population and comparisons were made with the indices from a previous UK-based stroke study presented by Turk (2011). However, it is not known how generalizable the measures are across two different populations (external validity). For example, Thai people may generally have greater PROM and less stiffness compared to the UK population. Therefore, to investigate the external validity of the redesigned wrist rig measures, a sub-study of healthy Thai participants (age and gender-matched to the stroke participants) was conducted in the matched pair study. It was important to establish impaired and non-impaired ranges and the differences between them, in the Thai population because the main longitudinal study (Chapter 8) was conducted in Thailand.

Previous research (Turk 2011) has tested the ability of impairment indices generated by the wrist rig to detect differences between stroke and healthy participants from the UK population. In this study, we have tested the ability of the indices to detect differences between stroke and healthy participants from the Thai population. Clinically, we have seen the differences between sub-acute and chronic stroke patients in particular for secondary motor impairments which tend to develop in chronic stroke patients. Therefore, differences of impairment indices between sub-acute and chronic stroke groups were also investigated.

7.2 Research question

Are there any differences in wrist impairments and ULFA between healthy, sub-acute and chronic stroke groups in the Thai population?

7.3 Objectives

1. To evaluate differences in wrist motor impairment indices (AROM, flexor and extensor IF, sine and step TI, path length, muscle onset timing, SI, sine CI,

PROM and MTI) between healthy, sub-acute and chronic stroke groups in the Thai population, as measured by the redesigned wrist rig. The findings were to address the construct validity (an ability to distinguish between sub-acute and chronic stroke and healthy participants) and external validity (a generalization in Thai population) of the redesigned wrist rig.

2. To investigate the normal range for each impairment index of Thai healthy participants.

7.4 Methodology

7.4.1 Study design

A cross-sectional study comparing wrist impairment indices in a convenience sample of participants from Thailand was conducted. Three samples of participants were tested: 25 sub-acute stroke participants (two weeks post-stroke), the same participants at 26 weeks, and 25 healthy participants who were match-paired for age (± 5 years), gender, height (± 10 cms) and weight (± 5 kgs).

7.4.2 Testing procedures

Demographic data and hand dominance of the healthy participants in the matched pair study were recorded by questioning. Subsequently, the SWMFT-S and wrist rig tests were administered on their dominant arm using the same process as used with stroke participants (see section 5.4.1.1 for more detail).

7.4.3 Statistical analysis

7.4.3.1 Descriptive statistics

As the characteristic data of the participants were non-normally distributed, there are presented as median (interquartile range). The exemptions were made for the height and weight, which were normally distributed, they are presented as mean (standard deviation).

Dot plots were used to illustrate distribution and values for each motor impairment. Data from maximum voluntary force (MVC) and the mean torque

index are plotted separately between male and female participants since there was great variability between genders.

7.4.3.2 Differences in the wrist motor impairments between Thai healthy and stroke participants

Wrist motor impairment indices of the healthy and stroke groups were normally distributed. Paired t-tests were used to estimate differences in wrist motor impairment indices between healthy and sub-acute stroke groups, healthy and chronic stroke groups and sub-acute and chronic groups. A p-value of <0.05 was considered as statistically significant. In addition, 95% CI of the mean differences were calculated to determine specifically where the statistically significant differences lay.

7.5 Results

This section presents characteristic data for three study groups: sub-acute stroke (2 weeks), chronic stroke (26 weeks) and matched healthy groups. Wrist motor impairment indices for each group is reported in three categories: negative, positive and secondary motor impairments as the clinical features of the UMN syndrome (see section 2.2 for more detail).

7.5.1 Participants' characteristics

Thirty-six stroke participants at 2 weeks, who were able to perform active wrist rig tests (AROM, MVC, and active tracking tasks), were included. Finally, data for 25 stroke participants at 2-week (sub-acute stroke group) and at 26-week (chronic stroke group) were analysed. Figure 7.1 illustrates the recruitment and loss to follow up of the stroke participants.

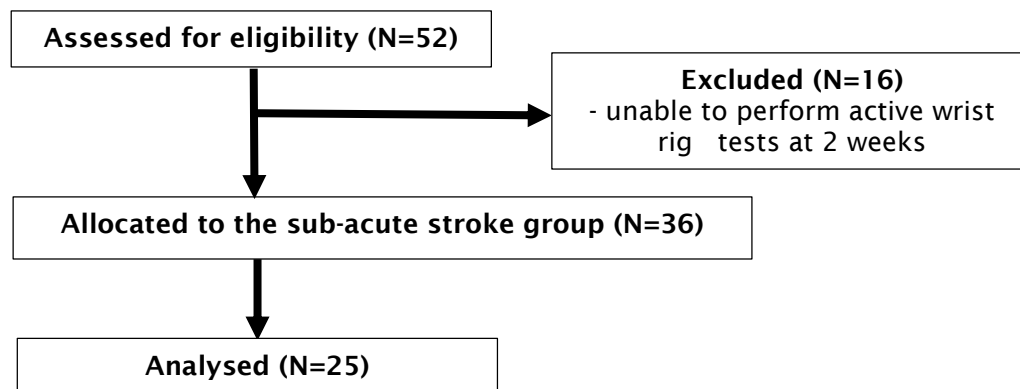


Figure 7.1 The recruitment and loss to follow up of the stroke participants in the matched pair study

Fifty-six healthy individuals who were members of Buddhachinaraj Hospital's Elderly Club, Phitsanulok, Thailand, were screened for eligibility for this study. Twenty-five participants who met the inclusion criteria (mean age 61.9 (12.1) years) were allocated to the healthy group. The recruitment of the healthy participants is illustrated in Figure 7.2.

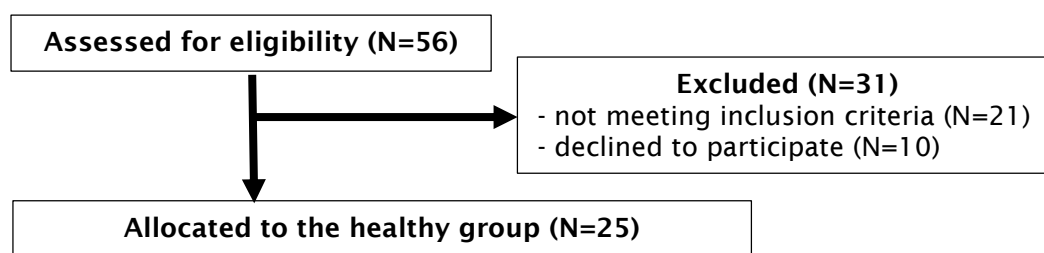


Figure 7.2 The recruitment of the healthy participants in the matched pair study

The clinical and demographic characteristics of participants from the three study groups are presented in Table 7.1. There was no significant difference in age, gender, height and age between the three groups of participants. The sub-acute participants (two weeks) had moderate to mild upper limb impairment (S-FM-UE from 4.00 to 10.00).

Table 7.1 Characteristics of study participants for the matched pair study (N=75)

	Groups		
	Sub-acute stroke (2 weeks) (N=25)	Chronic stroke (26 weeks) (N=25)	Matched healthy (N=25)
Age (years): Median (IQR)	64 (56-67.5)	64 (56-67.5)	63 (56.5-69)
Gender	14 male 11 female	14 male 11 female	14 male 11 female
Height (cm): mean (SD) [range]	161.20 (7.91) [150-178]	161.20 (7.91) [150-178]	167.43 (8.72) [157-182]
Weight (kg): mean (SD) [range]	61.28 (8.68) [47-80]	61.28 (8.68) [47-80]	63.45 (9.01) [49-76]
Side assessed	12 right	12 right	23 right
Right: Left	13 left	13 left	2 left
Spasticity- modified AS: Median (IQR)	0 (0-0) [0-0]	0 (0-0) [0-1]	0 (0-0) [0-0]
upper limb motor impairment (0-12)-S-FM-UE: Median (IQR)	7 (6-8) [4-10]	10 (8.25-10) [5-12]	12 (12-12) [12-12]
ULFA Function score (0-5)-SWMFT-S: Median (IQR)	2.5 (1.92-4.00) [3-4.8]	4.5 (3.67-4.91) [1-4.8]	5 (5-5) [5-5]

7.5.2 Negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

Individual differences between the three study groups are illustrated graphically in Figure 7.3 (a-g). A clear difference between the three study groups can be seen in all the negative wrist motor impairment indices. The sub-acute stroke group showed lesser AROM, flexor and extensor IF than the chronic stroke and healthy groups (note: greater index value is better). On the other hand, sine and step indices, path length and extensor onset timing in the sub-acute stroke group are greater than in the other two groups (note: lower index value is better). Variations in flexor and extensor IF were partly explained by gender difference. Differences between genders were further explored as shown in Figure 7.4 (a-d). It has been seen that the means of flexor and extensor IF in males, were noticeably greater than in females (Figure 7.4).

Table 7.2 shows the means (SD) for negative wrist motor impairment indices comparing sub-acute stroke (2 weeks), chronic stroke (26 weeks) and matched

healthy groups. The mean difference (95%CI) and p values between three study groups are also presented. All negative wrist motor impairment indices showed statistically significant differences between three study groups (Table 7.2).

Figure 7.3 a) AROM

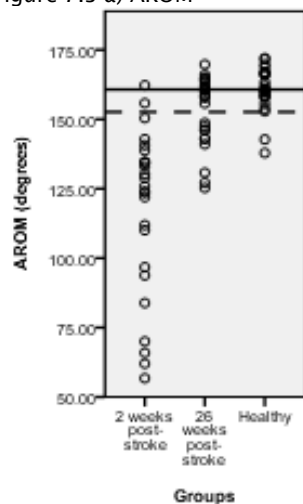


Figure 7.3 b) Flexor IF

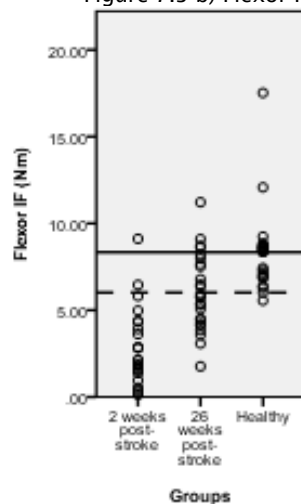


Figure 7.3 c) Extensor IF

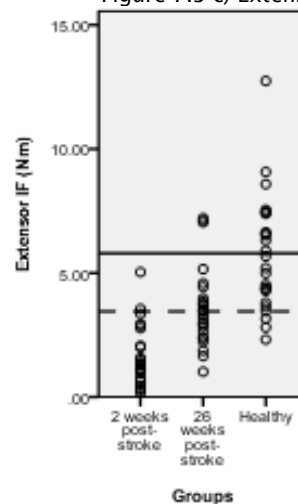


Figure 7.3 d) Sine TI (MAE)

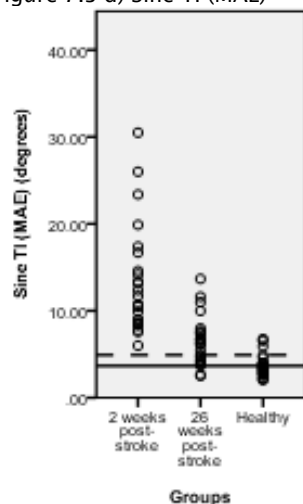


Figure 7.3 e) Step TI (MAE)

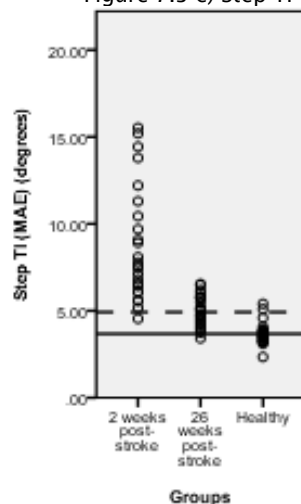


Figure 7.3 f) Path length

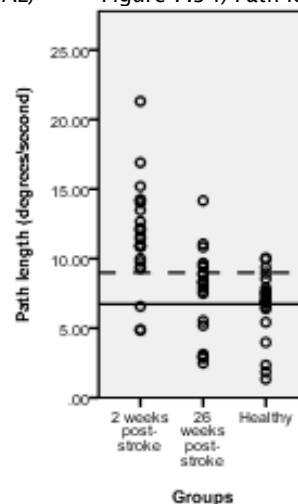


Figure 7.3 g) Extensor onset timing

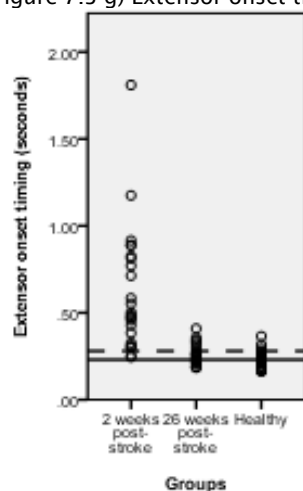


Figure 7.3 (a-g) Dot plots for negative impairment indices illustrating differences between participants in sub-acute stroke (2 weeks), chronic stroke (26-week) and matched healthy groups. The dashed line represents 2SD from the mean (solid line) for the healthy group. Values above the 2SD line (below for AROM, flexor and extensor IF) represent participants who are considered to be clinically impaired.

Figure 7.4 a) Flexor IF-male

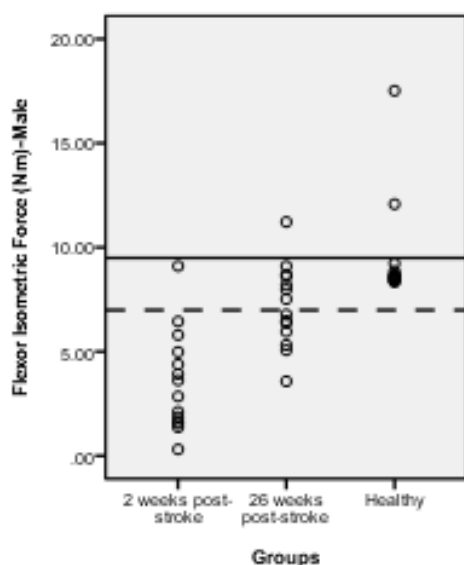


Figure 7.4 b) Flexor IF-female

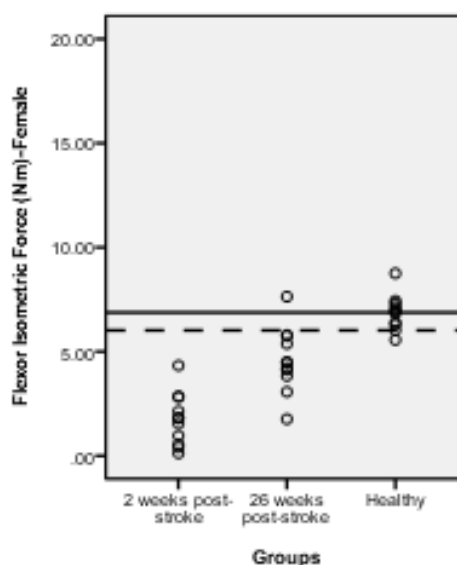


Figure 7.4 c) Extensor IF-male

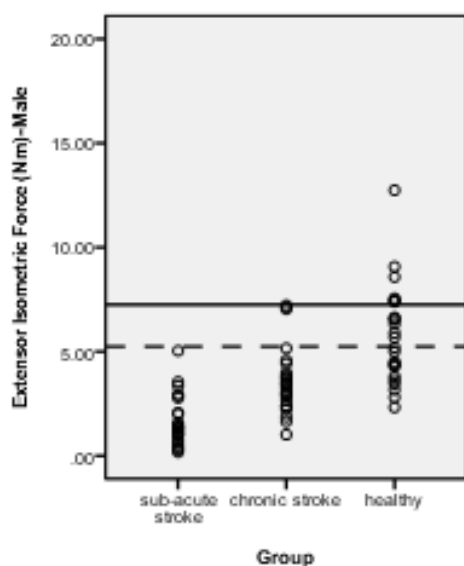


Figure 7.4 d) Extensor IF-female

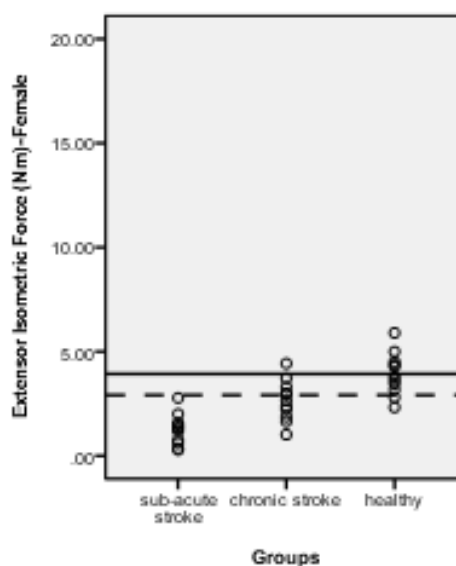


Figure 7.4(a-d) Dot plots for a), b) flexor IF and c), d) extensor IF illustrating differences between male and female participants in sub-acute stroke (2 weeks), chronic stroke (26-week) and matched healthy groups. The dashed line represents 2SD from the mean (solid line) for the healthy group. Value below the 2SD line represent participants who are considered to be clinically impaired.

Table 7.2 Mean (SD), mean difference (SD) and p values for negative wrist motor impairment indices comparing sub-acute stroke (2 weeks), chronic stroke (26-week post-stroke) and matched healthy groups. Statistical significance was tested using a paired sample T-test

Wrist motor impairment indices	Mean (SD)			Mean difference (SD) 95% CI			p value		
	2 weeks (N=25)	26 weeks (N=25)	Healthy (N=25)	2 weeks- healthy	26 weeks- healthy	2 weeks-26 weeks	2 weeks- healthy	26 weeks- healthy	2 weeks- 26 weeks
AROM (degrees) ¹	79.04±61.48	119.61±63.20	160.70±8.10	-43.41±26.60 (-54.39-(-32.43))	-7.64±12.44 (-12.78-(-2.50))	-35.77±29.11 (-47.79-(-23.76))	0.000***	0.005**	0.000***
Flexor IF (Nm) ¹	1.81±2.05	4.40±3.05	8.34±2.33	-5.57±2.85 (-6.75-(-4.39))	-2.29±1.98 (-3.10-(-1.47))	-3.28±2.12 (-4.16-(-2.41))	0.000***	0.000***	0.000***
Extensor IF (Nm) ¹	1.13±1.25	2.64±1.97	5.79±2.34	-4.15±2.39 (-5.14-(-3.17))	-2.16±1.74 (-2.88-(-1.44))	-1.99±1.78 (-2.73-(-1.26))	0.000***	0.000***	0.000***
Sine tracking index (MAE) (degrees) ²	13.79±5.70	6.80±3.19	3.67±1.25	9.69±5.90 (7.20-12.18)	2.79±2.29 (1.82-3.75)	6.93±6.25 (4.22-9.63)	0.000***	0.000***	0.000***
Step tracking index (MAE) (degrees) ²	9.18±3.46	5.31±1.19	3.67±0.63	5.14±3.15 (3.81-6.48)	1.41±1.00 (0.99-1.83)	3.62±2.95 (2.35-4.90)	0.000***	0.000***	0.000***
Path length (degrees/seconds) ²	6.77±3.60	2.82±1.61	1.83±0.51	4.96±3.68 (3.41-6.52)	0.94±1.74 (0.19-1.70)	3.62±3.58 (2.03-5.21)	0.000***	0.017*	0.000***
Extensor onset timing (seconds) ²	0.62±0.36	0.26±0.06	0.23±0.05	0.37±0.39 (0.21-0.54)	0.04±0.06 (0.01-0.07)	0.30±0.37 (0.15-0.46)	0.000***	0.008**	0.001**

¹Denotes greater index value is better; ²Denotes lower index value is better; * $p<0.05$; ** $p<0.01$; *** $p<0.001$

7.5.3 Positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

Individual differences between the three study groups are presented graphically in figure 7.5 (a-b), below. For sine CI, individual data was widely spread in the three study groups especially the sub-acute group. The number of sub-acute stroke participants who had coactivation was higher than the number of chronic or healthy participants. (Figure 7.5 a). There was a higher number of chronic stroke participants who had high SI compared to sub-acute or healthy participants, which suggested that spasticity developed in chronic stroke patients (Figure 7.5b).

The means (standard deviations), mean difference (95%CI) and p values compared between three study groups for positive wrist motor impairment indices are presented in table 7.3. There was no statistically significant differences between the three study groups for sine CI. Statistically significant differences between stroke and healthy groups were seen for the SI (Table 7.3).

Figure 7.5 a) Sine CI

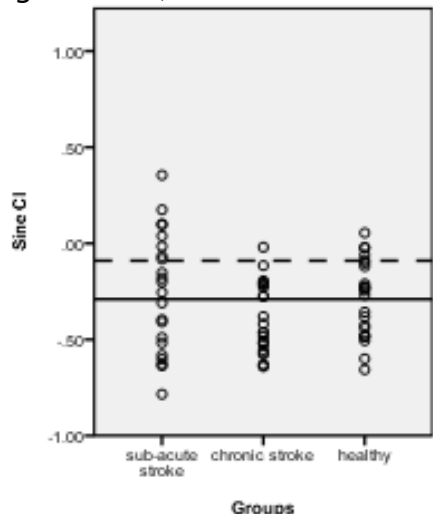


Figure 7.5 b) SI

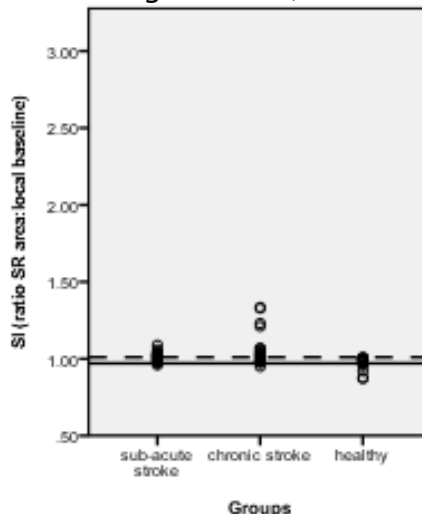


Figure 7.5(a-b) Dot plots for positive impairment indices illustrating differences between participants in sub-acute stroke (2 weeks), chronic stroke (26 weeks) groups and matched healthy groups. The dashed line represents 2SD from the mean (solid line) for the healthy group. Values above the 2SD line represent participants who are considered to be clinically impaired.

Table 7.3 Mean (SD), mean difference (SD) and p values for positive wrist motor impairment indices comparing sub-acute stroke (2 weeks), chronic stroke (26 weeks) and matched healthy groups. Statistical significance was tested using a paired sample t-test

Wrist motor impairment indices	Mean (SD) (range)			Mean difference+SD (95% CI)			<i>p</i> value		
	2 weeks (N=25)	26 weeks (N=25)	Healthy (N=25)	2 weeks- healthy	26 weeks- healthy	2 weeks-26 weeks	2 weeks- healthy	26 weeks- healthy	2 weeks- 26 weeks
Sine coactivation index	-0.27±0.28	-0.35±0.24	-0.29±0.20	0.03±0.38 (-0.15-0.20)	-0.10±0.26 (-0.22-0.01)	0.13±0.34 (-0.02-0.28)	0.794	0.083	0.090
Stretch index (3.5 Hz) (ratio SR: LBL)	1.02±0.06	1.12±0.20	0.97±0.04	0.04±0.06 (0.01-0.08)	0.07±0.08 (0.03-0.11)	-0.05±0.10 (-0.10-(-0.00))	0.013*	0.006**	0.058

p*<0.05; *p*<0.01

7.5.4 Secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

Figure 7.6 (a-b) below graphically present the individual PROM and MTI of the three study groups. There were participants whose PROM were considered to be impaired in each study group including the healthy. There were two participants in the chronic stroke group, who had more limited PROM than the other groups (Figure 7.6a). The MTI in the sub-acute stroke group showed greater variability than the chronic stroke and healthy groups (Figure 7.6b).

As with IF, the MTI could be partly explained by gender. Therefore, the data was divided into male and female groups. Generally, female participants, particularly in the sub-acute stroke and healthy groups, showed a smaller index value when compared to male participants (Figure 7.7a-b).

Table 7.4 illustrates the mean (standard deviation), the mean difference (95%CI) and the p values compared between the sub-acute stroke (2 weeks), chronic stroke (26 weeks) and matched healthy groups for secondary wrist impairments. Statistically significant differences between the three study groups were not seen in PROM and MTI except for the MTI between sub-acute and chronic stroke groups ($p<0.001$).

Figure 7.6 a) PROM

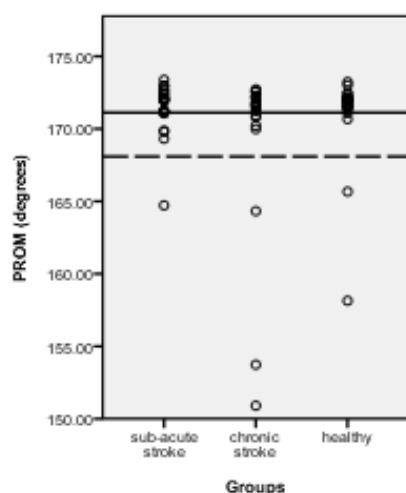


Figure 7.6 b) MTI

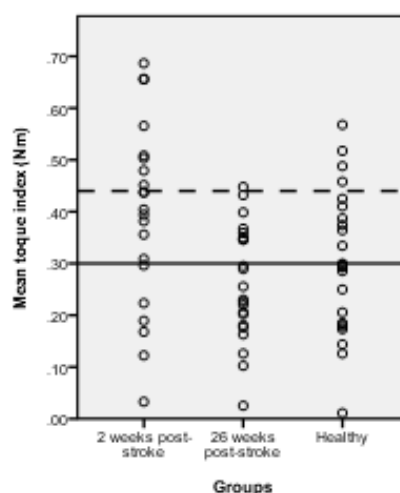


Figure 7.6(a-b) Dot plots for secondary impairment indices illustrating differences between participants in sub-acute stroke (2 weeks), chronic stroke (26 weeks) and matched healthy groups. The dashed line represents 2SD from the mean (solid line) for the healthy group. Values below the 2SD line for PROM and above 2SD line for MTI represent participants who are considered to be clinically impaired.

Figure 7.7 a) MTI-male

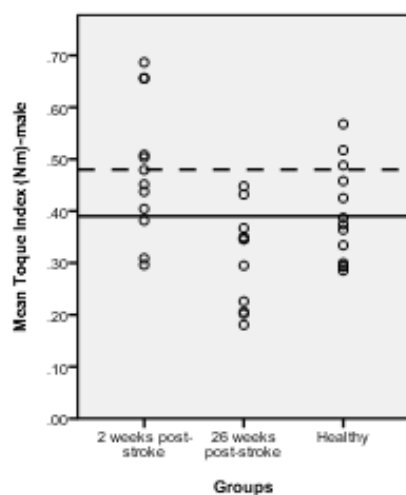


Figure 7.7 b) MTI-female

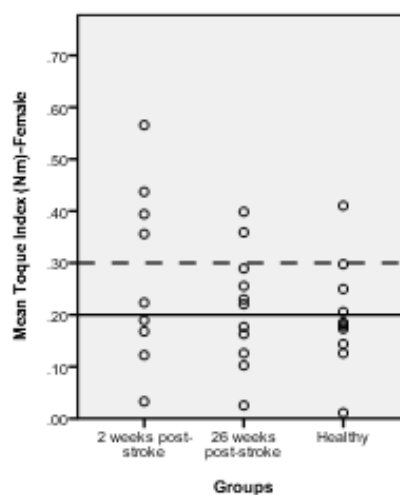


Figure 7.7(a-b) Differences between male and female participants. Dot plots for MTI illustrating differences between male and female participants in sub-acute stroke (2 weeks), chronic stroke (26 weeks) and matched healthy groups. Values above 2SD line for MTI represent participants who are considered to be clinically impaired.

Table 7.4 Mean (SD), mean difference (SD) and p values for secondary wrist motor impairment indices comparing sub-acute stroke (2 weeks), chronic stroke (26 weeks) and matched healthy groups. Statistical significance was tested using a paired sample t-test

Wrist motor impairment indices	Mean (SD) (range)			Mean difference \pm SD (95% CI)			<i>p</i> value		
	2 weeks (N=25)	26 weeks (N=25)	Healthy (N=25)	2 weeks- healthy	26 weeks- healthy	2 weeks-26 weeks	2 weeks- healthy	26 weeks- healthy	2 weeks- 26 weeks
PROM (degrees)	171.43 \pm 1.73	169.87 \pm 5.54	171.12 \pm 3.03	0.30 \pm 3.22 (-1.03-1.63)	-1.26 \pm 5.93 (-3.71-1.19)	1.56 \pm 5.66 (-0.77-3.89)	0.644	0.299	0.181
Mean torque index (Nm)	0.36 \pm 0.20	0.24 \pm 0.12	0.30 \pm 0.14	0.07 \pm 0.16 (-0.01-0.14)	-0.04 \pm 0.15 (-0.11-0.03)	0.15 \pm 0.14 (0.08-0.21)	0.089	0.223	0.000***

****p*<0.001

7.6 Summary of results

1. For all negative wrist motor impairment indices there were statistically significant differences ($p < 0.05$) between sub-acute, chronic stroke and healthy groups.
2. For the SI there was a statistically significant difference ($p < 0.05$) between stroke and healthy participants but not for sine CI.
3. There were no statistically significant differences between the sub-acute, chronic stroke and healthy groups in any secondary wrist impairments. The only exception was the difference between the sub-acute and chronic stroke group for the MTI.

7.7 Discussion

This is the first study that has taken a comprehensive approach to comparing wrist motor impairment indices between Thai stroke and healthy participants. We have established a normal range of all impairment indices for Thai participants, which is clinically useful to compare with any Thai stroke patients. The following sections discuss the results of the matched pair study comprehensively in the context of previously published research.

7.7.1 Participants' characteristic

Twenty-five of the stroke participants (who were the same individuals in the sub-acute and chronic phase) and their paired (for age, gender, height and weight) healthy individuals were recruited.

Several studies have revealed that age and gender contribute to muscle weakness. Men perform maximum voluntary contraction greater than females (Hunter and Enoka 2001; Brown et al. 2010). This might be because there are differences between their muscle fibre size (Frontera et al. 2000) and the different proportion of lean tissue between males and females (Miller et al. 1993). Older people lose their muscle mass, which results in declined muscle strength (Lynch et al. 1999). Furthermore, body weight and height have been

determined as the relative contributors of muscle size, and also related to muscle strength (Green and Gabriel 2012).

Wider differences between the impaired and non-impaired participants were expected for all impairment indices if moderate to low ULFA participants had been included. Only stroke participants who were able to perform all the active tests at the two week assessment were recruited so that all the impairments indices could be measured. However, this led to the inclusion of more high functioning participants and the omission of data from patients with moderate to low ULFA. This is a major limitation of the study and the results, therefore, need to be interpreted with caution. Specific examples of the study limitation are discussed in the following sections.

7.7.2 Negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

Our results showed that there was a clear differentiation between the sub-acute, chronic stroke and healthy groups for all the negative impairment indices.

These results were consistent with the previous similar study by Turk (2011) who found that AROM, extensor IF, sine and step TI and extensor onset timing showed statistically significant differences between the UK stroke and healthy participants. One difference was that Turk (2011) quantified sine TI using the cross correlation method whereas we used the mean absolute error (MAE). Our findings showed that the sine TI (MAE) had the ability to distinguish between sub-acute, chronic stroke and healthy participants. Further analysis of each individual participant's data illustrated in the dot plots showed that sine TI (MAE) showed less overlap between sub-acute and chronic stroke and healthy groups than sine TI (cross correlation) in Turk (2011). Hence, the MAE appears to be a valid method of measuring tracking accuracy. Significantly, our findings also showed less overlap for step TI and path length between the three study groups compared to the study by Turk (2011). This difference could be explained by the fact that the chronic stroke participants in the study of Turk (2011), who were different people from their acute stroke participants, were probably much more impaired than ours. Therefore, the sine and step TI and

path length in their chronic stroke group were overlapped much more with their acute stroke group.

We further investigated differences in muscle strength and non-neural stiffness between male and female participants. Our findings support the premise of previous studies, that male participants had greater muscle strength (Hunter and Enoka 2001; Brown et al. 2010; Turk 2011) than female participants.

There were two negative impairment indices (step TI and muscle onset timing) that we used which had the same method of analysis as the study by Turk (2011). We found that the Thai participants generated a similar range of values to the UK participants (Turk 2011). These findings confirm that the indices generated by the redesigned wrist rig could be generalized to be used with the Thai population.

Descriptive data from the dot plots showed that the majority of our sub-acute stroke participants had a degree of each index that could be considered to be clinically impaired. In contrast, a small number of chronic stroke participants were considered to be clinically impaired. This result may be explained by the fact that the stroke participants at two weeks had moderate to mild upper limb impairment at two weeks. Following that, they had very good recovery of all negative impairments at 26 weeks. If we recruit stroke participants at all level of upper limb impairment at two weeks, clearer different negative impairment indices between these two stroke groups may be observed.

To sum up, the negative impairments indices demonstrated a good construct validity and external validity.

7.7.3 Positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

The SI was the only positive impairment index that showed a significant difference between the healthy participants and both stroke groups. These findings are consistent with data obtained in the study by Turk (2011), which used the same method to analyse the sine CI and SI.

Turk (2011) found that one healthy participants (7% of N=14) had abnormal coactivation and that coactivation was found mostly in the chronic stroke

group. Contrary to expectations from previous research, we found participants who were considered to have abnormal coactivation in all three study groups. In addition, coactivation was found mostly in the sub-acute stroke group rather than the chronic stroke group. A note of caution is due here, since our normal range of CI could not distinguish between stroke and healthy participants. It is difficult to explain this result, but it might be related to the fact that our sub-acute stroke participants coactivated their wrist muscle to perform the sine tracking tasks. Following that, in their chronic phase, they were trained and needed less coactivation. Previous research by Prange et al. (2012), suggested that coactivation may be reduced after training to perform a task. However, further work is required to establish a method of analysis of coactivation which could distinguish between normal and abnormal coactivation.

For the SI, our findings were similar to the study by Turk (2011), in that spasticity was considered to develop in the stroke rather than the healthy participants. Notably, the stroke participants in Turk's study (2011) demonstrated greater SI than ours. Previous studies, which used neuromechanical equipment derived SI from stretch response test, used different methods to our study to quantify spasticity. Turk et al. (2008) quantified SI during passive tracking movement at a frequency of 1.5 Hz with a displacement of ± 30 degrees around each participant's midpoint. However, a more recent study by Turk (2011), which quantified SI during two different frequencies (1.5 Hz at ± 20 degrees of movement and 3.5 Hz at ± 5 degrees of movement), found that SI tested at 3.5 Hz could distinguish between stroke participants and normal healthy people better than data from 1.5 Hz. In addition, passive movement at 3.5 Hz could minimise voluntary movement of the participants more than at 1.5 Hz. Therefore, it is noted that the SI, which was measured at 3.5 Hz, may be much more valid. Sorinola et al. (2009) also found that their method to measure stretch response was able to distinguish spasticity between stroke and healthy participants. They normalised the EMG amplitude of muscle investigated to that of the MVC. Our method quantified stretch response as the median ratio of the flexor EMG area divided by the local baseline flexor EMG area, which was less complicated than their method and could provide meaningful data about spasticity. Therefore, it was an advantage to use our method to measure spasticity.

To sum up, our method of quantifying spasticity in this population distinguished between stroke and healthy participants, suggesting good construct validity. However, the method of analysis sine CI needs to be further investigated.

7.7.4 Secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

There were no statistically significant PROM between the healthy and either the sub-acute or the chronic stroke groups. MTI in the chronic stroke group was statistically significant lower than in the sub-acute group.

Surprisingly, contracture did not develop in our chronic stroke group, which was in contrast to previous studies, which found that contracture developed during the first six months following stroke (Pandyan et al. 2003; Kwah et al. 2012). However, we found two participants in our chronic stroke group had more limited PROM than the other groups, which suggested that contracture tended to develop in the chronic stroke group rather than the sub-acute group. As mentioned already, this study recruited participants with moderate to mild upper limb impairment. Thus, the majority of our chronic stroke participants had good recovery without the development of contracture. The construct validity of PROM needs to be interpreted with caution.

Our investigation of the differences in non-neural stiffness between male and female participants showed that male participants had greater non-neural stiffness than female participants, which corroborates with previous research (Turk 2011; Pennati et al. 2016). It is also surprising not to see a difference between healthy and stroke groups in terms of non-neural stiffness. The participants who had high torque values and who were considered to be impaired were all in the sub-acute stroke and healthy groups, not in the chronic stroke group. These findings differ from previous research, which used different methods from us to quantify non-neural stiffness, in that non-neural stiffness in chronic stroke participants was higher than the healthy participants (Mirbagheri et al. 2007). The study by Turk (2011), which used the same method of analysis with us to quantify MTI, presented that the chronic stroke participants had much higher non-neural stiffness than acute participants. However, there were only two chronic stroke participants (N=13) and another

one healthy participant (N=14) in Turk's study (2011) who had high torque values, which was considered to be impaired. Therefore, our measurement method may not be valid to measure non-neural stiffness. Further work is required to establish a measurement of non-neural stiffness, which could distinguish impaired and unimpaired participants.

To conclude, PROM and non-neural stiffness could not distinguish between stroke and healthy participants. However, the PROM may be able to distinguish between chronic stroke patients with low levels of ULFA and healthy individuals.

7.8 Conclusions

This chapter has presented a matched pair study to investigate the differences in wrist motor impairment indices with Thai stroke and their pair healthy individual. Our results indicate that AROM, flexor and extensor IF, sine and step TI, path length, muscle onset timing and SI were statistically significantly different between the healthy and stroke participants.

These findings suggest good construct validity (an ability to distinguish between sub-acute and chronic stroke and healthy participants) and external validity (a generalization of the Thai population) of the redesigned wrist rig. It is recommended that the redesigned wrist rig could be implemented in a further longitudinal study.

7.9 Summary of Chapter 7

This chapter has provided an introduction, the research question, objectives, methodology, results, discussion and conclusions of the matched pair study.

The longitudinal study is presented in the next chapter (Chapter 8), including an introduction, research questions, objectives, methodology and results.

Chapter 8: Longitudinal study

8.1 Introduction

The pilot studies undertaken with the redesigned wrist rig demonstrated that the rig was feasible to be used with sub-acute stroke participants. The redesigned wrist rig demonstrated good to excellent reliability. In addition, the wrist motor impairment indices (AROM, flexor and extensor IF, sine and step TI, path length, extensor onset timing, and SI) were found to be able to distinguish between stroke and healthy participants. This chapter presents research questions, methodology, results, discussion and conclusions relating to the longitudinal study, which was conducted in Thailand.

8.2 Research questions

The longitudinal study was conducted to address the following research questions:

1. How do upper limb impairment (measured by S-FM-UE), ULFA (measured by the SWMFT-S) and wrist impairments (measured in the redesigned wrist rig) change during the first 26 weeks following stroke?
2. What is the relationship between ULFA at 26 weeks and wrist impairments at two, four, eight, 12 and 26 weeks?
3. Which, if any, of the following wrist impairments: range of movement (flexion to extension AROM), muscle weakness (flexor and extensor IF), MCA (sine and step TI, path length), delayed muscle onset timing (extensor onset timing), spasticity (SI; flexor spasticity), coactivation (sine CI), muscle contracture (PROM; flexor contracture) and non-neural stiffness (MTI; flexor contracture) at two, four, eight and 12 weeks post stroke, predict ULFA at 26 weeks?

8.3 Objectives

To answer these research questions, the following objectives needed to be achieved.

1. Quantify upper limb impairment (measured by S-FM-UE), wrist impairments (measured in the redesigned wrist rig) and ULFA (measured by SWMFT-S) at two, four, eight, 12 and 26 weeks
2. Identify any relationships between ULFA at 26 weeks and wrist impairments at baseline (two, four, eight, 12 and 26 weeks)
3. Identify which, if any wrist impairments (at two, four, eight and 12 weeks) can predict ULFA at 26 weeks

8.4 Methodology

The study design, testing procedures and statistical analysis for the longitudinal study are presented in this section. Details regarding the study sample, selection criteria, outcome measures and ethical considerations for the longitudinal study have been presented in Chapter 4.

8.4.1 Testing procedures

The demographic data of the participants in the longitudinal study were recorded from each patient's chart and through questioning. The S-FM-UE, mRS, modified AS and Nottingham Sensory Assessment at wrist joint were then employed. The SWMFT-S and the wrist rig tests were conducted in the same order and with the same procedure as in pilot study 2. Rest break intervals were provided during the assessment sessions. The wrist rig data was checked at the end of each assessment. If there were any missing tests, the full assessment was repeated on another day within the same week.

The S-FM-UE, the SWMFT-S and the wrist rig tests were conducted at five time points. The first assessments were carried out within the first two weeks of stroke. Follow-up assessments were conducted at four, eight, 12 and 26 weeks (Figure 8.1).

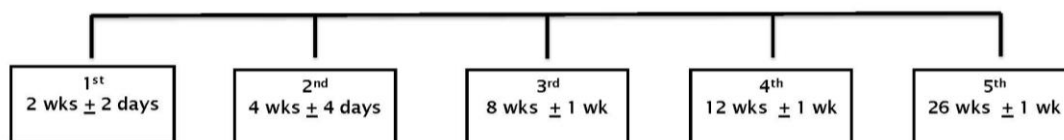


Figure 8.1 Timing of assessments for the longitudinal study

The first assessment session was conducted at the Department of Physiotherapy, Buddhachinaraj Hospital. The re-assessment sessions for patients were take place at Buddhachinaraj Hospital or at their community hospital.

8.4.2 Statistical analysis

All data was tested for normal distribution as described in Chapter 4, section 4.10. Statistical analysis related to the longitudinal study is presented in the following sections.

8.4.2.1 Descriptive statistics

Participants' ages were normally distributed, therefore mean (standard deviation) is reported for age. As clinical scores of stroke participants at baseline assessment (2 weeks) were not normally distributed, they are presented as median and interquartile range (IQR).

The median and interquartile range (IQR) for S-FM-UE, SWMFT-S, and wrist motor impairment indices of stroke at each assessment point and healthy participants are reported.

Line charts were plotted to show individual changes over time for S-FM-UE, SWMFT-S, and wrist motor impairment indices of stroke participants. The median scores of healthy participants were also plotted. As expected, there were large numbers of stroke participants in the longitudinal study who had maximum SWMFT-S time scores, therefore the researcher (WS) decided to report only the functional ability scale of the SWMFT-S.

The IF and MTI were plotted separately for male and female participants since there was between gender variability.

The S-FM-UE and SWMFT-S FAS at each assessment point are presented as percentage of the maximum value of each measurement. Improvements of each wrist motor impairment between two to 26 weeks were compared with the MDC, which was calculated in a reliability study (Chapter 6).

8.4.2.2 Relationship between SWMFT-S FAS at 26 weeks and wrist motor impairments

SWMFT-S FAS at 26 weeks and wrist motor impairment indices were not normally distributed. Relationships between impairment indices at two, four, eight, 12 and 26 weeks and SWMFT-S FAS at 26 weeks were estimated using Spearman's correlation coefficient, p value and 95% CI.

The strength of the relationships between wrist motor impairment indices were based on recommended values (Munro 2005) as follows.

0.00-0.25: little if any

0.26-0.49: low

0.50-0.69 moderate

0.70-0.89 high

0.90-1.00 very high

8.4.2.3 Prediction of SWMFT-S FAS based on wrist motor impairments

The dependent variable was ULFA (measured by SWMFT-S FAS) at 26 weeks. Possible determinants for development of a prediction model were AROM, wrist flexor and extensor IF, sine TI, step TI, path length, extensor onset timing, sine CI, SI, PROM and MTI at two, four, eight, and 12 weeks.

As the SWMFT-S FAS is an ordinal scale with a range from zero to five, and the SWMFT-S FAS at 26 weeks was not normally distributed, a logistic regression model was used to perform both univariate and multivariate analyses. The study sample at 26 weeks was categorised using the SWMFT-S FAS into two groups, functional and non-functional. In this research an arbitrary score of three or above denoted the functional ULFA group. This score indicated that all six tasks in SWMFT-S could be completed with some degree by synergy or were performed slowly or with effort. The non-functional ULFA group had a SWMFT-S FAS of less than three. As the wrist motor impairment indices have different units, all variables were normalised by dividing by their mean before applying the logistic regression analysis.

Univariate logistic regression analysis was used to select variables from motor impairment indices at two, four, eight, 12 and 26 weeks for further multivariate analysis. Wrist motor impairment indices that showed independent association with the SWMFT-S FAS (in terms of odds ratio with p -value < 0.05) were selected for model fitting in subsequent multiple logistic regression analyses.

A predictor with an odds ratio ($\text{EXP}(\beta)$), which was statistically significant and greater than 1, associated with high SWMFT-S FAS, i.e., higher scores of the predictor increase SWMFT-S FAS. In contrast, predictors with an odds ratio of less than 1 were associated with low SWMFT-S FAS (Scotia 2010).

8.5 Results

The results of the longitudinal study are presented in four sections. In the first section, recruitment rate and participants' characteristics are presented and missing data is explained. The following three sections address the main research questions:

Research Question 1: How do upper limb impairment, ULFA and wrist impairments change during the first 26 weeks following stroke? **Recovery profiles** as identified in the S-FM-UE, SWMFT-S FAS and wrist motor impairment indices between two and 26 weeks following stroke are presented.

Research Question 2: What is the relationship between ULFA at 26 weeks and wrist impairments at two, four, eight, 12 and 26 weeks? **Relationships** between wrist motor impairment indices and SWMFT-S FAS at 26 weeks are examined.

Research Question 3: What is a predictor of ULFA at 26 weeks based on wrist impairments? **Predictions** of SWMFT-S FAS at 26 weeks, based on wrist motor impairment at each time point, are identified.

8.5.1 Participants

8.5.1.1 Recruitment rate

Participants were recruited from August 2014 to January 2015. Fifty-two stroke participants who satisfied the selection criteria and who were less than or

equal to two weeks, were recruited for the study. The target participants was at least 40 (see section 4.4.4 for more detail) by the 26th week. In total, 52 participants were recruited by week 26. Figure 8.2 illustrates the actual recruitment rate in each month compared to the target recruitment rate.

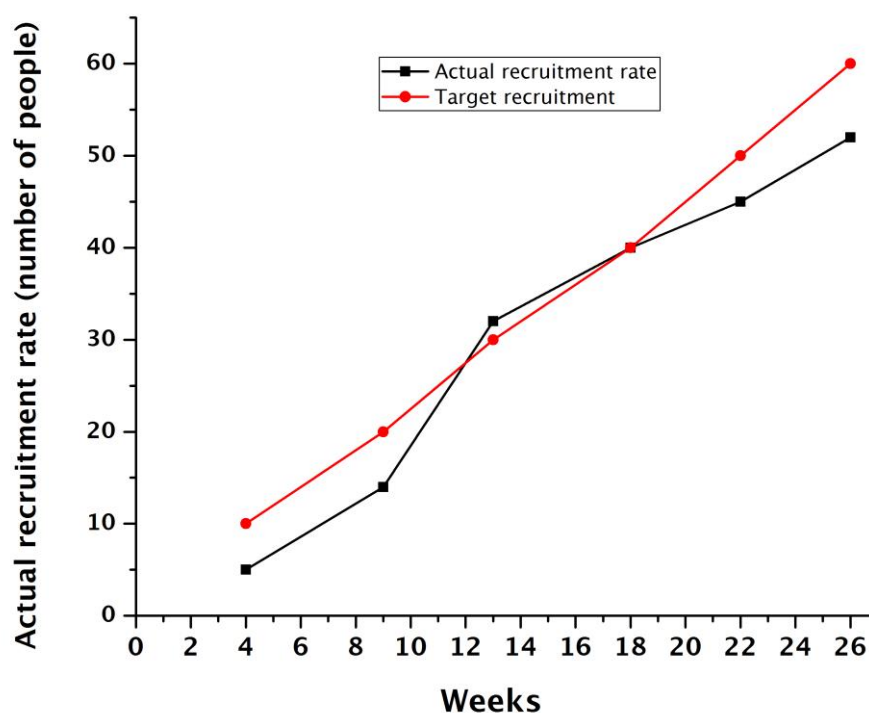


Figure 8.2 Participant recruitment tracker for the longitudinal study

Figure 8.3 illustrates the recruitment and loss to follow up of the participants at different assessment points. In total, 153 sub-acute stroke patients were screened for eligibility for this research. Eleven participants dropped out from the study and seven missed assessments because they had been discharged from hospital and were either unable to travel to Buddhachinaraj Hospital or did not have a caregiver to bring them.

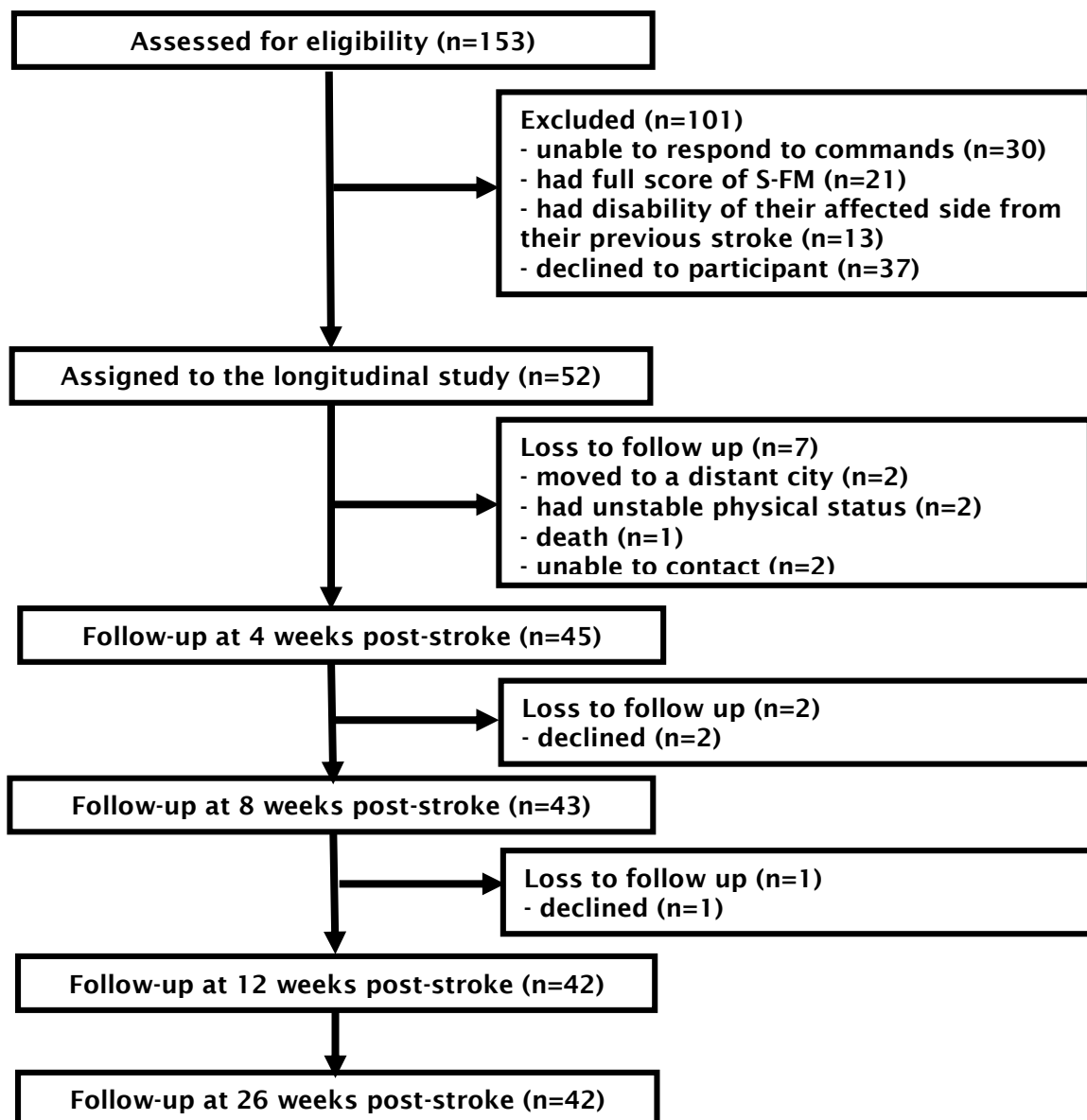


Figure 8.3 The recruitment and loss to follow up of the participants at different assessment points in the longitudinal study

8.5.1.2 Participants' characteristics at baseline assessment

The clinical and demographic characteristics of participants at 2 weeks are presented in Table 8.1. At recruitment, the median score of S-FM-UE and SWMFT for the participants were 50% and 36.6% of their full scores, respectively. Each participant was on follow-up at four, eight, 12 and 26 weeks. Data related to each participant's S-FM-UE, SWMFT-S FAS, and wrist impairments were gathered during the follow-up period.

The S-FM-UE scores at baseline assessment were classified into severe, moderate and mild upper limb impairment. As no previous study had classified the S-FM-UE scores, the S-FM-UE classification was converted from the classification of the FM-UE by comparing a percentage. The FM-UE scores can be classified as severe (0 to 19 points; 0-32% of full scores FM-UE), moderate (19 to 47; 32-78% of full scores FM-UE) or mild (47 to 60; 78-100% of full scores FM-UE) (Woodbury et al. 2013).

Table 8.1 Characteristics of study participants at baseline assessment for the longitudinal study (N=52)

Characteristics	mean (SD), median (IQR), range, percentage or number at 2 weeks (N=52)
Age (years): mean (SD) [min-max]	62.3 (13.6) [18-90]
Gender	25 male 27 female
Hand affected	21 left 31 right
Dominant hand affected	20 (38.46%)
Type of stroke	42 ischemic 10 haemorrhagic
Wrist joint position sense -Proprioception-Nottingham Sensory Assessment	38 normal 5 impaired 1 loss 8 not applicable
Wrist flexor spasticity-modified AS: Median (IQR) [min-max]	0 (0-0) [0-1]
Upper limb motor impairment-S-FM-UE (0-12): Median (IQR) [min-max]	6 (0-8) [0-11]
Number of participants with S-FM-UE	
≤ 3 (severe)	16
4 - 9 (moderate)	33
≥ 10 (mild)	3
Upper limb functional activity-SWMFT-S FAS (0-5): Median (IQR) [min-max]	1.83 (0-3.29) [0-4.8]

8.5.1.3 Missing data

There were various reasons for missing data that are described in section 4.8.2.5. The number of participants for whom usable data were collected at each time point and for each measure is presented in table 8.2. The results are reported for each motor impairment.

Table 8.2 Number of participants for whom usable data (for each wrist motor impairment index) were collected and analysed at each time point

Wrist motor impairment index	Number of participants who were assessed				
	wrist impairments				
	2 weeks N=52	4 weeks N=45	8 weeks N=43	12 weeks N=42	26 weeks N=42
AROM (degrees)	52	43	40	41	41
Flexor IF (Nm)	52	43	40	41	41
Extensor IF (Nm)	52	43	40	41	41
sine tracking index (MAE) (degrees)	34	34	31	32	30
step tracking index (MAE) (degrees)	34	34	31	31	31
Extensor onset timing (seconds)	34	32	29	32	31
Path length (sample/second)	34	34	31	31	29
Sine coactivation index (correlation coefficient)	30	32	30	31	27
Stretch index (3.5 Hz) (ratio SR: LBL)	44	32	37	32	34
PROM (degrees)	52	43	40	41	41
Mean torque index (Nm)	45	39	35	34	35

8.5.2 Profiles of recovery of clinical measures and wrist motor impairments

This section presents details of how upper limb impairment (S-FM-UE), ULFA (SWMFT-S FAS) and wrist motor impairment indices changed during the first 26 weeks following stroke. The results at two, four, eight, 12 and 26 weeks are tabulated and illustrated by line graphs. According to the clinical features of the UMN syndrome, motor impairments can be divided into negative phenomena (a reduction of motor activity), positive phenomena (excessive or inappropriate motor activity) and long-term secondary changes (Barnes 2001; Trochim 2006). Wrist rig data are therefore presented in three groups: negative, positive and secondary motor impairments.

Through observation and further analysis of each individual participant's data illustrated in the line graphs and tables, some categorisation of profiles of recovery became clear from the S-FM-UE, SWMFT-FAS, and some of the wrist motor impairment indices, which were detailed further in the following section.

8.5.2.1 Short form of the Fugl-Meyer motor scale (S-FM-UE) and streamlined Wolf motor function test-functional ability scale (SWMFT-S FAS)

Table 8.3 shows the change in median (IQR) of S-FM-UE and SWMFT-S FAS from 2 to 26 weeks and percentages of the maximum value of each scale. Figures 8.4 and 8.5 illustrate the individual changes in S-FM-UE and SWMFT-S FAS for all participants at each assessment point, including the median stroke score and median healthy score for reference.

The median S-FM-UE and SWMFT-S FAS increased markedly from two to four weeks before increasing slightly from four to 12 weeks and reaching a plateau from 12 to 26 weeks (see Table 8.3).

Table 8.3 Median (IQR) for S-FM-UE and SWMFT-S FAS at 2, 4, 8, 12 and 26 weeks

Outcome measure	Median (IQR) for S-FM-UE and SWMFT-S FAS at each time point				
	2 weeks	4 weeks	8 weeks	12 weeks	26 weeks
	N=52	N=45	N=43	N=42	N=42
S-FM-UE (0-12)	6.00 (50%) (0.00-8.00)	9.00 (75%) (5.00-10.00)	9.00 (75%) (6.00-10.00)	10.00 (83.33%) (6.50-11.00)	10.00 (83.33%) (6.50-12.00)
SWMFT-FAS (0-5)	1.83 (36.67%) (0.00-3.29)	3.00 (60.00%) (1.67-4.17)	3.58 (71.67%) (2.13-4.29)	3.92 (78.33%) (2.83-4.50)	4.00 (80.00%) (3.00-4.75)

S-FM-UE-Short Form of the Fugl-Meyer Motor Scale; SWMFT-FAS- Streamlined Wolf Motor Function Test-Functional Ability Scale

The most marked improvement of S-FM-UE for individual participants can be seen from two to four weeks. The participants who scored zero of S-FM-UE by four weeks had little or no recovery up to 26 weeks (Figure 8.4).

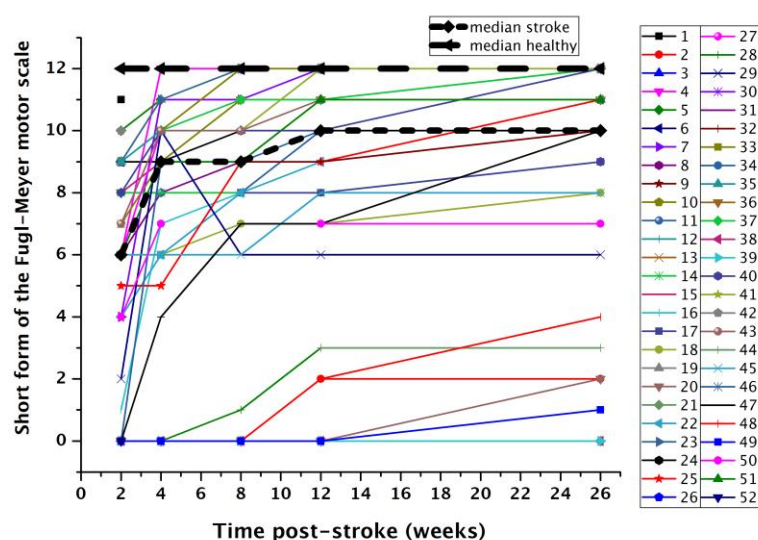


Figure 8.4 Line charts showing individual S-FM-UE scores during 26 weeks. The short dashed line is the median for S-FM-UE scores at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median S-FM-UE for the healthy group.

The line graph below (Figure 8.5) shows that the majority of participants greatly increased the SWMFT-S FAS from two to four weeks. As with the S-FM-UE, the participants who did not improve the SWMFT-S FAS within the first four weeks demonstrated little or no recovery up to 26 weeks after stroke.

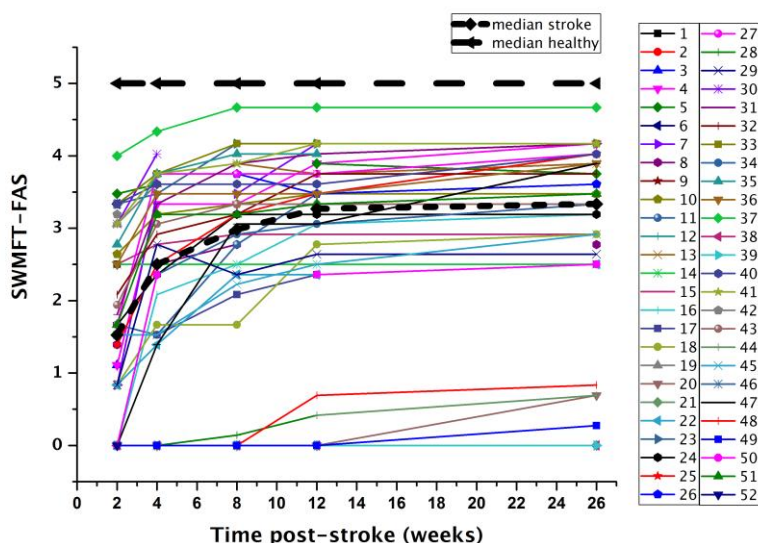


Figure 8.5 Line charts showing individual SWMFT-FAS scores during 26 weeks. The short dashed line is the median for SWMFT-FAS at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median SWMFT-FAS for the healthy group.

The scores for SWMFT-FAS ranged from zero to 30. The score was divided by the number of items in the assessment (6 items) to make it comparable with other studies, which have also used the WMFT with different number of items. Therefore, the score ranged from zero to five. Observation of the line graphs for S-FM-UE and SWMFT-S FAS (Figures 8.4 and 8.5) suggests that the 41 participants who were assessed at 2 weeks and followed up at 26 weeks obviously fall into three categories based on the median score of each assessment at 2 weeks (S-FM-UE=6.00, SWMFT-S FAS=1.83). *Category 1* is the participants with higher score (S-FM-UE ≥ 6 ; SWMFT-S FAS ≥ 1.83) at two weeks with good recovery by four weeks (S-FM-UE N= 22; SWMFT-S FAS N=21) and that continued up to 26 weeks. *Category 2* is the participants with low to moderate scores at two weeks ($0 < \text{S-FM-UE} < 6$; $0 < \text{SWMFT-S FAS} < 1.83$) who had a rapid recovery at week four or eight and that recovery continued up to 26 weeks (S-FM-UE N= 10; SWMFT-S FAS N=11). *Category 3* is the participants who scored zero at 2 weeks with little or no recovery thereafter (N= 9).

8.5.2.2 Negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

The median (IQR) scores of the negative impairment indices at each assessment point for stroke and healthy participants and the MDC for each impairment are reported in Table 8.4. Individual changes from two to 26 weeks were illustrated graphically in Figures 8.6 a-c and 8.7 a-d.

The median scores for the AROM, flexor and extensor IF (note: greater index value is better) and sine TI (note: lower index value is better) changed dramatically beyond their MDC within four weeks, with little change thereafter. The median score for the step TI, path length and extensor onset timing (note: lower index value is better) decreased markedly within the first four weeks; however, their changes more than MDC were found at eight weeks. Following that, there was a smaller decrease up to 12 weeks, reaching a plateau at 26 weeks (Table 8.4).

Table 8.4 Median (IQR) for negative impairment indices of stroke participants at 2, 4, 8, 12 and 26 weeks and healthy participants and the MDC for each index

Wrist motor impairment index median (IQR) for healthy participants	Median (IQR) for negative impairment indices					Minimal detectable change (MDC)
	2 weeks N=52	4 weeks N=45	8 weeks N=43	12 weeks N=42	26 weeks N=42	
AROM (degrees) ¹ 160.60 (158.04-166.65)	94.89 (0.00-134.42)	141.31 ^a (106.25-154.32)	141.92 (110.76-154.85)	144.38 (111.53-161.03)	146.22 (126.22-160.61)	±11.56
Flexor IF (Nm) ¹ 8.42 (6.95-8.67)	1.54 (0.00-92.85)	2.91 ^a (0.60-4.49)	3.74 (0.76-5.22)	3.83 (1.18-6.04)	4.40 (0.00-11.22)	±1.31
Extensor IF (Nm) ¹ 5.68 (4.04-7.41)	0.86 (0.00-1.90)	1.73 ^a (0.23-2.88)	2.36 (0.52-3.16)	2.40 (0.73-3.37)	2.96 (0.92-3.65)	±0.43
sine tracking index (MAE) (degrees) ² 3.41 (2.85-3.99)	12.76 (8.99-17.40)	9.43 ^a (6.57-14.90)	8.25 (5.44-10.99)	6.29 (4.58-8.75)	6.35 (4.36-7.73)	±2.62
Step tracking index (MAE) (degrees) ² 3.54 (3.26-3.83)	7.92 (6.35-11.52)	6.49 (5.30-9.10)	5.51 ^b (4.82-6.23)	5.34 (4.49-6.33)	5.13 (4.30-6.04)	±2.10
Path length (degrees/second) ² 1.89 (1.68-2.25)	6.37 (4.16-8.64)	3.77 (2.88-7.05)	2.52 ^b (1.88-3.98)	2.29 (1.78-4.53)	2.60 (2.07-3.96)	±3.29
Extensor onset timing (seconds) ² 0.23 (0.13-0.30)	0.52 (0.31-0.78)	0.41 (0.29-0.55)	0.38 ^b (0.28-0.41)	0.29 (0.24-0.36)	0.25 (0.21-0.34)	±0.13

¹denotes greater index value is better; ²denotes lower index value is better; ^adenotes recovery between 2 and 4 weeks that is greater than MDC; ^bdenotes recovery between 2 and 8 weeks that is greater than MDC

The line graphs for AROM, flexor and extensor IF (Figures 8.6a-c) show that these variables can also be placed in three categories based on the median score of each impairment at two weeks, in the same way as the S=FM and the SWMFT. *Category 1* is the high functioning participants (AROM $\geq 94.89^\circ$, flexor IF ≥ 1.54 Nm; extensor IF ≥ 0.86) at two weeks who continued to improve over 26 weeks (AROM N= 19; flexor IF N=20; extensor IF N=19). *Category 2* is the low to moderate functioning participants ($0^\circ < \text{AROM} < 94.89^\circ$; $0 \text{ Nm} < \text{flexor IF} < 1.54 \text{ Nm}$; $0 \text{ Nm} < \text{extensor IF} < 0.86 \text{ Nm}$) at two weeks who improved over 26 weeks (AROM N=13; flexor IF N=12 and extensor IF N=13). *Category 3* is the low functioning participants who had scored zero of AROM, flexor and extensor IF at two weeks with no or only a very small improvement up to 26 weeks (AROM, flexor and extensor IF N= 9) (Figures 8.6 a-c).

Figure 8.6 a) AROM

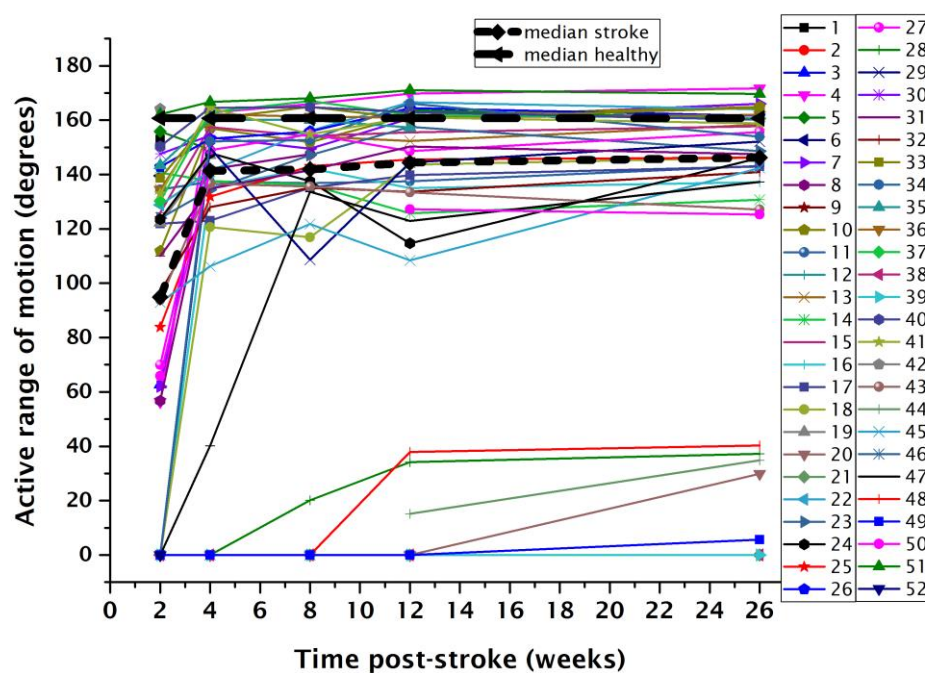


Figure 8.6 b) Flexor IF

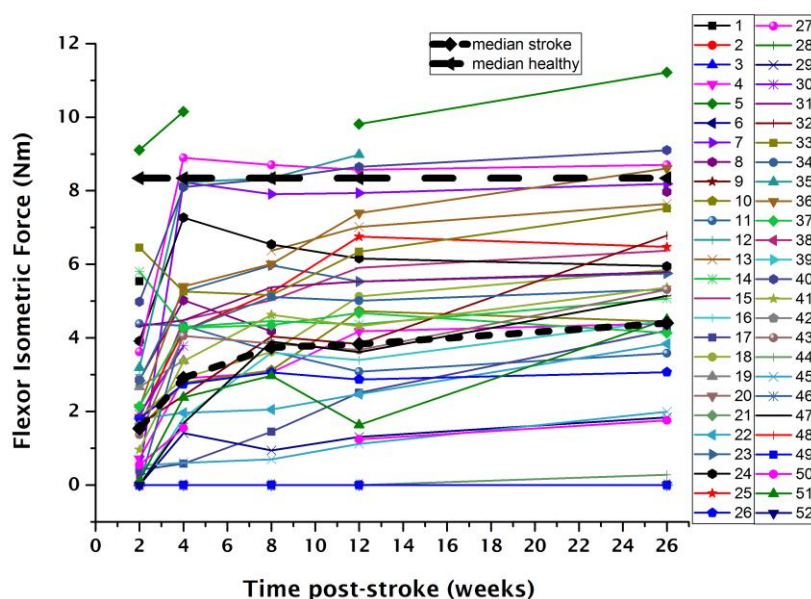


Figure 8.6 c) Extensor IF

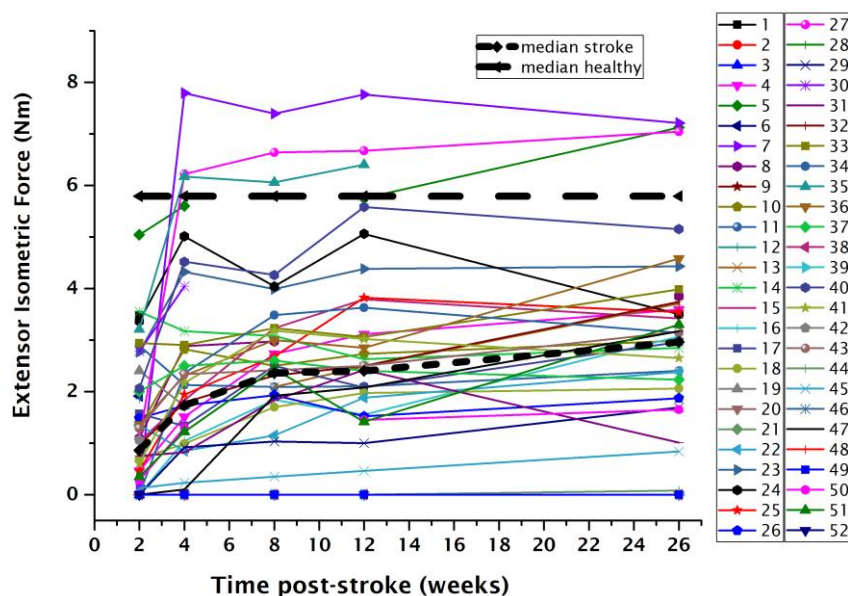


Figure 8.6(a-c) Line charts showing individual a) AROM, b) flexor IF and c) extensor IF during 26 weeks. The short dashed line is the median for negative wrist motor impairments at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median of each negative wrist motor impairment for the healthy group.

As with the S-FM-UE and SWMFT-S FAS, AROM, flexor IF and extensor IF variables showed a similar trend in profiles of recovery, categorisation for

these variables was compared to evaluate if participants fall into the same category for each variable. Data for the subgroup of participants, which was assessed at two and 26 weeks (N=41), is presented in Table 8.5. The majority of participants (74%) were in the same category for each variable. It is noted that there were 14 participants who had scored zero for five variables (S-FM-UE, SWMFT-S FAS, AROM, flexor IF and extensor IF) at two weeks. Nine of these participants were placed in category 3 for the S-FM-UE, SWMFT-FAS, AROM, flexor IF and extensor IF; the other five participants were placed in category 2.

Table 8.5 Categorisation of S-FM-UE, SWMFT-S FAS, AROM, flexor IF and extensor IF for participants who for whom those variables were measured at 2 and 26 weeks. Shaded cells are participants in category 1 (yellow), category 2 (red) and category 3 (blue).

Category of S-FM-UE, SWMFT-S FAS, AROM, flexor IF and extensor IF (N=41)																																																		
Participant ID	2	4	5	7	8	10	11	13	14	15	16	17	18	20	21	22	23	24	25	26	27	28	29	31	32	33	34	36	37	38	39	40	41	43	44	45	47	48	49	50	51									
S-FM-UE	3	1	1	2	1	1	1	1	1	1	2	1	1	3	3	2	1	1	2	1	1	3	2	1	1	1	2	1	1	3	3	1	1	1	3	1	2	3	3	2	1									
SWMFT-S FAS	3	2	1	2	2	1	1	1	1	1	2	1	2	3	3	2	1	1	2	1	1	3	2	1	1	1	2	1	1	3	3	1	1	1	3	1	2	3	3	2	1									
AROM	3	2	1	2	2	1	1	1	1	1	2	1	2	3	3	1	1	1	2	1	2	3	2	1	1	1	2	1	1	3	3	1	1	2	3	2	2	3	3	2	1									
Flexor IF	3	2	1	2	1	1	1	1	1	1	2	2	1	3	3	1	1	1	1	1	1	3	2	1	1	1	2	1	1	3	3	1	2	2	3	2	2	3	3	2	2									
Extensor IF	3	2	1	2	1	1	1	1	1	1	2	1	2	3	3	1	1	1	2	1	1	3	2	2	1	1	2	1	1	3	3	1	2	1	3	2	2	3	3	2	2									

1: category 1 the high functioning participants at two weeks who continued to improve over 26 weeks; 2: category 2 the low to moderate functioning participants at two weeks who improved over 26 weeks; 3: category 3 the low functioning participants who had scored zero at two weeks with little or no improvement up to 26 weeks

The remaining negative wrist impairments (sine TI, step TI, path length and muscle onset timing) showed a rapid decrease (improvement) from two to four weeks and decreased gradually up to 26 weeks (Figures 8.7 a-d). However, the categories that have been applied to previous variables could not be applied to these variables.

Figure 8.7 a) Sine TI (MAE)

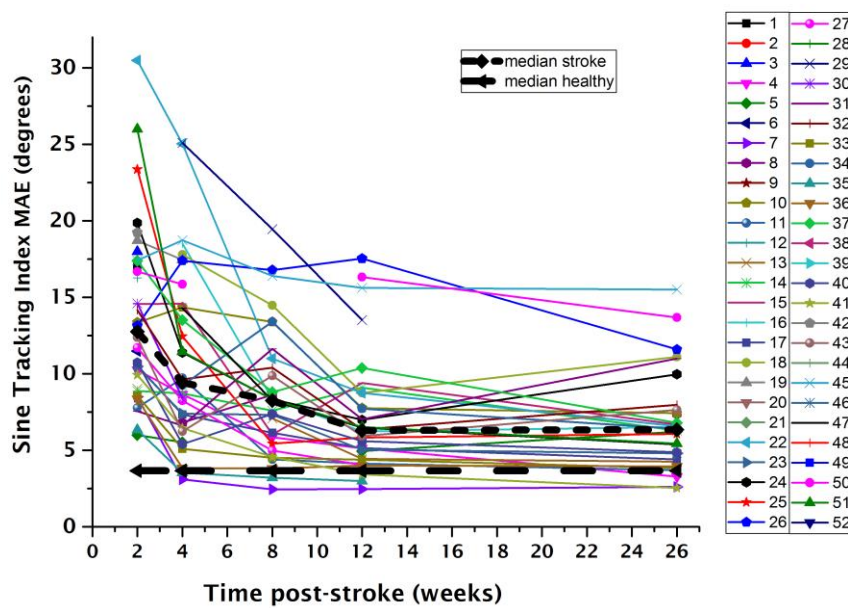


Figure 8.7 b) Step TI (MAE)

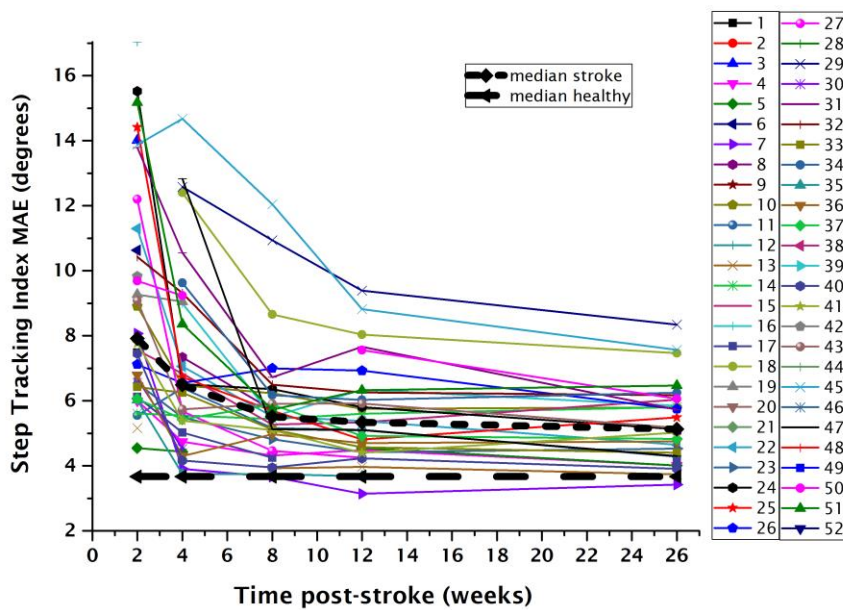


Figure 8.7 c) Path length

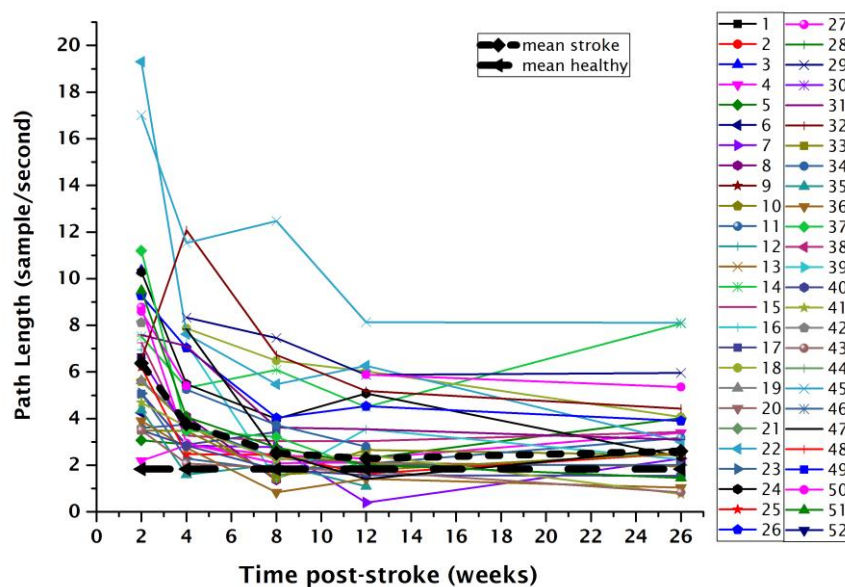


Figure 8.7 d) Muscle onset timing

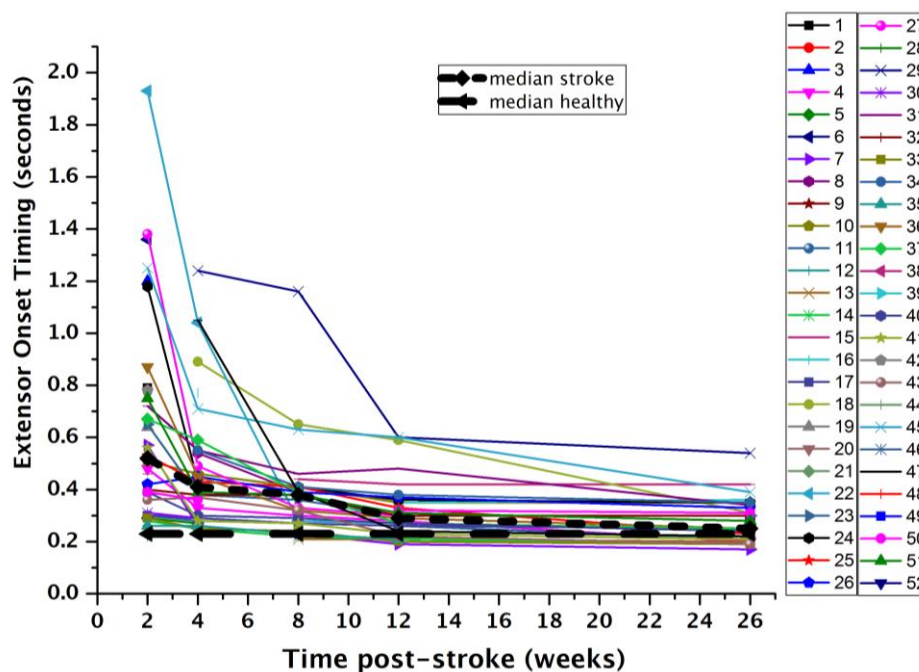


Figure 8.7(a-d) Line charts showing individual a) MAE sine tracking, b) MAE step tracking, c) path length and d) extensor onset timing during 26 weeks. The short dashed line is the median for negative wrist motor impairments at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median of each negative wrist motor impairment for the healthy group.

As mentioned in section 8.4.3.1 that there was variability between genders for the flexor and extensor IF, therefore the line graphs are divided into male and female to show the differences between genders. Figures 8.8 (a-d) reveal that male participants produced greater flexor and extensor IF than female participants at each time point.

Figure 8.8 a) Flexor IF-male

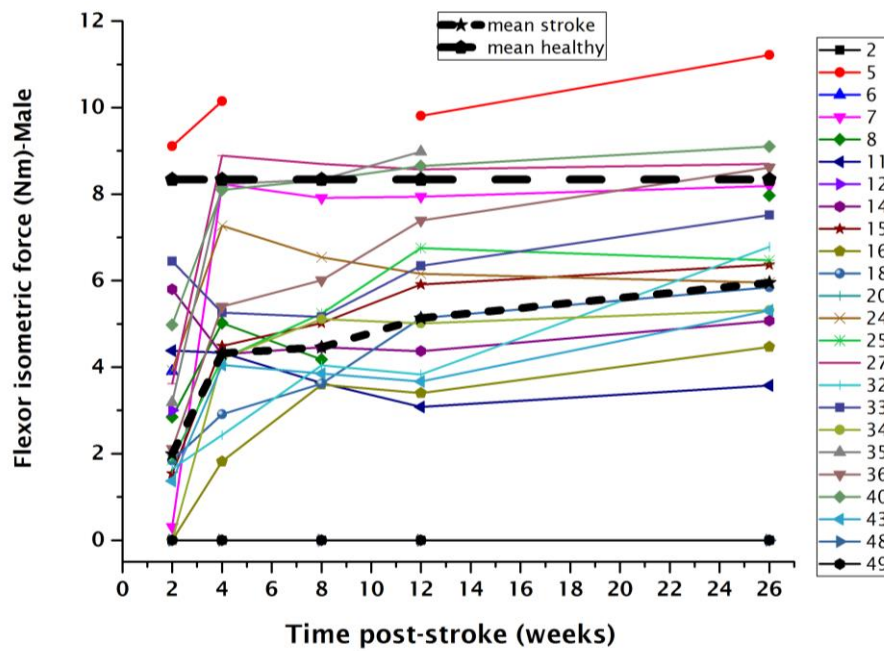


Figure 8.8 b) Flexor IF-female

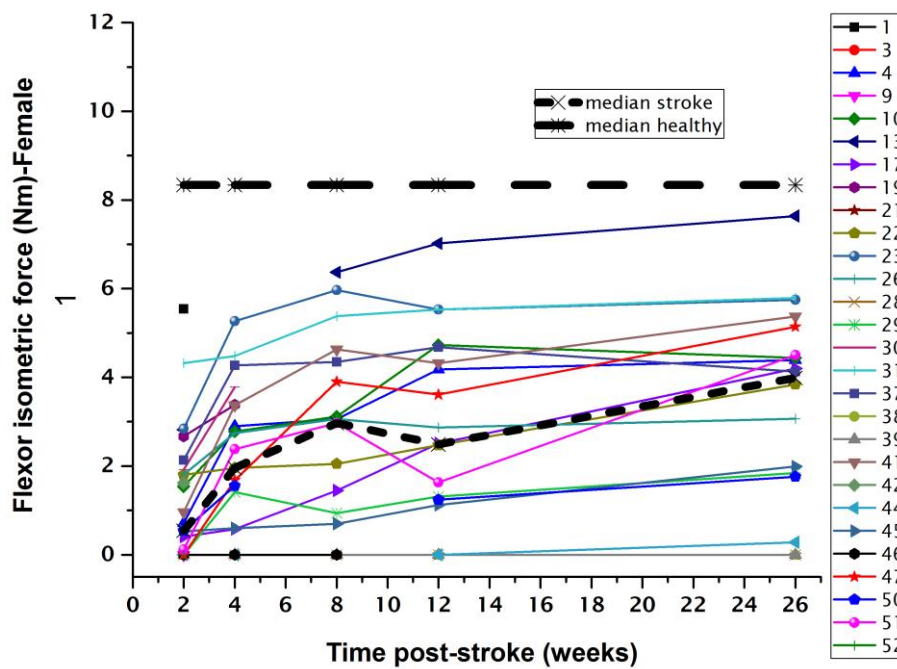


Figure 8.8 c) Extensor IF-male

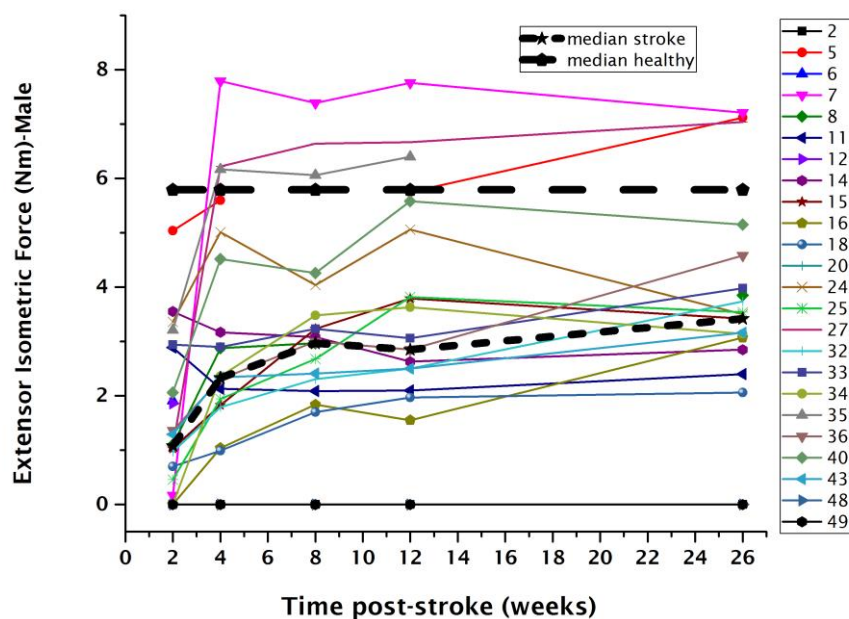


Figure 8.8 d) Extensor IF-female

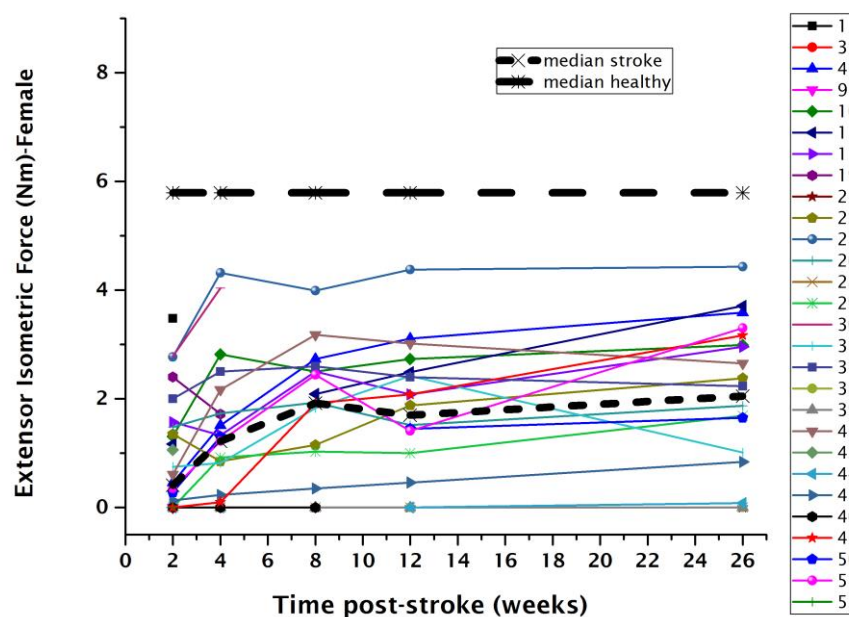


Figure 8.8(a-d) Line charts showing individual a), b) flexor IF and c), d) extensor IF for males (N=24) and females (N=28) during 26 weeks, respectively. The short dashed line is the median for flexor and extensor IF at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median flexor and extensor IF for the healthy group.

8.5.2.3 Positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

Table 8.6 shows the median (IQR) of the sine CI and SI at each time point up to 26 weeks and the MDC for each impairment. For reference, normal median and IQRs are also shown. Individual changes of sine CI and SI at each time point are illustrated graphically in Figures 8.9 and 8.10, respectively, in which both normal and cohort median is also shown.

A negative median for sine CI indicates reciprocal activation. The median for SI increased slightly at four weeks and maintained steadily up to eight weeks, reaching a peak at 12 weeks. At 26 weeks, the median for SI decreased slightly. None of positive wrist impairments changes was greater than their MDC at any assessment point (Table 8.6).

Table 8.6 Median (IQR) for positive impairment indices of stroke participants at 2, 4, 8, 12 and 26 weeks and healthy participants and MDC for each index

Wrist motor impairment index Normal median (IQR)	Median (IQR) for positive impairment indices at each time point					Minimal detectable change (MDC)
	2 weeks N=52	4 weeks N=45	8 weeks N=43	12 weeks N=42	26 weeks N=42	
Sine coactivation index (correlation coefficient) -0.26 (-0.47-0.10)	-0.31 (-0.50-(-0.07))	-0.41 (-0.53-(-0.32))	-0.47 (-0.57-(-0.31))	-0.43 (-0.56-(-0.29))	-0.38 (-0.52-(-0.21))	±0.21
Stretch index (3.5 Hz) (ratio SR: LBL) 0.99 (0.96-1.00)	1.00 (0.99-1.03)	1.01 (1.00-1.06)	1.01 (0.99-1.08)	1.05 (1.01-1.12)	1.04 (0.99-1.21)	±0.16

SR-Stretch response; LBL-Local baseline

The line graph below (Figure 8.9) illustrated that there was more variability and some positive values (indicating coactivation in N=5 out of 30) at two weeks, which then all became negative at four and eight weeks. The majority of stroke participants (N=21 out of 30 at two weeks, N=30 out of 32 at four weeks, N=29 out of 30 at eight weeks, N=31 out of 31 at 12 weeks and N=27 out of 27 at 26 weeks) showed less coactivation than the median for healthy participants (CI=0.09).

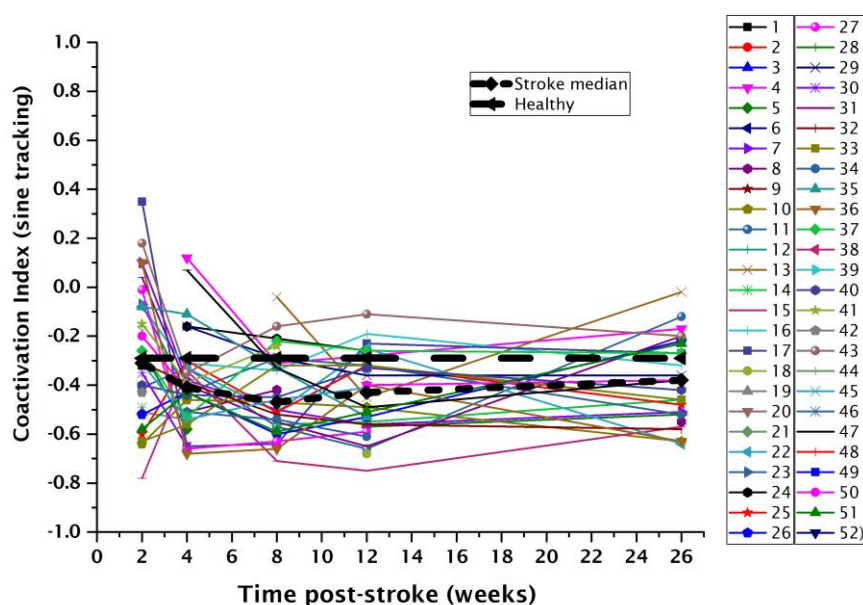


Figure 8.9 Line charts showing individual sine CI during 26 weeks. The short dashed line is the median for sine CI at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median sine CI for the healthy group.

As shown in Figure 8.9, there is variability of sine CI between two and four weeks. Although the numbers are small, there appears to be a relationship between a reduction in coactivation and improved ability to follow the tracking signal. A subgroup of participants (N=22) who were able to perform sine tracking task at two and four weeks is further analysed. The changes in sine CI and sine TI between two and four weeks are explored.

Table 8.7 presents data for sine CI and sine TI of 22 participants who were assessed and had usable data at two and four weeks. Thirteen out of the 22 participants (59%) decreased sine CI from more positive scores (indicating coactivation) to more negative scores (indicating reciprocal activation) more

than the MDC for sine CI (0.21). Fifteen of the 22 participants (68%) also had a decreased in sine TI, which was greater than the MDC for sine TI (2.62) (note: lower index value is better). Ten of 13 participants (76%) who had a reduced sine CI were the same participants who had a reduced sine TI.

Table 8.7 Sine CI and sine TI and changes between two to four weeks for a subgroup of participants who were able to perform the active tracking task at both assessments. Shaded cells are participants who both sine CI and sine TI reduced (i.e. improved).

Sine CI and sine TI and changes of sine CI and sine TI for each participant (N=22)																						
Participant ID	5	7	10	11	15	17	22	23	25	26	27	31	32	33	36	37	40	41	43	45	50	51
Sine CI at 2weeks	-0.26	0.1	-0.64	-0.41	-0.78	0.35	-0.08	-0.07	-0.6	-0.52	-0.01	0.04	-0.31	-0.63	0.1	-0.26	-0.4	-0.15	0.18	-0.31	-0.2	-0.58
Sine CI 4weeks	-0.58	-0.38	-0.46	-0.33	-0.34	-0.65	-0.33	-0.43	-0.3	-0.43	-0.66	-0.40	-0.39	-0.56	-0.68	-0.53	-0.44	-0.39	-0.35	-0.54	-0.42	-0.43
Changes of sine CI	0.32 ^a	0.48 ^a	-0.18	-0.08	-0.44	1 ^a	0.25 ^a	0.36 ^a	-0.3	-0.09	0.65 ^a	0.44 ^a	0.08	-0.07	0.78 ^a	0.27 ^a	0.04	0.24 ^a	0.53 ^a	0.23 ^a	0.22 ^a	-0.15
Sine TI at 2 weeks	5.99	8.49	13.36	7.77	14.56	10.55	30.48	10.49	23.36	13.15	11.71	7.56	14.17	8.57	8.35	17.39	10.74	9.92	12.37	17.41	16.68	25.99
Sine TI at 4 weeks	5.52	3.10	14.35	9.73	14.58	7.33	25.03	7.40	12.44	17.39	8.24	6.62	9.63	5.1	3.84	13.51	5.41	6.45	6.24	18.73	15.85	11.45
Changes of sine TI	0.47	5.39 ^b	-0.99	-1.96	-0.02	3.22 ^b	5.45 ^b	3.09 ^b	10.92 ^b	-4.24	3.47 ^b	0.94 ^b	4.54 ^b	3.47 ^b	4.51 ^b	3.88 ^b	5.33 ^b	3.47 ^b	6.13 ^b	-1.32	0.83	14.54 ^b

^a denotes reduced sine CI \geq 0.21; ^b denotes reduced sine TI \geq 2.62

Figure 8.10 illustrates individual changes for SI from two to 26 weeks. The majority of the stroke participants' SI remained at similar levels, which were slightly above the median SI for healthy participants over time; however, for some SI increased dramatically, generally from 8 weeks (Figure 8.10).

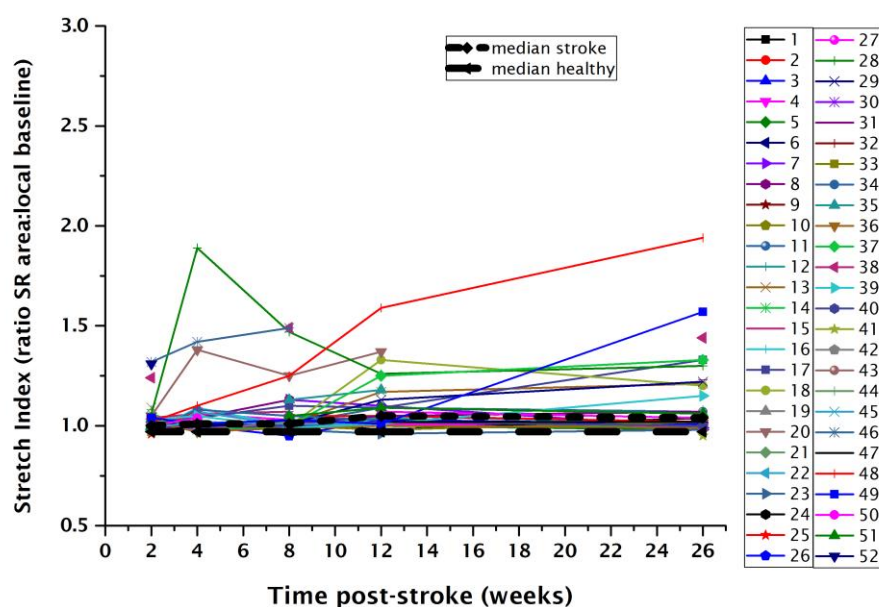


Figure 8.10 Line charts showing individual SI during 26 weeks. The short dashed line is the median for SI at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median SI for the healthy group.

It is apparent from Figure 8.10 that the SI of some stroke participants increased markedly from two to 26 weeks. Even though they were only a small number, it is interesting to investigate whether an increase of SI interrupted the participants' ULFA or not. Further analysis of the relationship between SI and ULFA is shown in Table 8.8.

The participants who had a SI at 26 weeks that was greater than 2SDs above the normal mean (1.05) and whose SI changes between two and 26 weeks were greater than the MDC for SI (0.16) were considered to have an abnormally high SI. A subgroup of participants (N=31) who had usable data for SI at two and 26 weeks, is presented in Table 8.8. Eight participants (25%) had abnormally high SI at 26 weeks, four of them were in the SWMFT-S FAS group 1 (# 15, #17 and #37) or 2 (# 29). Another four participants were categorised into the SWMFT-S FAS group 3.

Table 8.8 Categorisation of SWMFT-S FAS and SI (SI) at two and 26 weeks for a subgroup of participants who had usable data for SI at two and 26 weeks. Shaded cells are participants with abnormally high SI who were categorised into category 1 (yellow), category 2 (red) and category 3 (blue)

	Category of SWMFT-S FAS and SI and changes of SI for each participant (N=31)																															
Participant ID	4	5	7	8	10	13	14	15	16	17	22	23	24	25	26	27	28	29	31	33	36	37	38	39	40	41	44	47	48	49	50	
SWMFT-S FAS	2	1	2	2	1	1	1	1	2	1	2	1	1	2	1	1	3	2	1	1	1	1	3	3	3	1	1	3	2	3	3	2
SI 2 weeks	0.99	1.02	1.03	1.03	1	1.09	1.06	1.04	0.97	1.03	0.98	1.01	1.04	0.96	1.01	1.02	1.06	1.02	1	0.97	1.02	0.99	1.24	1.03	0.98	0.98	1	0.97	1.02	1.04	1	
SI 26 weeks	1	0.98	0.99	1.04	1.02	1.21	0.98	1.23	1.01	1.33	1.01	0.98	1.04	1.02	1.01	0.98	1.3	1.22	1.07	1.02	0.99	1.33	1.44	1.15	1	0.95	1.08	1.02	1.94	1.57	1.04	
Changes of SI	0.01	-0.04	-0.04	0.01	0.02	0.12	-0.08	0.19 ^a	0.04	0.3 ^a	0.03	-0.03	0	0.06	0	-0.04	0.24 ^a	0.2 ^a	0.07	0.05	-0.03	0.34 ^a	0.2 ^a	0.12	0.02	-0.03	0.08	0.05	0.92 ^a	0.53 ^a	0.04	

1: category 1 the high functioning participants at two weeks who continued to improve over 26 weeks; 2: category 2 the low to moderate functioning participants at two weeks who improved over 26 weeks; 3: category 3 the low functioning participants who had scored zero at two weeks with little or no improvement up to 26 weeks; ^adenotes SI increased ≥ 0.16

8.5.2.4 Secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

Table 8.9 shows the median (IQR) scores of the PROM and the MTI for healthy participants and stroke participants during 26 weeks; also indicated the MDC for the PROM and the MTI. Figures 8.11 and 8.12 illustrate the individual changes of the PROM and the MTI during 26 weeks. The median PROM for stroke participants during 26 weeks at each time point was constant, which is similar to the median PROM for healthy participants. However, the lower quartile of stroke participants' PROM scores decreased from 170.12 at 12 weeks to 165.33 at 26 weeks.

The median of the MTI for stroke participants at two weeks was the highest, compared to any other assessment time point and was slightly higher than the median of the MTI for healthy participants. The change in the MTI, at any assessment point, was not greater than its MDC (Table 8.9).

Table 8.9 Median (IQR) for secondary impairment indices of stroke participants at 2, 4, 8, 12 and 26 weeks and healthy participants and the MDC for each index

Wrist motor impairment index Normal median (IQR)	Median (IQR) for secondary impairment indices at each time point					Minimal detectable change (MDC)
	2 weeks N=52	4 weeks N=45	8 weeks N=43	12 weeks N=42	26 weeks N=42	
PROM (degrees)	171.56	171.63	171.93	171.64	171.44	±1.83
171.90 (171.46-171.13)	(170.12-172.35)	(170.53-172.30)	(170.94-172.63)	(162.89-172.39)	(165.33-172.00)	
Mean torque index (Nm)	0.38	0.27	0.29	0.25	0.23	±0.11
0.30 (0.18-0.40)	(0.19-0.50)	(0.18-0.42)	(0.14-0.36)	(0.15-0.38)	(0.17-0.36)	

PROM-Passive range of motion; Nm-Newton metre

Further analysis of the individual data illustrated in the line graph showed that the majority of participants presented fairly constant PROM during 26 weeks (Figure 8.11). Some stroke participants showed a general decrease in PROM from week eight.

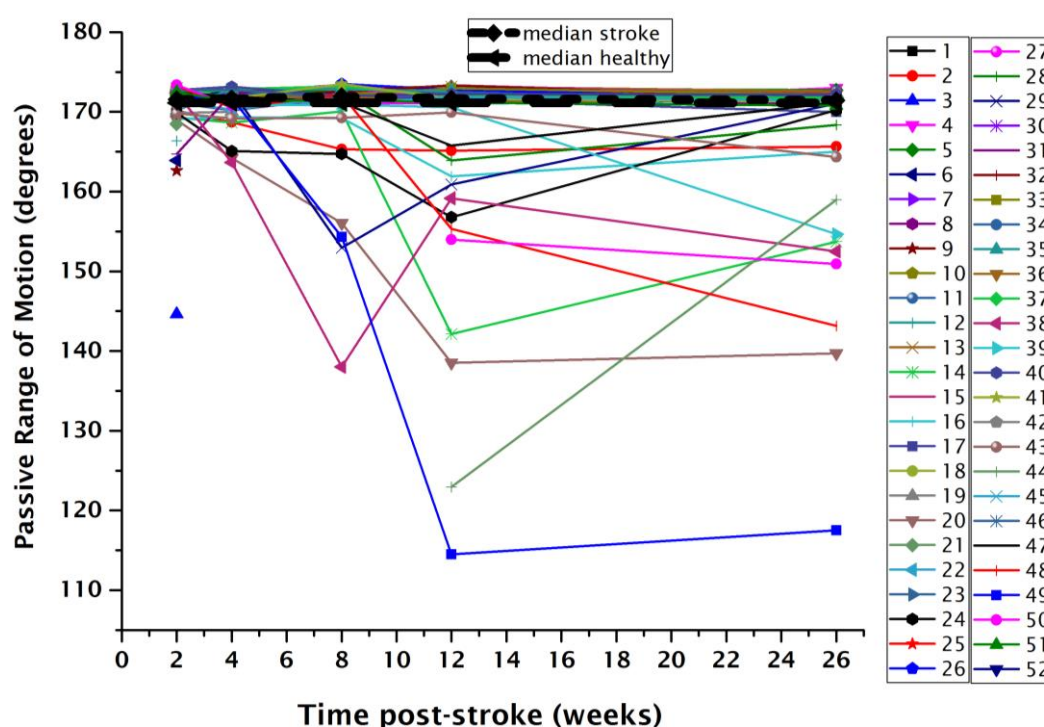


Figure 8.11 Line charts showing individual PROM during 26 weeks. The short dashed line is the median for PROM at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median PROM for the healthy group.

Some participants had a decrease in PROM between two and 26 weeks. There seemed to be a relationship between poor recovery of ULFA and reduction in PROM. A further analysis was therefore made to investigate the relationship between PROM and ULFA.

Data for a subgroup of participants (N=41) who were assessed for PROM at two and 26 weeks are presented in Table 8.10. The participants who decreased their PROM by more than the MDC for the PROM (1.83) were defined as developing contracture. Twelve participants (29%) had a developing contracture. Eight of 12 participants (67%) were categorised into the SWMFT-FAS category 3, but only two into category 1 (# 14 and #43) and 2 into category 2 (# 16 and #50).

Table 8.10 Categorisation of SWMFT-S FAS, PROM at two and 26 weeks and changes of PROM from two to 26 weeks of the participants who were assessed at two and 26 weeks. Shaded cells are participants with a developing contracture at 26 weeks who were categorised into category 1 (yellow), category 2 (red) and category 3 (blue).

Category of SWMFT-S FAS, PROM at two and 26 weeks and changes of PROM from two to 26 weeks (N=41)														
Participants ID	2	4	5	7	8	10	11	13	14	15	16	17	18	20
SWMFT-S FAS	3	2	1	2	2	1	1	1	1	1	2	1	2	3
PROM 2 weeks	170.15	171.13	172.62	171.23	172.15	171.94	171.98	172.98	169.31	171.98	169.07	171.13	171.56	169.01
PROM 26 weeks	165.64	172.97	172.73	171.75	172.6	171.67	172.58	172.56	153.72	172.04	165.02	169.99	171.83	139.72
Changes of PROM	-4.51 ^a	1.84	0.11	0.52	0.45	-0.27	0.6	-0.42	-15.59 ^a	0.06	-4.05 ^a	-1.14	0.27	-29.29 ^a
Participants ID	21	22	23	24	25	26	27	28	29	31	32	33	34	36
SWMFT-S FAS	3	2	1	1	2	1	1	3	2	1	1	1	2	1
PROM 2 weeks	168.5	171.23	171.16	169.87	171.23	172.15	171.98	171.56	172.1	164.71	171.07	171.13	171.78	172.38
PROM 26 weeks	171.27	171.44	171.77	170.22	172.27	171.59	172.21	168.35	171.05	170.92	171.63	172.17	171.96	171.54
Changes of PROM	2.77	0.21	0.61	0.35	1.04	-0.56	0.23	-3.21 ^a	-1.05	6.21	0.56	1.04	0.18	-0.84
Participants ID	37	38	39	40	41	43	44	45	47	48	49	50	51	
SWMFT-S FAS	1	3	3	1	1	1	3	1	2	3	3	2	1	
PROM 2 weeks	172.09	172.34	172.36	172.73	172.97	169.8	172.29	172.89	172.39	173.26	171.9	173.37	172.46	
PROM 26 weeks	171.79	152.5	154.64	172.19	171.24	164.33	158.99	171.47	171.14	143.16	117.51	150.9	170.8	
Changes of PROM	-0.3	-19.84 ^a	-17.72 ^a	-0.54	-1.73	-5.47 ^a	-13.3 ^a	-1.42	-1.25	-30.1 ^a	-54.39 ^a	-22.47 ^a	-1.66	

1: category 1 the high functioning participants at two weeks who continued to improve over 26 weeks; 2: category 2 the low to moderate functioning participants at two weeks who improve over 26 weeks; 3: category 3 the low functioning participants who had scored zero at two weeks with little or no improvement up to 26 weeks; ^a denotes decreased PROM ≥ 1.83 degrees

Observation of the individual MTI shows that it generally fluctuates for each participant, showing no real trend in recovery. The median for stroke participants decreased more than its MDC between two to four weeks, before increasing slightly at eight weeks. Afterwards, the median MTI for stroke participants had a slight decrease up to 26 weeks (Figure 8.12).

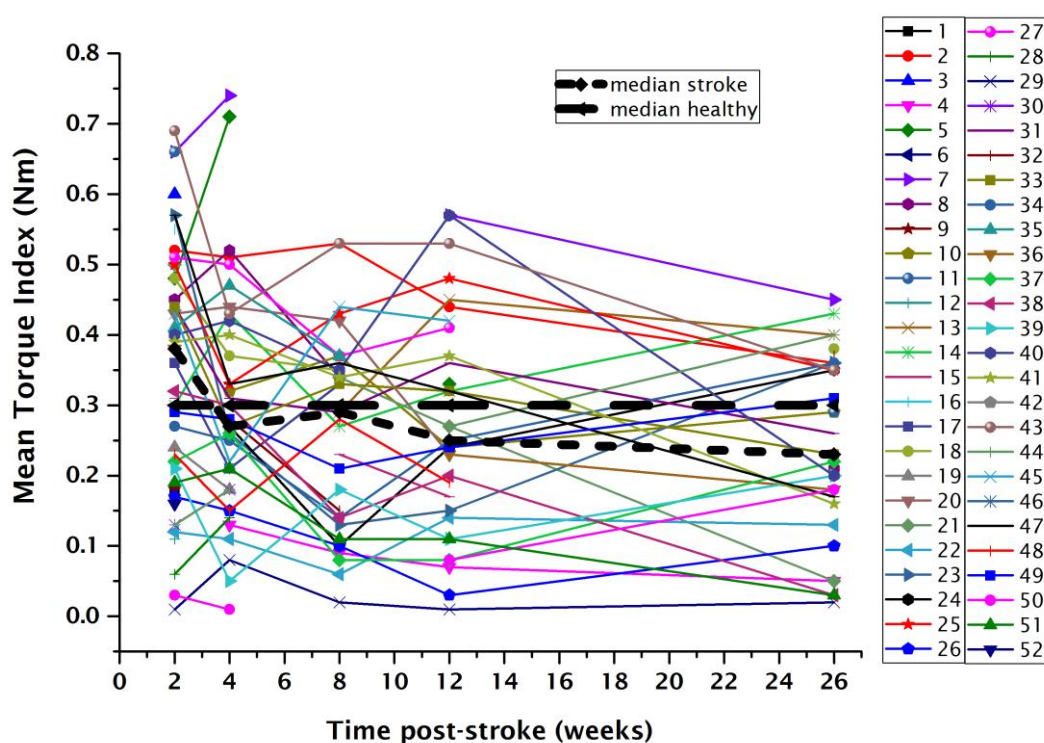


Figure 8.12 Line charts showing individual MTI during 26 weeks. The short dashed line is the median for MTI at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median MTI for the healthy group.

To take account of the gender variability of MTI, the males' and females' MTI scores were plotted separately. The majority of male participants had a higher MTI than the female participants and are therefore presented separately here (Figures 8.13 a-b). The female stroke participants tended to have a lower MTI than the healthy group's median, whereas the male stroke participants' MTI was slightly higher than the normative median.

Figure 8.13 a) MTI-male

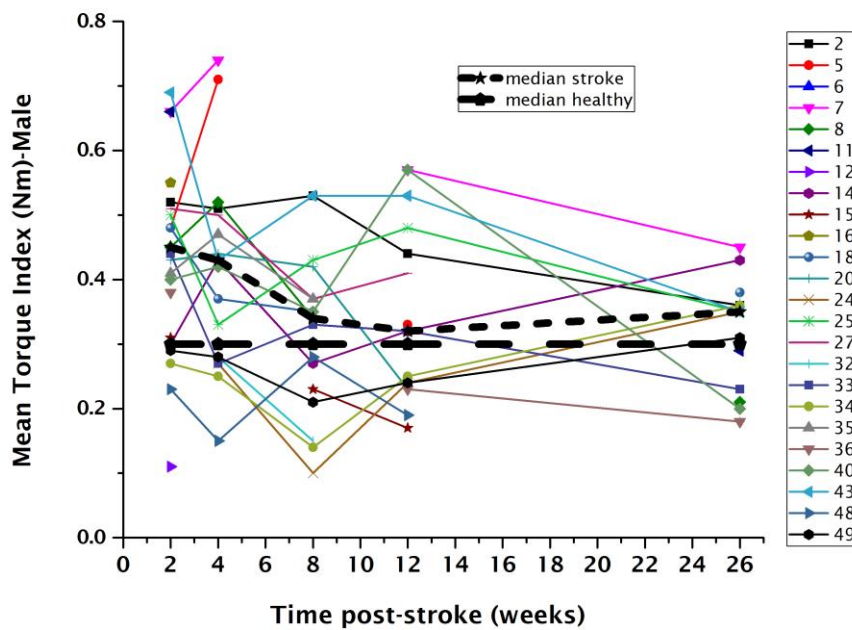


Figure 8.13 b) MTI-female

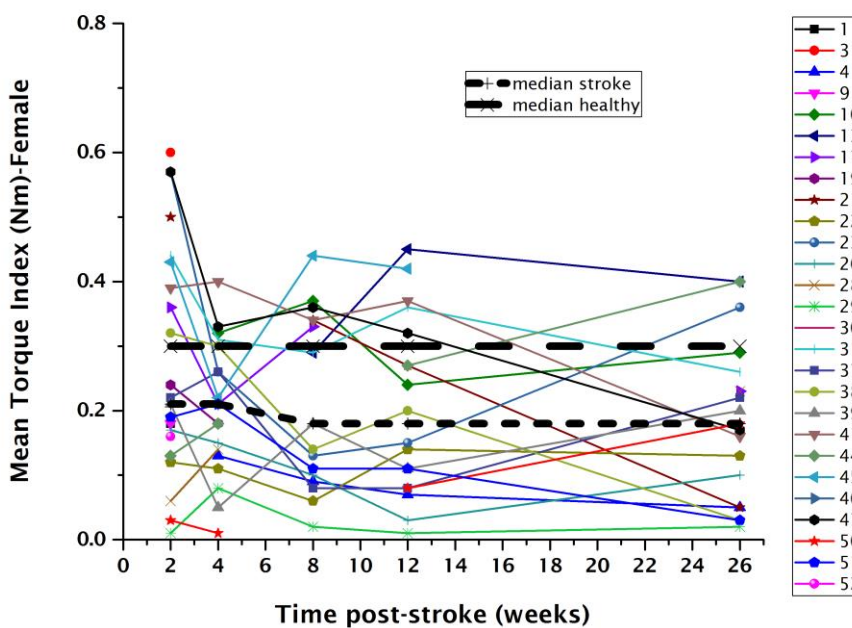


Figure 8.13 (a-b) Line charts showing individual MTI a) male (N=24) and b) female (N=28) during 26 weeks. The short dashed line is the median for MTI at 2, 4, 8, 12 and 26 weeks of stroke participants. The dashed line is the median MTI for the healthy group.

8.5.3 Relationships between SWMFT-S FAS at 26 weeks and wrist motor impairment indices at each time-point

Spearman's correlation coefficients between ULFA at 26 weeks and impairment indices at two, four, eight, 12 and 26 weeks are tabulated. The results in this section are presented in three groups, informed by the concept of upper motor neurone syndrome: negative, positive and secondary motor impairments.

8.5.3.1 Relationships between SWMFT-S FAS at 26 weeks and the following wrist negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

Correlation coefficients between negative wrist impairments at each assessment point and SWMFT-S FAS at 26 weeks are presented in Table 8.11. Statistically significant ($p < 0.01$) correlation coefficients between SWMFT-S FAS at 26 weeks and AROM, flexor IF and extensor IF were identified from two to 26 weeks. These positive correlations were moderate to high. The SWMFT-S FAS at 26 weeks shows a low correlation and statistical significance ($p < 0.05$) with sine TI at two weeks. By four weeks, there was a low to moderate correlation and statistical significance ($p < 0.05$) between the SWMFT-S FAS at 26 weeks and sine TI, step TI and path length. The SWMFT-S FAS at 26 weeks shows both low correlation and statistical significance ($p < 0.05$) with muscle onset timing at only 26 weeks.

Table 8.11 Spearman's correlation coefficients (95% CI) between SWMFT-S FAS at 26 weeks and negative wrist motor impairment indices for stroke participants at 2, 4, 8, 12 and 26-weeks.

Wrist motor impairment indices	Dependent variable: SWMFT-S FAS at 26 weeks				
	Spearman's correlation coefficients (95% CI)				
	2 weeks N=52	4 weeks N=45	8 weeks N=43	12 weeks N=42	26 weeks N=42
AROM (degrees)	0.55** (0.29-0.73)	0.67** (0.45-0.81)	0.74** (0.55-0.86)	0.71** (0.51-0.84)	0.71** (0.51-0.83)
Flexor IF (Nm)	0.60** (0.36-0.77)	0.73** (0.54-0.85)	0.77** (0.59-0.87)	0.78** (0.62-0.88)	0.72** (0.52-0.84)
Extensor IF (Nm)	0.51** (0.24-0.71)	0.66** (0.44-0.81)	0.69** (0.47-0.82)	0.77** (0.60-0.87)	0.72** (0.53-0.84)
sine tracking index (MAE) (degrees)	-0.40* (-0.68-(-0.01))	-0.52** (-0.74-(-0.20))	-0.45* (-0.70-(-0.01))	-0.57** (-0.77-(-0.27))	-0.50* (-0.73-(-0.18))
Step tracking index (MAE) (degrees)	-0.19 (-0.53-0.22)	-0.44* (-0.69-(-0.10))	-0.39* (-0.66-(-0.03))	-0.66** (-0.83-(-0.40))	-0.52** (-0.74-(-0.20))
Path length (degrees/second)	-0.35 (-0.65-0.05)	-0.45* (-0.70-(-0.12))	-0.39* (-0.66-(-0.03))	-0.69** (-0.84-(-0.43))	-0.42* (-0.68-0.06)
Extensor onset timing (seconds)	0.12 (-0.28-0.49)	-0.24 (-0.55-0.14)	-0.22 (-0.55-0.16)	-0.33 (-0.61-0.03)	-0.43* (-0.68-(-0.08))

* $p \leq 0.05$; ** $p \leq 0.01$

8.5.3.2 Relationships between SWMFT-S FAS at 26 weeks and the following positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

Table 8.12 presents correlation coefficients between SWMFT-A FAS at 26 weeks and positive wrist impairments at each time point. SWMFT-S FAS at 26 weeks was statistically significant ($p \leq 0.05$) with SI at two, four and 26 weeks. Those correlations were low to moderate. There was no statistically significant correlation between SWMFT-S FAS and sine CI over 26 weeks (Table 8.13).

Table 8.12 Spearman's correlation coefficients (95% CI) between SWMFT-S FAS at 26 weeks and positive wrist motor impairment indices for stroke participants at 2, 4, 8, 12 and 26-week groups.

Wrist motor impairment indices	Dependent variable: SWMFT-S FAS at 26 weeks Spearman's correlation coefficients (95% CI)				
	2 weeks	4 weeks	8 weeks	12 weeks	26 weeks
	N=52	N=45	N=43	N=42	N=42
Coactivation (sine tracking)	0.14 (-0.29-0.52)	0.08 (-0.29-0.44)	0.26 (-0.12-0.57)	0.06 (-0.30-0.40)	0.15 (-0.23-0.50)
Stretch index	-0.43** (-0.66-(-0.13))	-0.40* (-0.67-(-0.03))	-0.30 (-0.58-0.04)	-0.26 (-0.56-(-0.11))	-0.54** (-0.74-(-0.26))

* $p \leq 0.05$; ** $p \leq 0.01$

8.5.3.3 Relationships between SWMFT-S FAS at 26 weeks and the following secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

Table 8.13 illustrates correlation coefficients between secondary wrist impairments and SWMFT-S FAS from two to 26 weeks. Statistically significant correlations ($p < 0.01$) between SWMFT-S FAS at 26 weeks and PROM were observed at four, eight, 12 and 26 weeks. Those correlations were low to moderate. A low correlation and statistical significance between SWMFT-S FAS at 26 weeks and MTI was identified at two weeks (Table 8.13).

Table 8.13 Spearman's correlation coefficients (95% CI) between SWMFT-S FAS at 26 weeks and negative wrist motor impairment indices for stroke participants at 2, 4, 8, 12 and 26-week.

Wrist motor impairment indices	Dependent variable: SWMFT-S FAS at 26 weeks Spearman's correlation coefficients (95% CI)				
	2 weeks	4 weeks	8 weeks	12 weeks	26 weeks
	N=52	N=45	N=43	N=42	N=42
PROM (degrees)	-0.05 (-0.26-(-0.35))	0.54** (0.27-0.73)	0.49** (0.20-0.70)	0.54** (0.35-0.76)	0.66** (0.44-0.80)
Mean torque index (Nm)	0.37* (0.05-0.62)	0.23 (-0.11-0.52)	-0.04 (-0.67-(-0.11))	0.20 (-0.15-0.51)	0.09 (-0.25-0.41)

** $p \leq 0.01$

8.5.4 Prediction of SWMFT-S FAS at 26 weeks based on wrist motor impairment indices

Table 8.14 shows odds ratio (OR) and 95% CI between SWMFT-S FAS at 26 weeks and wrist impairments from two to 12 weeks. The SWMFT-S FAS at 26 weeks was statistically significant predicted by AROM, flexor and extensor IF, SI and PROM at different time point. The odds ratio between SWMFT-S FAS at 26 weeks and all those variables from two to 12 weeks is tabulated.

The SWMFT-S FAS at 26 weeks is statistically significant ($p \leq 0.05$) predicted by negative wrist impairments (AROM and flexor IF) at two weeks. A prediction of SWMFT-S FAS at 26 weeks by flexor IF continued to be statistically significant ($p \leq 0.05$) over 12 weeks. The SWMFT-S FAS at 26 weeks is also statistically significant ($p \leq 0.05$) predicted by extensor IF from four to 12 weeks. Predictions of SWMFT-S FAS at 26 weeks by positive wrist motor impairment (SI) and negative wrist motor impairment (PROM) were subsequently significant ($p \leq 0.05$) at eight and 12 weeks, respectively.

Table 8.14 Wrist impairments at 2, 4, 8 and 12 weeks that are good predictors of SWMFT-S FAS at 26 weeks.

Wrist motor impairment indices at each time point	Prediction of SWMFT-S FAS at 26 weeks				
	OR	<i>p</i>	Percentage correct	95% CI for OR	
				Lower	Upper
2 weeks					
AROM (degrees)	1.02	0.004*	80.0	1.01	1.04
Flexor IF (Nm)	1.89	0.044*	70	1.02	3.50
Extensor IF (Nm)	2.55	0.066	70	0.94	6.92
Stretch index	0.38	0.118	67.6	0.11	1.28
PROM (degrees)	0.86	0.086	70	0.72	1.02
4 weeks					
AROM (degrees)	1.03	0.001*	89.5	1.01	1.05
Flexor IF (Nm)	3.59	0.002*	86.8	1.58	8.16
Extensor IF (Nm)	4.77	0.005*	86.8	1.62	14.04
Stretch index	0.06	0.194	78.6	0.00	4.07
PROM (degrees)	1.13	0.285	71.1	0.90	1.43
8 weeks					
AROM (degrees)	1.05	0.011*	73.7	1.01	1.09
Flexor IF (Nm)	3.24	0.001*	89.2	1.61	6.52
Extensor IF (Nm)	7.00	0.001*	91.9	2.18	22.48
Stretch index	0.25	0.040*	82.4	0.07	0.94
PROM (degrees)	1.11	0.080	78.4	0.99	1.25
12 weeks					
AROM (degrees)	1.05	0.018*	92.3	1.01	1.09
Flexor IF (Nm)	3.32	0.001*	87.2	1.60	6.89
Extensor IF (Nm)	6.35	0.001*	87.2	2.10	19.16
Stretch index	0.48	0.105	73.3	0.20	1.17
PROM (degrees)	1.19	0.009*	82.1	1.05	1.36

* $p \leq 0.05$

8.6 Summary of results

This chapter presented the results of the longitudinal study. Fifty-two subacute stroke participants in Thailand were recruited at 2 weeks. Their recovery of upper limb impairment (measure by S-FM-UE), ULFA (measured by the SWMFT-S) and wrist impairments (measured in the redesigned wrist rig) were subsequently followed up for 26 weeks. There were 41 stroke participants who were assessed at 26 weeks. This section summarises the key findings of the longitudinal study.

8.6.1 Recovery profiles of clinical measures and wrist motor impairments

1. Upper limb impairment (measured by the S-FM-UE), ULFA (measured by SWMFT-S FAS) and negative wrist impairments (range of active movement [AROM], muscle weakness [flexor and extensor IF] and tracking performance [sine TI]) improved rapidly within the first four weeks with considerably slower improvement between four and 26 weeks. An improvement of the remaining negative wrist impairments (tracking performance [step TI and path length] and delayed muscle onset timing [muscle onset timing]) occurred at week eight, with smaller improvements up to 26 weeks.
2. Data from S-FM-UE, SWMFT-S FAS, AROM and flexor and extensor IF of the participants can be divided into three categories in terms of profiles of recovery. *Category 1* refers to the high functioning participants at two weeks who continued to improve over 26 weeks. *Category 2* is the low to moderate functioning participants at two weeks who improve over 26 weeks. *Category 3* refers to the low functioning participants who had scored zero at two weeks with little or no improvement up to 26 weeks.
3. There was no trend in change of coactivation (sine CI) through the 26 weeks testing period, except for between two and four weeks. For those participants whose sine CI decreased from more positive scores (indicating coactivation) to more negative scores (indicating reciprocal activation) from two to four weeks (N=10 out of 13) were the same people who improved their tracking performance (sine tracking).

4. Eight stroke participants were considered to have abnormally high spasticity (SI) at 26 weeks. Four out of those eight participants were categorised into SWMFT-S FAS groups 1 or 2 (high recovery). Another four participants were categorised as belonging to SWMFT-S FAS group 3 (low recovery).
5. The majority of participants maintained their range of passive movement (PROM) steadily from two to 26 weeks. Twelve participants showed a development of contracture (decreased PROM). Eight out of 12 participants were categorised into the SWMFT-FAS category 3 whereas another four of them were grouped to either category 1 or 2.

8.6.2 Relationships between SWMFT-S FAS at 26 weeks and wrist motor impairments

1. Moderate to high and statistically significant correlations between ULFA at 26 weeks and range of active movement and muscle strength were identified from two to 26 weeks.
2. ULFA at 26 weeks showed a low and statistically significant correlation with sine tracking performance at two weeks. Afterward, both sine and track tracking performances showed a significant correlation with ULFA at 26 weeks.
3. A low and statistically significant correlation between ULFA at 26 weeks and delayed muscle contraction was identified at 26 weeks.
4. Low to moderate and statistically significant correlations between ULFA at 26 weeks and spasticity were found at two, four and 26 weeks.
5. Low to moderate and statistically significant correlations between ULFA at 26 weeks and contracture were found from four to 26 weeks.

8.6.3 Prediction of SWMFT-S FAS at 26 weeks based on wrist motor impairments

Predictions of ULFA at 26 weeks, based on a range of active movement, was statistically significant at two, four, eight and 12 weeks. ULFA at 26 weeks was

predicted by wrist flexor strength from two to 12 weeks at a statistically significant level, whereas wrist extensor strength predicted ULFA at 26 weeks significantly from four to 12 weeks. ULFA at 26 weeks was predicted at a statistically significant level by spasticity at eight weeks and contracture at 12 weeks.

8.7 Summary of Chapter 8

This chapter has presented the research methodology and results of the longitudinal study. Our findings presented the recovery of motor impairments over multiple time points and evaluated relationship to ULFA.

The following chapter presents a comprehensive discussion, limitations of the longitudinal study, recommendations for future research, original contributions to the body of knowledge in stroke rehabilitation and the conclusions to be drawn from this PhD study and its results.

Chapter 9: Discussion and Conclusions

9.1 Introduction

Our study aimed to increase understanding of upper limb motor impairment and ULFA recovery; in particular, to understand the impact of wrist impairments on the recovery of ULFA. An objective novel instrument, the redesigned wrist rig, based on neuromechanical method, was used to measure wrist impairments. Although there have been a few previous longitudinal studies using neuromechanical equipment to investigate multiple upper limb impairment, they measured only muscle weakness, spasticity and contracture (Ada et al. 2006), muscle weakness and dexterity (MCA) (Canning et al. 2004), and spasticity and contracture (Malhotra et al. 2011). As far as we know, this is the first longitudinal study to use a neuromechanical device to measure wrist range of movement, muscle weakness, MCA, delayed muscle onset timing, spasticity, coactivation, contracture and non-neural stiffness in a single assessment over a period from two to 26 weeks. The participants' ULFA were obtained by the SWMFT-S FAS.

This is the first time that the redesigned wrist rig was used to measure wrist impairments in very early acute stroke patients (at less than two weeks). Therefore, the wrist rig protocol, and the clinical measures, were piloted in six healthy participants and six chronic stroke participants in the UK. Following that, the redesigned wrist rig was delivered to Thailand for the purpose of conducting another pilot study with six Thai chronic and eight Thai sub-acute stroke participants. The results of the pilot studies showed that the wrist rig tests, and clinical measures were feasible to be used with sub-acute stroke patients in terms of the time needed for assessment and the comfort of the participants. Methods of analysis for wrist motor impairment indices produced similar trends of indices when compared with a previous study (Turk 2011), which employed an earlier prototype of the wrist rig.

The reliability study (Chapter 6) was conducted to determine the between day test-retest reliability of the indices from the redesigned wrist rig. Furthermore, the MDC for wrist AROM, flexor and extensor IF, sine and step TI, path length, extensor onset timing, sine CI, SI, PROM and MTI were calculated to report the

benchmark values for defining true change of patients' wrist impairments in the subsequent longitudinal study. The redesigned wrist rig demonstrated good to excellent reliability with all of the variables (ICC 0.78-0.99).

The construct validity of the redesigned wrist rig (the ability to distinguish healthy and stroke participants) was evaluated in the matched pair study (Chapter 7). There was a clear distinction between stroke and healthy participants for AROM, flexor and extensor IF, sine and step TI, path length, extensor onset timing, and SI ($p < 0.05$). In contrast, sine CI, PROM and MTI were not statistically significantly different between the stroke and healthy participants.

The longitudinal study (Chapter 8) found that some negative wrist impairments (AROM, muscle weakness and sine tracking performance) recovered mostly during the first four weeks, whereas step tracking performance improved markedly at eight weeks. For positive motor impairments, spasticity developed significantly in 25% of the participants and most of the development occurred from week eight. Coactivation was not observed in the majority of participants. However, it is noted that the sine CI of thirteen participants (59%) moved from more positive scores (indicating coactivation) to more negative scores between two to four weeks. Eight out of 12 participants (67%) who developed contracture had little or no recovery of ULFA. ULFA at 26 weeks was more strongly correlated with negative motor impairments than positive or secondary motor impairments. In the same way, negative motor impairments were stronger predictors of ULFA at 26 weeks, than positive and secondary motor impairments.

The pilot (Chapter 5), reliability (Chapter 6), and matched pair (Chapter 7) studies have been discussed within each chapter. The following sections discuss the results of the longitudinal study (Chapter 8) comprehensively in the context of previously published research and expands the clinical importance of our findings. In addition, recommendations for ULFA rehabilitation, other factors which might influence ULFA recovery post-stroke, limitations of the study, recommendations for future research, original contributions to the body of knowledge in stroke rehabilitation and clinical practise and the conclusions of this thesis are presented.

9.2 Discussion of the longitudinal study

This section is divided into; participants and recruitment rate; recovery profiles of clinical measures and wrist impairments; relationship between ULFA at 26 weeks and wrist impairments; and prediction of ULFA at 26 weeks based on wrist impairments.

9.2.1 Participants and recruitment rate

Participants were recruited over a six-month period and were followed up in another six months. Fifty-two participants were recruited at baseline (two weeks). Forty-one participants (79%) remained in the study at 26 weeks.

Stroke participants were recruited from a single rehabilitation unit. Therefore, all patients received the usual care according to the stroke surveillance protocol at Buddhachinaraj Hospital, Thailand.

Seven participants missed one or more assessment sessions, but returned to participate in the study for the next assessment session, and as such were not classified as dropouts. An example is one participant who moved away to stay with her son at the time her eight week assessment was due, and then moved back to Phitsanulok province in time for her 12 week assessment.

Some participants had difficulty in travelling to the hospital and therefore, they requested to be assessed at their house rather than the hospital. Although the redesigned wrist rig is movable, it is basically a lab-based piece of equipment that is more suited for use in a hospital environment. It is difficult to set up in the participant's house because the rig needs enough space for it to be appropriately positioned. This issue highlights the importance of assessment equipment that is usable in the home environment, as, such equipment mobility will not only reduce dropout rates and increase recruitment rates in trials such as these, but also are potential assessment tools that are useful for routine clinical practise.

In order to evaluate recovery of wrist impairments and ULFA in a stroke sample that is as generalizable as possible to any stroke population, all stroke participants who presented with upper limb movement deficit (defined as a score of less than 12 (highest score) on S-FM-UE) were invited to participate in

the study. Recruitment was based on participants who fitted the study inclusion criteria. Exclusion criteria were stroke patients with skin allergies to alcohol wipes, sEMG electrodes, and sticky tape; and stroke patients who had had a previous stroke affecting the same side. However, the patients with previous stroke who had made a full recovery, operationally defined as gaining a mRS score of 0, could be included in the research. Therefore, it can be assumed that we included stroke patients who had upper limb impairment deficits at all levels of upper limb impairment. To support this assumption, the S-FM-UE scores at baseline assessment were classified into severe, moderate and mild upper limb impairment. According to the classification suggested by Woodbury et al. (2013), 16 (31%), 33 (63%) and 3 (6%) of our participants (N=52) had severe, moderate and mild upper limb impairment, respectively. Therefore, participants with all severity levels of upper limb impairment were included in this study. However, the majority of the participants had moderate upper limb impairment at two weeks.

The median upper limb impairment scores (S-FM-UE) for participants at recruitment (2 weeks) were 50% of the maximum score. This median was higher than the baseline upper limb impairment scores in several other longitudinal studies investigating upper limb recovery post-stroke, i.e. 34% of the maximum FM-UE (Verheyden et al. 2008), 32% of the maximum FM-UE (Gebruers et al. 2014) and 31% of the maximum FM-UE (Kyoung Bo et al. 2015), suggesting that our participants may have had a better recovery of upper limb impairment than those in previous research. The differences in baseline upper limb impairment between our study and all the previous studies may be explained by differences in the inclusion criteria and differences in the participants' medical status. The previous studies recruited stroke participants with an FM-UE less than 60 out of 66 points (Verheyden et al. 2008; Kyoung Bo et al. 2015). Although those criteria were quite similar to ours, stroke participants in the study by Verheyden et al. (2008) and Kyoung Bo et al. (2015) assessed upper limb impairment at less than one week, which is a period in which their participants may have been in a medically unstable condition, and may have less recovery than at two weeks. Gebruers et al. (2014) recruited stroke patients who had scored the National Institute of Health Stroke Scale motor item of the upper limb at more than zero. Therefore, their participants may have had more severe upper limb impairment than our

participants. This is a limitation of our study to generalize our findings to stroke patients with severe upper limb impairment.

Stroke patients who were receiving rehabilitation at the Department of Physiotherapy at the Hospital were screened for eligibility for this study. However, the patients in the neuro-medical wards or the neuro-surgical wards who were diagnosed by a neurologist as having an unstable medical condition at two weeks, missed being invited to take part in the study. Otherwise, stroke patients with insufficient language and cognitive ability to understand the purpose of the study were not included in the study. These issues limited a number of stroke patients with severe upper limb motor recovery.

To sum up, this longitudinal study successfully achieved its aim of recruitment of adequate sample size of 41 stroke participants, who were assessed from two to 26 weeks.

9.2.2 Missing data and loss to follow up

Fifty-two stroke participants were recruited at two weeks; but it was not possible to obtain consistent data at each assessment point. The numbers of participants who were assessed at four, eight, 12 and 26 weeks were 43, 40, 41 and 41, respectively. The reasons for data being missed, and loss of follow up are discussed in this section.

The longitudinal study design has a benefit for those researchers wishing to study mechanisms that are associated with recovery, as it involves the realistic clinical practise of repeated observations. However, one of the limitations of the longitudinal study model is that there is almost always a loss of participants over time; the longer the study, the greater the loss (Guralnik and Kritchevsky 2010). The loss of follow up is inevitable in an observational longitudinal study, which may then lead to bias and loss of statistical power (Fewtrell et al. 2008). Although this longitudinal study did not use a powered sample size, an increasing drop in the follow up rate could affect the study's validity. There are no universally agreed criteria for acceptable follow up rates. However, it is usually suggested that a rate of 50-80% follow up is acceptable in the context of a cohort study (Kristman et al. 2004; Fewtrell et al. 2008). The common causes of loss to follow up in a longitudinal study are death and participants declining to continue in the study (Gebruers et al. 2014; Kyoung

Bo et al. 2015; Opheim et al. 2015). In this study, 11 (20%) participants dropped out during the study period; 2 moved to a distant city; 2 had unstable physical status; 1 died; 2 were unable to be contacted; 4 declined to continue to participate in the study. A possible reason for the participants who declined to continue to participate in the study could be that the participants and/or their caregivers did not want to come to hospital since, by doing so, they would lose their income when they were absent from work. In an attempt to minimise dropout rates, further assessment sessions for the longitudinal study were provided at the nearest community hospital that was convenient for the participants to attend. It was observed that all 12 participants who lived in more remote communities preferred to be re-assessed at their nearest community hospital or their house rather than the Buddhachinaraj Hospital. Therefore, the researcher (WS) followed them up at their preferred community hospital, which minimised dropouts. However, other reasons for dropouts were uncontrollable.

The 20% dropout rate in our study was judged to be acceptable. This rate was similar to the loss of follow up rates in another longitudinal upper limb studies in which the participants were also first recruited at two weeks. A previous study using neuromechanical equipment, which measured elbow motor impairment between two weeks and one year (N=27), had dropout rates of 19% and 30% at 26 weeks and one year, respectively (Ada et al. 2006). Other studies which recruited participants within one week following stroke, showed dropout rates that were higher than our research. A 12-week study by Gebruers et al. (2014) showed a 31% dropout rate (N=129) at 12 weeks. A 26 week follow up study by Kyoung Bo et al. (2015) (N=29) had a 31% dropout rate at 26 weeks. Opheim et al. (2015) (N=117) assessed at 10 days, four weeks and one year. In total, 76 participants were assessed at one year (a 35% dropout rate). However, there were another studies which were conducted in more than one setting, which showed low dropout rates, even when the participants were recruited at very early stage after stroke (Nijland et al. 2010b; Meyer et al. 2015). Nijland et al. (2010b) recruited 188 participants within 72 hours following stroke and ended up with 156 participants at 26 weeks (a 17% dropout rate). All participants were recruited from nine acute hospital stroke units in the Netherlands. A recent study by Meyer et al. (2015) recruited 532 first stroke participants on admission and re-assessed at eight weeks, 26

weeks and five years. Their project was collaboration between four European rehabilitation centres. Dropout rates at eight and 26 weeks were only 2% and 13%, respectively before increasing to 55% at the five years mark. Taken together, there are several reasons causing the loss of follow up. Recruitment at the very early stage may increase the rate of dropout. In contrast, a study which is very well controlled and with more than one setting may reduce the rate of dropout.

The other critical issue to address is missing data. There are several reasons why data is missing. Firstly, some participants who could not perform active tests were assessed only for the passive tests. Secondly, there were poor quality signals or artefacts for the EMG data of some participants that could not be analysed. Such a distortion can be due to technical problems such as movement artefacts or internal noise. The internal structure of the subject, such as blood flow velocity, measured skin temperatures and the muscle and fat tissue structure, directly affects EMG signal quality. In addition, movement artefacts could be created during muscle activation (Chowdhury et al. 2013). Skin abrasion by rubbing skin is found to reduce the movement artefacts (Tam and Webster 1977). The researcher (WS) needed to replace the electrodes frequently, especially when data collections were conducted in non-air-conditioned rooms at the community hospitals; only two of the five hospitals had closed rooms with air conditioning. Thirdly, there were participants who missed assessments because they could not manage to come to the hospital. Although the researcher (WS) provided an assessment session at their nearest hospital, it was still difficult for them to access transport. This issue was beyond the researcher's control.

In summary, our loss of follow up rate was considered to be acceptable. Any future research conducting the same experiment, using EMG, should be located in an air conditioned environment and participants' skin needs to be very well prepared to increase the quality of the EMG signals.

9.2.3 Recovery profiles of clinical measures and wrist motor impairments

Most recovery of upper limb impairment, ULFA and some of negative wrist impairments (range of active movement [AROM], muscle weakness [flexor and

extensor IF] and tracking performance [sine TI]) occurred within the first four weeks following stroke with a slower rate of improvement up to 26 weeks. Range of active movement and muscle weakness have the most similar recovery profiles to upper limb impairment and ULFA. Spasticity and contracture developed during later stages of the assessments for a small number of individuals.

Recovery profiles of upper limb impairment, ULFA and wrist impairments during the first 26 weeks are comprehensively discussed in the following sections.

9.2.3.1 Recovery of upper limb motor impairment (Short Form of the Fugl-Meyer Motor Scale; S-FM-UE) and ULFA (Streamlined Wolf Motor Function Test-Functional Ability Scale; SWMFT-S FAS)

This study addressed the issue of upper limb impairment and ULFA recovery during the first 26 weeks post-stroke. Our principal findings are that upper limb impairment and ULFA made the greatest improvement within four weeks, with a small improvement up to 12 weeks; reaching a plateau at 26 weeks. The upper limb impairment and ULFA of the participants could be placed into three categories. Category 1: the participants who started with high scores at two weeks and had a good recovery up to 26 weeks. Category 2: the participants who started with zero to moderate scores at two weeks and showed a good recovery over 26 weeks. Category 3: the participants who started with zero score and attained little or no recovery over 26 weeks. The results of the profiles of recovery for these two variables are discussed below.

The full version (33-item) FM-UE has been found to be the most common upper limb impairment outcome measure in intervention studies (Murphy et al. 2015; Santisteban et al. 2016) and observational studies (Verheyden et al. 2008; Gebruers et al. 2014; Kyoung Bo et al. 2015; Opheim et al. 2015; Persson et al. 2015; Winters et al. 2015) after stroke. Our research is the first longitudinal study to use the S-FM-UE (6-item) to measure upper limb impairment recovery. The S-FM-UE was selected because it showed high reliability and concurrent validity with the FM-UE ($r \geq 0.93$) (Hsieh et al. 2007) and obviously saves time compared to the FM-UE.

The MDC of the S-FM-UE was reported as 1.5 (Hsueh et al. 2008). We found that the median of S-FM-UE in our study changed dramatically beyond its MDC within the first four weeks with no or little change thereafter. Several studies which have investigated the recovery of upper limb impairment measured by the FM-UE have had similar findings to ours. Verheyden et al. (2008) (N=32) investigated upper limb impairment recovery evaluated at one, four, 12 and 26 weeks. It was observed that the most striking improvement for their upper limb impairment occurred from between one to four weeks. A significant improvement of upper limb impairment ($p<0.001$) was found between one and 12 weeks post-stroke, but not from 12 to 26 weeks (Verheyden et al. 2008). Kyoung Bo et al. (2015) investigated changes in upper limb impairment at one, two four, 12, 16, 20, and 26 weeks in 26 stroke participants. Again their results showed that upper limb impairment recovery was relatively rapid during the first four weeks ($p<0.01$), and there was no significant difference between 12 and 26 weeks. Recently, Wee (2015) investigated the recovery profile of upper limb impairment every four weeks during the first 26 weeks, and also found that the maximum rate of change for upper limb impairment was in the first four weeks. Taken together, our findings provide evidence to suggest that the upper limb impairment improved rapidly within the first four weeks post-stroke.

We found that the upper limb impairment of our stroke participants at 26 weeks had improved (83.33% of full score of S-FM) more than in the previous studies by Verheyden et al. (2008) and Kyoung Bo et al. (2015) (75% and 47% of maximum FM-UE). This result may be explained by the fact that our stroke participants seemed to have higher levels of upper limb impairment at the baseline compared to other studies (Verheyden et al. 2008; Gebruers et al. 2014; Kyoung Bo et al. 2015) (section 9.2.1).

The SWMFT-FAS was used to evaluate ULFA recovery in our study. There has been no previous research investigating the MDC of the SWMFT-FAS. Lin et al. (2009) reported the MDC of the WMFT as 0.37 points. Based on the MDC of the WMFT FAS, our participants improved their ULFA markedly between two and 12 weeks, reaching a plateau by 26 weeks. Previous studies have investigated recovery of ULFA, although using different clinical measures, and found a similar recovery pattern of ULFA to our findings. Ada et al. (2006) (N=27) evaluated changes of ULFA, as measured by the MAS. The results visually

showed that the recovery rate of ULFA improved rapidly within 12 weeks, followed by a slight increase up to 26 weeks and reaching a plateau at up to 52 weeks. Kong and Lee (2013) (N=100) also investigated ULFA recovery, as measured by the MAS. The descriptive results revealed that an improvement of ULFA occurred between rehabilitation admission (mean MAS = 0.5 (0-3)) and 12 weeks post-stroke (mean MAS = 6 (3-6)). No improvement was found from 12 to 52 weeks. A large study by Meyer et al. (2015) (N = 532) revealed that ULFA, measured by the Rivermead motor assessment arm function (RMA-A), improved markedly between admission and the first eight weeks (mean change scores = 2.04; $p < 0.0001$; linear mixed models analysis). Subsequently, ULFA improved slightly from eight to 26 weeks (mean change scores = 0.91; $p < 0.0001$). Only the study by Meyer et al. (2015) found a statistically significant improvement of ULFA between eight and 26 weeks. However, it is necessary to interpret that data with caution because small differences in a large sample size study may become statistically significant. A recent study by Wee (2015), which used the eight items of SWMFT-S FAS to measure ULFA, showed that the maximum rate of change for SWMFT-S FAS occurred during the first four weeks.

We reported data about upper limb impairment and ULFA descriptively and graphically because the statistical analysis of serial measurements, such as the t-test or the Wilcoxon signed-rank test, may give a misleading impression of the ways in which individual subjects typically respond over time. In addition, information about variations among subjects in their response over time may be misinterpreted (Matthews et al. 1990). Traditional methods to analyse repeated measures data such as repeated measures analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA), were not considered because they are appropriate to be used with normally distributed data (Field 2009). Linear mixed models analysis, such as that used in a study by Meyer et al. (2015) was not applied due to the small sample size of this study. It was suggested that this model required a sample size of at least 100 (Curran et al. 2010). In addition, our data varied considerably, as can be seen in the way that the participants obviously fell into different three categories.

At 26 weeks, nine out of 41 participants (22%) in this research experienced little or no recovery of ULFA, whereas 32 (78%) showed moderate to high ULFA at 26 weeks. These findings contrast with previous studies that found less than half of the stroke participants regained moderate to high ULFA at 26 weeks.

Kwakkel et al. (2003) noted that only 11.6% of participants (N=102) presented completed ULFA, as measured by the Action Research Arm Test (ARAT) and another 38% of participants had moderate ULFA at 26 weeks. Au-Yeung and Hui-Chan (2009) found that 47% of participants (N=57) had poor ULFA (ARAT <10) at 26 weeks. The difference in degree of ULFA between previous studies and our study at 26 weeks may be explained by our participants having ULFA at their initial assessment that was higher than the participants in those previous studies (Kwakkel et al. 2003; Au-Yeung and Hui-Chan 2009). Although our study was conducted in different settings with different participants' characteristics and may have had a different therapy duration compared with those studies, the baseline scores of the participants seem to be the most important reason for resulting in the different levels of recovery between ours and other studies. This premise is supported by a study by Houwink et al. (2013), which found that high ULFA, as measured by the Stroke Upper Limb Capacity Scale (SULCS), at initial assessment (on admission) may be associated with a high level of ULFA at discharge. On admission, their 125, 58 and 116 participants had low, medium and high ULFA, respectively. At discharge, 41% of those 125 with low ULFA regained moderate ULFA, while 78% of the 58 stroke participants with medium ULFA had regained high ULFA (Houwink et al. 2013).

Our study confirms the importance of the 3 months period for upper limb impairment and ULFA recovery after stroke. Intensive treatment targeting upper limb impairment and ULFA, early after stroke, may be beneficial for patients' recovery.

9.2.3.2 Recovery of negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

The main finding was that the greatest recovery of wrist AROM, flexor and extensor IF and sine TI occurred between two and four weeks then continued up to 26 weeks, but at a slower rate. In comparison, step TI, path length and muscle onset timing improved later (during the first eight weeks) with a slower improvement to 26 weeks. The recovery profiles for all negative wrist motor impairment are discussed in this section.

Our findings build on the existing literature, which examines recovery of upper limb AROM. A previous study by Beebe and Lang (2009) showed that the stroke participants (N=31) recovered a composite of nine upper limb segments on the hemi-paretic limb (shoulder flexion, elbow flexion, forearm supination/pronation, wrist flexion/extension, fingers flexion) from 72% to 99% of normal range by 12 weeks. However, the question arises as to when AROM was mostly recovered, as the researcher investigated upper limb AROM at only four and 12 weeks. We measured wrist AROM at two, four, eight, 12 and 26 weeks and found that the wrist AROM recovered mostly during the first four weeks.

Wrist range of movement and muscle weakness demonstrated faster recovery times than MCA and delayed muscle onset timing. MCA is a more complex movement than AROM, requiring sustained motor control, AROM, muscle strength, concentration etc. and could be impaired due to other factors such as spasticity and contracture. It is unsurprising therefore MCA (step TI) improved more slowly than AROM and muscle weakness. Sine tracking and step tracking tasks were performed to quantify MCA. The sine tracking task was a rhythmic continuous movement, without interval breaks and could be compared to cycling, swimming and walking. The step tracking task was a discrete movement point-to-point, goal-oriented or target oriented movement which could be compared to reaching to grasp a glass or place an object at a location (Hogan and Sternad 2007). ULFA often involves a combination of rhythmic and discrete movements, such as handwriting, wiping a table and playing the piano (Sternad and Dean 2003).

Based on our data the rhythmic movement seems to improve faster than discrete movement. This is the first time comparing recovery period between sine and step tracking performance. A recent research found that the smoothness of rhythmic movement was less affected post-stroke than discrete movement. Leconte et al. (2016) investigated levels of disability in performing rhythmic and discrete movements in 11 chronic stroke and age-matched control participants. The participants performed discrete and rhythmic movements, which consisted of elbow flexion and extension. The results demonstrated that discrete movement of the paretic arm was more severely disrupted than the rhythmic movement (Leconte et al. 2016), which combined with our findings, suggests that recovery of rhythmic movement is easier than discrete movement. Further studies using functional imaging shed more light

on this. A study of rhythmic and discrete movements (Schaal et al. 2004) showed that a small number of unilateral primary motor areas were activated during rhythmic movement, whereas a variety of additional contralateral non-primary motor areas were activated during discrete movement. Furthermore an observation from a study of neural control of rhythmic arm cycling after stroke provides evidence of an alteration of cutaneous reflex in stroke participants (Zehr et al. 2012) which suggests that not only subcortical areas govern the rhythmic movement of the arm, but that spinal pattern generating networks (e.g., locomotor central pattern generators) are also shown to do so (Zehr et al. 2012). Therefore, once rhythmic movements are initiated, the stroke patients might be able to perform mainly by relying on those undamaged low-level circuits. According to the impact of time on recovery of sine and step tracking performance, a rehabilitation programme, which aims to improve ULFA, may initially focus on rhythmic movement training because it is easier than discrete movement. Consequently, stroke patients then need to practise movement that involves both tasks to promote their ULFA.

Although we investigated MCA during single joint movement, our findings revealed a similar recovery profile of MCA to another study, which investigated MCA during multiple joints movement. The study by van Kordelaar et al. (2014) evaluated the smoothness of the individual's paretic arm, when performing functional reaching and grasping tasks, using 3-dimensional kinematic measurements (N=44). Assessments were done at weeks one, two, three, four, five, eight, 12, and 26 weeks. The results demonstrated that MCA improved significantly during the first eight weeks before reaching a plateau up to 26 weeks. Therefore, the MCA of a single joint may be governed by similar mechanisms of brain recovery as multiple joints movement.

The path length is the MCA at the target end point, specifically the amount of corrective sub-movements. It is a useful assessment, which has been used to measure the ability to control movement in patients with multiple sclerosis, who presented with intention tremor (Feys et al. 2006). Our findings revealed that stroke participants also had poor control of their movement at the end point, especially during the first two weeks. The majority of stroke participants who exhibited improved their path length during 26 weeks were the same participants who exhibited an improvement of step TI (note: lower index value

is better). A similar pattern of recovery for these two indices might be because they were both taken from the step tracking task.

Muscle onset timing in our stroke patients mostly improved during the first eight weeks with a smaller improvement up to 26 weeks. At two weeks, all stroke participants had a delayed wrist extensor muscle onset time compared to the median muscle onset timing in healthy participants. This finding corroborates previous research, where delayed muscle onset timing at wrist muscle has been found in acute stroke patients (mean=nine days post-stroke) during a reaching task (Wagner et al. 2007a). Wrist extensor onset timing in the stroke participants at 26 weeks was greater than in the healthy participants (note: lower index value is better), which is consistent with previous studies which showed delayed muscle onset timing in stroke participants at more than 26 weeks (Dewald et al. 1999; Chae et al. 2002a). An issue that needs to be further investigated is whether or not delayed muscle onset timing, at the early post-stroke stage, is the main contributor of ULFA limitation.

Recovery profiles for AROM, flexor and extensor IF of the participants, who were assessed at two and 26 weeks (N=41), could be categorised into three categories same as the S-FM-UE and the SWMFT-S FAS. As 30 of the participants (74% of those 41) were in the same category for each variable, it suggests that the recovery profiles of wrist range of movement and strength occur together, maybe involving the same or similar mechanisms, and reflect recovery of ULFA.

In summary, our findings have provided a better understanding of negative wrist motor impairment recovery. Range of movement, muscle weakness and the ability to control rhythmic movement, improved noticeably during the first four weeks. The ability to control discrete movement improved later than those other impairments. Simple assessments of wrist AROM and IF, which have strong associations with ULFA, could be surrogate markers of recovery of function.

9.2.3.3 Recovery of positive wrist motor impairments: sine CI (coactivation) and SI (spasticity)

The sine CI showed no clear pattern of a recovery profile over 26 weeks. Unexpected findings were observed during the first four weeks when it was found that 76% of the participants who had decreased sine CI were the same

individuals who had improved sine TI. For the majority of the participants, their SI did not increase above normal. Only 25% of the participants at 26 weeks had an abnormally high SI. A half of them was categorised into the SWMFT-S FAS groups 1 or 2 and another half was into the SWMFT-S FAS group 3. This section discusses the recovery profile of the sine CI and SI.

Thirteen stroke participants decreased sine CI from more positive scores (indicating coactivation) to more negative scores (indicating reciprocal activation) between weeks two and four. Therefore, we further investigated whether they were the same people who improved in MCA. What is interesting in this data is that 10 out of those 13 participants were the same people who improved in their sine TI (note: lower index value is better). One explanation for this could be that at 2 weeks they used coactivation to stabilise their wrist, but as their control improved they no longer needed to do this. Some coactivation is normal for joint stability and fixation of one body part while another moves (Sheean 2001; Frey-Law and Avin 2013). The coactivation which was observed in those 13 participants may have been due to either poor muscle strength, poor motor control or both. However, the sine tracking task, which was used to evaluate coactivation, required minimal muscle strength, suggesting that increased coactivation was more related to poor MCA. Canning et al. (2000) investigated coactivation and MCA at the elbow joint in 16 chronic stroke participants, who were divided into high (N=10) and poor (N=6) MCA groups. They found that low MCA after stroke was characterised by coactivation. A previous study using a similar task and similar neuromechanical equipment to measure muscle coactivation revealed a correlation between MCA and coactivation in both acute and chronic stroke groups (Turk 2011). Our findings also confirm the association between MCA and coactivation.

Abnormal coactivation was not observed in any of the participants between four weeks to 26 weeks, which was slightly surprising as it has been reported in previous research (Canning et al. 2000; Chae et al. 2002b; Turk 2011), all of whom observed coactivation in chronic stroke patients. A possible explanation, of course, may be that coactivation does not become apparent until later than 26 weeks post-stroke; e.g. 12 to 156 months (Canning et al. 2000), eight to 110 months (Chae et al. 2002b) and 12 to 91 months (Turk 2011). In addition, it may be that we excluded the low functioning patients.

We defined an abnormally high SI as a value greater than two standard deviations (2SDs) above the mean for healthy participants (1.05), and an increase in SI between two and 26 weeks greater than the MDC for SI (0.16). Numerous studies have used clinical assessment, such as the Ashworth Scale (AS) in both modified or original versions to evaluate the recovery of spasticity (Sommerfeld et al. 2004; Lundström et al. 2008; Lundstrom et al. 2010; Wissel et al. 2010; Opheim et al. 2014). However, as the use of the AS and modified AS has been questioned regarding their validity and reliability to assess spasticity (Malhotra et al. 2009; Fleuren et al. 2010), the researcher (WS) decided to discuss the findings in the context only of studies that used neuromechanical equipment. A 36-week longitudinal observational study, which used neuromechanical equipment to measure spasticity, revealed that 28 (92%) of participants demonstrated signs of spasticity throughout the study period (Malhotra et al. 2011). However, they did not determine any clear definition of signs of spasticity. A simple method to interpret abnormally high SI that can be applied in clinical practise is presented in our study.

Further analysis of the spasticity data showed that the eight people who developed spasticity were just as likely to be category 1 and 2 ($n=4$) as 3 ($n=4$). This finding suggests that in some patient, spasticity interferes with function, but not in all cases and that it does not seem to relate to how high the SI is. These findings further support previous studies that demonstrated no relationship between spasticity and ULFA in people who have had stroke (Burridge et al. 2009; Malhotra et al. 2011).

To sum up, coactivation was observed at only two weeks for stabilising the wrist joint and did not become apparent over 26 weeks. A development of spasticity was found in 25% of the participants at 26 weeks, but it may not be related to ULFA.

9.2.3.4 Recovery of secondary wrist motor impairments: PROM (contracture) and MTI (non-neural stiffness)

Development of contracture and non-neural stiffness are secondary motor impairments, and these were evaluated. Contracture developed in 29% of the participants at 26 weeks. The majority (67%) of them were categorised into the SWMFT-FAS category 3. Non-neural stiffness showed no trend in the profiles of recovery over 26 weeks.

Contracture at several joints is a common complication after stroke, which can be observed during the first year (Sackley et al. 2008; Kwah et al. 2012). Our operational definition for developing contracture was 'decreased PROM by more than the MDC for the PROM (1.83)'. Twelve of the 41 participants at 26 weeks had a developing contracture. Eight of those 12 were categorised into the SWMFT-FAS category 3. This finding suggests that poor ULFA be associated with contracture. Pandyan et al. (2003) also observed contracture formation in 14 stroke participants who had non-functional upper limb movement (measured by the Action Research Arm Test (ARAT) and the Nine-Hole Peg Test (NHPT)), which was similar to our findings. The time course for developing contracture was comparable to a study by Ada et al. (2006), which also found that contracture increased over the first two months. Another four participants who developed contracture were grouped into categories 1 (# 14 and #43) and 2 (# 16 and #50). The observed decrease in PROM of these participants could be attributed to complications during the study period. It was recorded that the # 14, #16 and #50, who decreased AROM 15.59, 4.05 and 22.47 degrees respectively, had joint pain and hand oedema at week 12. There was no complication in the #43 and her PROM had decreased at 26 weeks.

Non-neural stiffness did not show a clearly pattern in the recovery profile. The individual MTI for the stroke participants fluctuated over 26 weeks, with a decrease of the median of the MTI over time. Our findings were in contrast to the study by Turk (2011), which found that chronic stroke patients had higher non-neural stiffness than acute stroke patients. The chronic stroke participants in Turk's study (2011) were more than one year post-stroke with poor ULFA. The study by Kamper et al. (2006) found that the chronic stroke participants with severe impairment exhibited statistically greater non-neural stiffness in the metacarpo-phalangeal joints of the finger, than the participants who were moderately impaired. Taken together, the non-neural stiffness may be increased in only chronic stroke patients with poor ULFA. The stroke participants, who decreased their non-neural stiffness during the two to 26 weeks post stroke period, were the participants who had great improvement in recovery of their upper limb impairment and ULFA. Therefore, an increase in non-neural stiffness was not observed in our chronic stroke participants (26 weeks). However, an increased or decreased non-neural stiffness cannot be fully explained at this stage.

In conclusion, contracture is likely to develop in non-functional stroke participants. Several questions about non-neural stiffness remain unanswered at present.

9.2.3.5 Neural recovery and rehabilitation programme after stroke

The background to the recovery profiles of the clinical measures and wrist impairments is discussed below in the context of neural process.

Motor recovery in stroke patients is a complex process, including spontaneous recovery during the initial days and weeks after stroke (Nudo 2011) and the plasticity that occurs over longer time scales (Hallett 2001; Byblow et al. 2015). After stroke, removal of thromboses can greatly improve patients' outcomes. In addition, for many stroke sufferers rehabilitation involves the training of spare brain areas and fibre tracts improves their function (Starkey and Schwab 2014). Previous research agrees that spontaneous recovery is not expressed only the first hours after stroke, but may happen in several months (Cramer 2008; Nudo 2011; Byblow et al. 2015), and that there are interactions between rehabilitation and spontaneous recovery after a stroke (Stinear and Byblow 2014). The changes in the connectivity of the brain regarding the growth of new nerve fibre branches are referred to as structural plasticity. There is evidence to support the idea that the peri-infarct region close to the brain lesion, and other regions that have similar functions to the damaged region, are the most likely to be plastic after stroke. Active use of an affected limb, or stimulation through activity or electrification of affected neural pathways, play a significant role in cortical plasticity (Starkey and Schwab 2014).

Neuroplasticity is the maximal in a specific time window after a brain lesion, which may coincide with the optimal time to intervene with rehabilitation. The critical window for neural plasticity is still being investigated (McDonnell et al. 2015). Neuroplasticity involves increased strength of synaptic connections, or the creation of new synapses (synaptogenesis), and dendritic branching. Therefore, a significant improvement of upper limb impairment, ULFA and some of the negative wrist impairments, which were found in our study, may be mostly explained by spontaneous recovery. A further improvement of upper limb impairment, ULFA and wrist impairments, which occurred after week four, may depend on neural plasticity.

Current evidence suggests that the most effective treatment to stimulate neural plasticity is high intensity training in complex environments (Lohse et al. 2014). The upper limb rehabilitation programme should be a programme that focuses on usage of the affected arm, is task specific, intense and repeated (Takeuchi and Izumi 2013; Westlake and Byl 2013). A rehabilitation programme that begins as early as possible may provide better functional outcomes for stroke patients than the late rehabilitation programme (Krakauer 2006; Krakauer et al. 2012; Lynch et al. 2014; Lele 2015). There are several rehabilitation programmes, which are related to ULFA improvements, such as original or modified constraint-induced movement therapy (CIMT), robot-assisted arm training (Veerbeek et al. 2014) or functional electrical stimulation (Wenjuan et al. 2013). An investigation of motor impairment highlighted the true recovery of stroke participants rather than simply restoration of function, which may involve by compensation (Krakauer 2005). Therefore, a crucial consideration to customise a rehabilitation programme may be to first examine, which impairments are contributing to the present functional status of the patient.

An interesting finding relevant to clinical practise, is that the participants who were assessed as category 3 could not improve their ULFA. This might be due to three factors. Firstly, the recovery of stroke patients depends on the severity of their stroke, based on the extent of the symptoms, and is involved with ULFA improvement (Winters et al. 2015). Secondly, the stroke participants, who did not have non-functional ULFA, may learn non-use of their affected upper limb. Stroke patients with FM-UE scores from zero to 33.33% of its maximal scores represent non-functional ULFA (ARAT 0-10) (Hoonhorst et al. 2015). Our participants who showed little or no improvement of ULFA also had zero to 33.33% of the total S-FM score over 26 weeks, indicating that they had non-functional ULFA and may learn non-use later on. Thirdly, what therapeutic intervention does for those participants in category 3 may not be enough to improve their ULFA. An average length of stay for inpatients who needed intensive rehabilitation in Thailand, was about four weeks (28.4 ± 18.3 days) (Kuptniratsaikul et al. 2016), whereas the majority of participants in our study were admitted for less than two weeks. They received standard rehabilitation treatment at the hospital during their admission. However, following discharge, the amount of therapeutic intervention received by patients depended on their

economic status, because they needed to pay for transportation to hospital themselves in order to receive the rehabilitation treatment. A recent systematic review of randomised control trial studies investigating the effect of extra rehabilitation in addition to the usual rehabilitation for people after stroke has suggested that increasing the amount of usual rehabilitation resulted in improvement in ULFA (Schneider et al. 2016). Their findings support our hypothesis. Therefore, the rehabilitation treatment, which aims to improve motor recovery for those patients in the category 3, may need to overcome the above three factors.

To conclude, brain recovery after stroke is both spontaneous (Natural recovery) and due to neuroplastic changes related to therapy. An objective and early, targeted rehabilitation programme will need to promote functional outcomes for stroke patients

9.2.4 Relationships between ULFA at 26 weeks and wrist motor impairment indices at each time-point

We tracked changes in the correlation between a wide range of wrist motor impairment and ULFA over 26 weeks. Generally, negative impairments seem to limit recovery of ULFA more than positive or secondary impairments, which is in line with previous research (Chae et al. 2002b; Ada et al. 2006; Burridge et al. 2009).

This section presents a discussion regarding the relationships between ULFA at 26 weeks and wrist impairments at each time point in the context of negative, positive and secondary motor impairments as a feature of upper motor neurone syndrome.

9.2.4.1 Relationships between SWMFT-S FAS at 26 weeks and the following wrist negative wrist motor impairments: AROM, flexor and extensor IF, sine TI, step TI, path length and extensor onset timing

Our findings indicate that only wrist range of movement, muscle weakness and sine tracking performance at two weeks showed statistically significant correlations with high ULFA at 26 weeks. These correlations were stronger between four to 26 weeks. MCA during sine and step tracking performance

showed smaller correlations with ULFA at 26 weeks compared to AROM and muscle weakness. Only muscle onset timing at 26 weeks showed a statistically significant low correlation with ULFA at 26 weeks.

These results are consistent with the literature, which indicated that upper limb muscle strength measured by IF is strongly correlated with ULFA, including shoulder (Mercier and Bourbonnais 2004; Harris and Eng 2007), elbow (Canning et al. 2004; Ada et al. 2006; Harris and Eng 2007), wrist (Chae et al. 2002b; Harris and Eng 2007; Burridge et al. 2009; Renner et al. 2009; Turk 2011) and hand muscles (Sunderland et al. 1989; Boissy et al. 1999; Mercier and Bourbonnais 2004; Harris and Eng 2007; Renner et al. 2009; Ng et al. 2011) from the acute to chronic stage post-stroke. The correlation between ULFA at 26 weeks and AROM and muscle strength increased markedly from two to four weeks, slightly increased up to 12 weeks, with a strong correlation at 26 weeks. This finding suggests that quick and easy assessment of wrist AROM and muscle strength is important because they can approximate the degree of ULFA, especially after four weeks. A study by Renner et al. (2009), examined the relationship between muscle strength (hand grip, wrist flexors and extensors, elbow flexors and extensors) as measured by IF and ULFA as measured by ARAT. Surprisingly, the researchers found no statistically significant correlations between muscle strength (hand grip, wrist flexors, elbow flexor and extensor) and ULFA at either three or six weeks. A moderately statistically significant correlation was only found between wrist extension and ULFA at three weeks. Their unexpected results may be explained by the variability in muscle strength across their small sample size (N=16). Therefore, they found no strong correlation between hand grip, elbow flexors and extensors, wrist flexor muscle strength and ULFA after stroke.

A strong correlation between wrist AROM, wrist flexor and extensor IF and ULFA at 26 weeks may be explained by strength being a prerequisite for function. Without at least enough strength to move against gravity, it is not possible to perform everyday tasks. In addition, the SWMFT-S FAS, which was used to assess ULFA, mainly focuses on evaluating the gross motor functions of the arm, which include wrist movement. Wrist muscle contraction is essential for all items in the SWMFT-S (hand to table, hand to box, reach and retrieve, lift can to mouth, lift pencil from table, and fold towel).

Another obvious finding to emerge from our analysis is that wrist muscle strength at any time point showed stronger significant correlations with ULFA at 26 weeks than MCA. This matched the findings observed in a study by Canning et al. (2004) which focused on the elbow. In line with this evidence, rehabilitation programmes may need to be directed towards improving upper limb muscle strength to regain ULFA. Poor MCA is a separate problem from muscle weakness following stroke (Ada et al. 1996). Similar to the previous research (Ada et al. 1996), we evaluated MCA during a tracking task which required minimal strength to ensure that the investigation of MCA was separated from muscle strength. The relationship between step tracking performance and ULFA had not been investigated in a longitudinal study before. Three indices were obtained from the step tracking task: step TI, path length and muscle onset timing. The results provide insight into motor control during rhythmic and discrete movement by the wrist joint, which are necessary for ULFA in daily life. One interesting finding is that only the sine TI from two to 26 weeks showed a statistically significant correlation with ULFA at 26 weeks. The step TI, path length and muscle onset timing exhibited a statistically significant correlation with ULFA at 26 weeks from four to 26 weeks. A possible explanation for the different results between sine and step tracking performance may be that at two weeks the discrete movement was more disrupted than the rhythmic movement. This comment is supported by the way in which the recovery profile of step TI improved later than sine TI (see section 8.5.2.2 for more detail). Although the correlations between sine and step tracking performance and ULFA were weaker than between muscle weakness and ULFA, these findings suggest that the MCA was essential to be targeted in terms of improving ULFA in stroke patients. These results further support the idea of the MCA contributing to ULFA in acute (Canning et al. 2004) and chronic stroke patients (Burrage et al. 2009; Turk 2011).

Previous studies also found an association between wrist extensor onset timing and ULFA in chronic stroke patients (duration post-stroke from 7.5 to 110 months) (Chae et al. 2002a; Turk 2011), which was similar to our findings. Chae et al. (2002a) assessed muscle onset timing during isometric contraction of the wrist extensor, whereas a previous study by Turk (2011) and this current research evaluated the wrist muscle onset timing during dynamic movement. Our current observations showed that delayed muscle onset timing was only

related to ULFA at 26 weeks. This finding suggests that delayed muscle onset time is more likely to be a problem in people in the chronic phase rather than early acute stroke. In contrast, a study by Wagner et al. (2007b) found that delayed anterior deltoid and wrist extensor muscle onset timing in acute stroke patients (duration post-stroke from one to 15 weeks) was significantly correlated with the changes in reaching performance. Wagner et al. (2007b) quantified muscle onset timing during functional task (reaching task) whereas we did this during a single joint movement. It could be implied that, muscle onset time during a functional task, not a single joint movement, was a contributor to ULFA. A further study with a focus on the relationship between muscle onset timing during a functional task in activity daily living is therefore suggested.

9.2.4.2 Relationships between ULFA at 26 weeks and the following positive impairment: sine CI (coactivation) and SI (spasticity)

The CI at any assessment point showed little correlation and no statistical significance with ULFA at 26 weeks. The SI at two, four and 26 weeks showed statistically significantly low to moderate negative correlations with ULFA at 26 weeks.

This is a novel study exploring changes in the relationships between either sine CI or SI (measured by a neuro mechanical equipment) and ULFA at 26 weeks during the first 26 weeks. An observational study by Ada et al. (2006), showed that spasticity was present at two weeks and remained relatively constant across the year but did not make a significant contribution to ULFA limitation. A cross-sectional study by Burrridge et al. (2009) also agreed that there was no statistically significant relationship between spasticity and ULFA in chronic stroke patients. In general, therefore, it seems that spasticity does not relate to ULFA. Contrary to expectations, our findings revealed statistically significantly low to moderate correlations between spasticity and ULFA at 26 weeks. The differences in the results may be explained by the SI (spasticity) in our study being tested during passive movement at 3.5 Hz within 5 degrees around the subject's AROM midpoint, which is a higher frequency of movement (a frequency that may be able to elicit stretch reflex in stroke participants) than employed in previous research (Burrridge et al. 2009; Malhotra et al. 2011). These results are consistent with data obtained by Turk (2011), who used the

same testing protocol to measure SI as was employed in this current research. Turk (2011) found a strong association between spasticity and ULFA in chronic stroke patients. However, the recovery profiles of spasticity over 26 weeks did not show any similarity with the ULFA recovery profiles (see section 8.5.2.3 for more detail). This suggests that the statistically significant relationship between spasticity and ULFA at 26 weeks in our study may be not clinically important because just eight (25%) participants developed spasticity (changed SI more than the MDC for SI; 0.16), and of those four (50%) were moderate to high functioning participants (category 1 or 2) (see section 8.5.2.3 for more detail). A study with a larger sample size of people with stroke who developed spasticity is needed to confirm the relationship between spasticity and ULFA.

A statistically significant relationship between ULFA at 26 weeks and CI at any time point was not found. At two weeks, only five out of 22 participants, who were assessed for sine CI, had positive scores of sine CI (indicating coactivation) and, after this, all participants had negative scores of sine CI (indicating reciprocal activation). The median scores of CI at all assessment points were negative values (indicating reciprocal activation). Because of the very small number of participants who presented with coactivation, it was difficult to investigate the correlation between coactivation and ULFA. It may be that coactivation is not a problem in acute stroke but it may become present over time. In addition, our sample, whose sine CI was able to be assessed (who had active tracking movement), in general were quite high functioning. However, such coactivation may be found to occur in the lowest functioning patients. The previous studies have found a correlation between wrist coactivation and ULFA in chronic stroke participants (Chae et al. 2002b; Turk 2011). There might be more participants (N=13) in Turk's study (2011) who presented coactivation than in ours. Another related study by Turk et al. (2009) suggested that those who did coactivate were at the lowest level in terms of upper limb function. The study by Chae et al. (2002b) used a very different method to measure coactivation and did not report the number of participants who showed coactivation, so comparisons cannot be made. There is still the unanswered question about the development of coactivation in people with stroke. A future, longer, observational study than our study, with a large sample size should be conducted to investigate the relationship between muscle coactivation and ULFA.

9.2.4.3 Relationships between ULFA at 26 weeks and the following secondary impairments: PROM (contracture) and MTI (non-neural stiffness)

PROM between four and 26 weeks had statistically significant low to moderate correlations with ULFA at 26 weeks. Non-neural stiffness at two weeks had a statistically significant low correlation with ULFA at 26 weeks.

Our findings differ from a previous longitudinal study of the elbow, which revealed that contracture made a separate contribution to ULFA at only six weeks during a one year post-stroke timeframe (Ada et al. 2006). The differences between the study by Ada et al. (2006) and our study might be due to differences in the stroke participants' functional level, the joint which was assessed and the method used for measuring muscle contracture. However, Ada et al. (2006) also found that a combination of contracture and muscle weakness, and spasticity, was correlated with ULFA at two, four, six, nine, 17, 26, 39, 52 weeks, which suggests that contracture is another important impairment that related to ULFA. A more recent cross-sectional study demonstrated a moderate correlation between wrist flexor contracture and ULFA in acute stroke patients (Turk 2011). Another longitudinal study found that wrist contracture is more likely to develop in stroke patients who have not recovered ULFA (Malhotra et al. 2011). In line with our findings, eight out of 12 participants, who decreased PROM at 26 weeks, were the participants in the category 3. Taken together, contracture is likely to relate to ULFA. An implication of this finding is that rehabilitation programmes for stroke patients should target PROM maintenance in order to improve their ULFA, as contracture is likely to develop in the chronic stage. A future study investigating changes between contracture and ULFA over a longer period than 26 weeks would be very interesting.

9.2.4.4 Summary of relationships between ULFA at 26 weeks and wrist motor impairment indices at each time-point

In conclusion, AROM and muscle weakness appear to be primary motor impairments limiting the recovery of ULFA. However, MCA and delayed muscle onset timing also need to be targeted to improve ULFA later on. Although the correlations did not indicate causation, resistance training of upper limb

muscle after stroke may effect ULFA recovery. Low to moderate associations between spasticity and ULFA have been found. However, it may not be possible to extrapolate the results to all stroke patients. The low correlation and lack of statistical significance between coactivation and ULFA still needs to be further investigated. Contracture is the secondary wrist motor impairment, which was correlated to ULFA at 26 weeks. However, use of correlation was limited as it is simply evaluating the direct relationships between two factors and does not take into account any other factors that may affect ULFA. A regression analysis, as used in the next prediction section, will provide a much more robust indication about which of these impairments are most closely related to ULFA.

9.2.5 Prediction of ULFA at 26 weeks based on wrist motor impairments at each time point

We found that ULFA at 26 weeks was predicted by wrist AROM and flexor IF at two, four, eight and 12 weeks; wrist extensor IF at four, eight and 12 weeks; spasticity at eight weeks; and contracture at 12 weeks.

These results suggest that ULFA at 26 weeks can already be predicted at two weeks by negative impairments (AROM and muscle strength). Subsequently, positive (spasticity) and secondary (contracture) impairments can also predict ULFA at 26 weeks. Hence, wrist motor impairment data during 12 weeks are not only useful for tailoring a rehabilitation programme for stroke patients, but are also good predictors of ULFA at 26 weeks. Although it was suggested that neuroimaging and neurophysiological assessments may offer a more accurate prognosis for ULFA recovery (Stinear 2010; Zarahn et al. 2011; Stinear and Ward 2013; Byblow et al. 2015; Bigourdan et al. 2016) than motor impairments, those methods cannot be accessed routinely in rehabilitation settings. In addition, motor impairment assessment is cheaper and easier to apply than neuroimaging and neurophysiological assessments.

Our results confirm a classical finding that AROM is a very strong predictor of the paretic ULFA. Previous studies showed that upper limb AROM at less than two weeks after stroke is a positive sign for a favourable outcome for ULFA. A previous study (N=71) presented that shoulder shrug and hand movement (i.e. index finger extension or opposition fingers to thumb) at admission period (mean = 11 days post-stroke) were strong predictors of hand movements at

eight and 12 weeks (Katrak et al. 1998). Smania et al. (2007) revealed that finger extension (N=48) at one week had a high probability of achieving good performance of their upper limbs (measured by the Motricity index) at 26 weeks. Nijland et al. (2010b) (N=188) reported that finger extension and shoulder abduction at 72 hours were valid predictors of ULFA (measured by ARAT) at 26 weeks. AROM at after two weeks was continuously found to be a good predictor of ULFA. A study by Beebe and Lang (2009) (N=33) found that shoulder and middle finger AROM at admission (mean = 18 days post-stroke) strongly predicted ULFA at 12 weeks. Their ULFA was achieved by a comprehensive test battery involving: 1) grip strength, 2) pinch strength, 3) the ARAT, 4) the Jebsen Taylor Hand Function Test, 5) the NHPT and 6) SIS hand function subscale (Beebe and Lang 2009). In contrast, a more recent study (N=50) presented that initial shoulder flexion and wrist extension (mean = 2 days post-stroke) were weak predictors of ULFA. Their ULFA at 12 weeks was obtained from a comprehensive test battery those were 1) grip strength, 2) the NHPT, 3) the ARAT, and 4) the SIS hand function subscale (Prager and Lang 2012). One possible explanation for the differences between a study by Prager and Lang (2012) and other previous research (Beebe and Lang 2009; Nijland et al. 2010b) is that the dichotomisation of the dependent variable (ARAT) was broad (score of <10 was non-functional ULFA and 10 to 57 was functional ULFA). The participants who had scores of 10 or slightly above may have had a small degree ULFA and may have had small degrees of movement. Although Prager and Lang (2012) used the same cut-off point as Nijland et al. (2010b), their sample size was very small. Therefore, dividing ARAT using this cut-off point, may not provide sufficient information for an accurate prognosis. Our study defined functional participants at 26 weeks as having a SWMFT-S FAS score of three or above (maximum score=5). This score indicated that all six tasks in SWMFT-S could be completed to some degree by synergy, or were performed slowly or with effort. Hence, the score three could reflect an ability to perform upper limb movement. This cut-off point may be the optimal dichotomisation for the SWMFT-S FAS.

AROM a few days post-stroke (Prager and Lang 2012) was a less good predictor of ULFA than AROM at three weeks (Beebe and Lang 2009). Similarly, we found AROM at 12, eight, and four weeks were stronger predictors of ULFA at 26 weeks, than at two weeks. AROM a few days post-stroke may reflect only the

participant's severity, whereas motor recovery may occur later. Therefore, a prediction of ULFA at a later stage may be more accurate than at the initial post-stroke stage.

Beebe and Lang (2009) and Prager and Lang (2012) used a battery of clinical tests to avoid the 'floor and ceiling' effect of any one test and for assessing a range of movement across the tests (Beebe and Lang 2009). However, this method is a complicated approach that takes a long time to complete, and which, therefore, may be not appropriate in daily clinical routines, especially with participants shortly after stroke. A simple assessment that provides information about ULFA is needed in the clinical setting.

As with AROM, muscle strength is a good predictor of ULFA. Although there is a lack of research that has investigated prediction of ULFA based on muscle strength (measured by IF), the current observations are in line with those of previous studies. Wagner et al. (2007c), examined a predictor of reaching performance based on wrist flexor and extensor IF with 39 stroke participants (mean = 8 days post-stroke). Reaching performance was measured at 15 weeks. Another study (N=100) showed that a composite of muscle strength (measured by Medical Research Council (MRC) scale for muscle strength) on admission to rehabilitation unit (mean = 5 weeks post-stroke) strongly predicted ULFA (measured by the MAS) at one year (Kong and Lee 2013). They tested wrist muscle strength at multiple time points and showed that increasing flexor and extensor IF during 12 weeks are essential to improve ULFA at 26 weeks. Considerably more work will need to be done to investigate the predictive value of wrist muscle strength to predict ULFA at more than 26 weeks.

MCA (sine and step TI and path length) and delayed muscle onset timing that were measured during sine and step tracking tasks at any time point of assessment, could not predict ULFA at 26 weeks. A possible explanation for these results may be that only a small number of participants were able to be assessed for MCA, compared to AROM and muscle weakness. Only the participants who could perform active tests did tracking tasks. Further research with a larger sample size should be undertaken to investigate this issue.

The SI was the only positive wrist motor impairment that was a statistically significant predictor of ULFA at 26 weeks. An increase of the spasticity at eight

weeks was associated with low ULFA at 26 weeks. This result may be explained by the fact that most of the spasticity development in the participants of this current research developed at week eight. However, the findings of the current study do not support the previous studies, which did not find a correlation between spasticity and ULFA (Ada et al. 2006; Burrridge et al. 2009; Malhotra et al. 2011). Further study with a larger sample size should be undertaken to investigate the prediction of ULFA based on spasticity.

A high PROM at 12 weeks was associated with high scores ULFA at 26 weeks. One of the issues that emerged from these findings is that stroke participants may develop contracture at 12 weeks. Consequently, contracture at 12 weeks was correlated with ULFA limitation.

Although there are several predictors of SWMFT-S FAS at 26 weeks, based on wrist impairments, there was no significant multiple logistic regression. There is a possible explanation, in that predictors should not have multicollinearity (Field 2009). However, those wrist impairments were highly correlated (Turk 2011).

To sum up, wrist impairments from two to 12 weeks are good predictors of ULFA at 26 weeks. The negative motor impairments are stronger predictors of ULFA at 26 weeks than positive and secondary motor impairments.

9.3 Recommendations for ULFA rehabilitation

Our findings suggested that wrist impairments (AROM, muscle strength, motor control, delayed muscle onset timing, spasticity and PROM) were correlated to ULFA. We studied motor impairments at the wrist, which is one example joint of the upper limb. However, this does not imply that the therapist should focus on the wrist. Although causation was not tested, patients with mild wrist impairments tended to have high levels of ULFA. Further work is needed to identify whether a rehabilitation programme that reduced wrist impairment also improved ULFA.

Patients with different prognoses need different rehabilitation goals. Stinear et al. (2012), who developed the PREP algorithm to predict potential for ULFA recovery, suggested that the rehabilitation programme for patients with a predicted complete recovery should focus on task specific training to facilitate

fully recovery of ULFA in their activities of daily living. On the other hand, the programme for patients with a predicted non-recovery may need to focus on prevention of secondary impairments and reduction of their disability, by learning to use their unaffected limbs to complete their ULFA. Furthermore, they may need to learn how to do compensation movement, which is alternative movement patterns (Levin et al. 2009). For example, if they lock their elbow in a synergistic pattern, it could compensate for their elbow weakness when they perform a task (Kwakkel et al. 2004). In addition, they may have to learn to use a compensatory muscle when they cannot generate sufficient force with their typical agonist muscle (McCrea et al. 2005).

9.4 Others factors which might influence ULFA recovery post-stroke

According to the ICF model, our study focused on impairments (body function and structures) and ULFA (activities). However, it is acknowledged that participation (involvement of the people in their society), which is another domain that could influence ULFA recovery, has not been addressed in this research and other prediction studies. In addition, the individual's health condition and personal and environmental factors could affect patients' impairments, ULFA and participation (World Health Organisation 2001). A recent study by Atler et al. (2015) showed that an improvement of impairments and ULFA did not relate to the participation outcome. Therefore, participation post-stroke appears to be complex and may involve issues beyond the return of impairment and ULFA. Their findings are in line with a study by Wolf and Koster (2013), which found that impairments in people with mild stroke were unlikely to be the main reasons for limiting levels of participation. Daily activities (e.g. nutrition, fitness and personal care) and social roles (e.g. community life, education and recreation) were found to have a statistically significant effect on participation levels (Rochette et al. 2007). Therefore, effective rehabilitation programmes to improve patients' ULFA should not only improve the impairments and ULFA, but also be concerned with all factors that may limit patients' accomplishment of daily activities and social roles.

9.5 Limitations of the study

The results of this study need to be interpreted, whilst acknowledging the limitations of the study. This section addresses the limitations of the study that could not have been averted.

1. The wrist rig

The redesigned wrist rig had not been tested for concurrent validity, by investigating the relationship between the motor impairment measured by the redesigned wrist rig and a gold standard method, such as Vicon motion capture for motor control and a dynamometer for maximum voluntary force. However, the redesigned wrist rig was calibrated in order to ensure that the rig and output data were valid and reliable.

Angle and torque was calibrated before data collection in pilot study 1 re-calibrated every 2 days. It was also calibrated after transportation, such as to a community hospital, or every 2 weeks if the rig had not been moved.

2. Sample size

An important limitation of the current study is the small sample size of the longitudinal study. A reasonable ratio of cases for predictive study that we determined was 138 participants (Allen et al. 2014), and we only had 41 participants at 26 weeks, limiting the strength of the statistical findings. Moreover, the small sample did not allow for identifying clinical factors characterising poor recovery of participants in category three. The majority of participants were categorized into categories one and two. Hence, results presented here are less generalizable to the stroke population especially those with more severe stroke.

For the main objective, to investigate predictors of ULFA at 26 weeks based on wrist impairments, a powered sample size calculation had not been estimated to test the correlation between ULFA at 26 weeks and each wrist motor impairment. Therefore, our findings concerning relationships between ULFA at 26 weeks and wrist impairments may be underpowered. A future study should calculate powered sample size. Since there are various wrist impairments, estimation of sample size should be based on the largest sample size to

ensure that all the outcome measures are fully powered (McCrum-Gardner 2010).

3. Cause and effect was not investigated

The results of the longitudinal study may provide insights into underlying motor impairments which impact on ULFA recovery. However, cause and effect was not investigated. We only investigated motor impairment at wrist flexors and extensors due to the ease of accessibility of those points and their obvious involvement with upper limb functional activity. For example, wrist muscle strength is a good predictor of ULFA; however, it does not mean that strengthening exercise of wrist extensor will increase ULFA.

4. Motor impairments were only measured at the wrist

Although it has been found that wrist impairments are related to ULFA, and are good predictors of ULFA, multi directional and multi joint movements contribute to upper limb function. Investigation of motor impairments at other upper limb joints and multiple joint, ideally during the performance of functional movement needs to be addressed.

5. Lack of severely affected stroke participants

Participants with severe communication, memory or language deficits that could interfere with the testing protocol were not included. In addition, we only included participants who were able to conduct all tests within their first two weeks post-stroke. These two factors led to a small number of severe stroke participants, resulting in bias in our findings. The majority of our participants had moderate upper limb impairment at baseline. Therefore, our findings may be less, or not at all, generalizable to stroke patients with severe upper limb impairment. For example, CI, spasticity and contracture are likely to develop in severe stroke participants. It is recommended that further research be undertaken with a larger sample size, consisting of a wider spread of people with upper limb impairment levels.

6. Comparison between the affected and unaffected sides

Following stroke, there is a reduction of muscle strength on the side contralateral to the brain lesion. Recovery of upper limb impairment, ULFA and wrist impairments were only focused on the hemiplegic limb. However, there is an increasing body of evidence indicating that the ipsilateral side can also be affected (Baskett et al. 1996; Laufer et al. 2001; Jung et al. 2002; Kiyama et al. 2011; Suzuki et al. 2011; Metrot et al. 2013; Pandian and Arya 2013; Jang and Jang 2016). Therefore, it would be useful to investigate the recovery profile of bilateral upper limb impairments.

7. Assessor bias

The researcher (WS) was the only assessor and collected all data. Therefore, the assessor was not blinded to the post-stroke stage of each participant. This issue may have resulted in bias in the clinical assessment scales (S-FM and SWMFT), which are more subjective than a neuromechanical equipment. Assessor bias can be eliminated if the assessor is blind to the post-stroke stage of each patient. However, it was difficult to control this bias within the constraints of this PhD research programme's resources. We minimized the bias by training the assessor to administer tests, and the whole assessment session was observed by the PhD supervisors until the researcher (WS) was proficient at performing those clinical scales accurately and consistently.

8. Sensorimotor factors that could influence the finding

Unilateral spatial neglect (USN), hemianopia and other visual disturbances may limit tracking the performances of the participants. The USN is a neuropsychological disorder which occurs as a result of lesions on the brain. A patient with USN fails to report events occurring on the space side that is usually contralateral to the side of a unilateral lesion (Rabuffetti et al. 2012). The target display of the wrist rig is on both sides of the midline. Therefore, those patients may not be able to pay attention to the other side of the target display. A star cancellation test, which is a simple and short assessment, can be applied to screen the presence of unilateral spatial neglect (Wilson et al. 1987). A future study should administer this assessment as a screening assessment.

9.6 Recommendations for future research

This research has thrown up many questions that now need further investigation. The following studies are suggested for future research.

1. A follow-up study of the participants in the longitudinal study at one year post stroke i.e. in the chronic phase, using the same testing protocol. The purpose of this follow up would be to evaluate recovery profiles of upper limb and wrist impairments and ULFA, from the two to more than 26 weeks post-stroke, to deepen the understanding of natural recovery, relationships between impairments and ULFA, and prediction of ULFA.
2. To investigate the relationship between time to rehabilitation, duration and intensity of therapy, and motor impairments and ULFA to determine whether the rehabilitation programmes influence recovery of ULFA.
3. To develop robust portable equipment that by uses a similar method to derive motor impairments' indices. The portable equipment would be useful to take to a patient's house, rather the large, delicate and not very portable lab-based wrist rig equipment
4. To investigate predictors of ULFA based on wrist impairments in a powered number of sample size. A larger study is needed to confirm the results of this PhD study.
5. To investigate correlations between wrist impairments and extent of corticospinal tract damage. It was observed that each impairment recovered markedly at a different time point.

9.7 Original contributions to the body of knowledge in stroke rehabilitation and clinical practise

The following findings are the original contributions made to the body of knowledge in stroke rehabilitation that arise from our study.

1. Wide range of wrist impairments (measured with the wrist rig) that can potentially impact on ULFA are reported at two, four, eight, and 26 weeks. In addition, a category of ULFA and wrist impairments is presented. This

information will enable therapists to tailor a rehabilitation programme to suit the needs of stroke patients at each stage of stroke.

2. Knowing the predictors of ULFA, the clinician is able to make an accurate prognosis of stroke survivors and to select the most appropriate rehabilitation intervention to optimise ULFA.
3. The recovery profiles of upper limb impairment, ULFA and wrist impairments, enables the clinician to estimate how changes will develop overtime of each motor impairment and ULFA.
4. Neurophysiological and neuromechanical equipment that can assess a wide range of wrist impairments in a single assessment was tested for reliability, and showed that it was feasible to be used in for research in a hospital.
5. Results could be used to generate data to inform power calculations for future studies.

9.8 Conclusions

This is the first study which has evaluated multiple motor impairments at the wrist, using neuromechanical methods, during the first 26 weeks after stroke. The redesigned wrist rig was used to measure the wrist impairments was tested for reliability and validity before being employed in the longitudinal study. The MDC for each wrist motor impairment index is presented as benchmark values for determining changes of wrist impairments over time. Recovery profiles of upper limb impairment, ULFA and wrist impairments are presented descriptively. Relationships between ULFA at 26 weeks and wrist impairments at two, four, eight, 12 and 26 weeks have been investigated, and prediction values for ULFA at 26 weeks, based on wrist impairments at two, four, eight, 12 weeks.

Results from the study confirmed good reliability and validity of the redesigned wrist rig. Upper limb impairment, ULFA and some wrist impairments (AROM, muscle weakness and sine tracking performance) improved rapidly within four weeks, followed by a smaller improvement up to 26 weeks. Recovery profiles of these variables can be divided into three categories. Category 1 is the participants with high scores at two weeks who improved continuously over 26

weeks. Category 2 is the participants with low to moderate scores at two weeks who also improved over 26 weeks. Category 3 is the participants with zero scores at two weeks who had little or no improvement over 26 weeks. The remaining negative wrist impairments (step tracking performance, path length and delayed muscle onset timing) improved significantly at week eight, with smaller improvements up to 26 weeks. ULFA at 26 weeks is associated with AROM, muscle strength, sine and step tracking performance, path length, delayed muscle onset timing, spasticity and contracture at the wrist. Generally, ULFA at 26 weeks is more related to negative motor impairments than positive or secondary motor impairments. AROM, muscle strength spasticity and contracture are good predictors of ULFA at 26 weeks. It is important to point out that negative motor impairments from two to 12 weeks could predict ULFA at 26 weeks. However, the positive and secondary motor impairments are good predictors afterwards: at eight and 12 weeks respectively. Motor impairment should be measured in clinical practise, in order to target each motor impairment that resulted in ULFA improvement.

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Appendices

Appendix A Ethical approval forms by the Faculty of Health Sciences Ethics Committee, UoS (ETHICS ID: 8747 and 12917) and the Ethics Committee of the Buddhachinaraj Hospital, Phitsanulok, Thailand (ETHICS ID: 35/57)

Ethics and Research Governance Online
ERGO

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UNIVERSITY OF Southampton

Main Menu

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- Submissions to review
- Downloads
- Adverse Incident

My Research

Create a research project

ID	Submission Name	Status
16653	Prediction of upper limb recovery post-stroke using wrist motor impairments: pilot study 2 and main study (Amendment 4)	Approved
8747	Prediction of upper limb recovery post-stroke using wrist motor impairments: Pilot study 1	Approved

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03:51 26/07/2015



เอกสารรับรองโครงการวิจัยในมนุษย์
คณะกรรมการจริยธรรมเกี่ยวกับการวิจัยในมนุษย์
โรงพยาบาลพุทธชินราช พิษณุโลก

35/57

ชื่อโครงการ	การทำนายการฟื้นตัวของการทำงานของแขนและมือ หลังเกิดโรคหลอดเลือดสมอง โดยใช้ความบกพร่องทางการเคลื่อนไหวของข้อมือ: การวิจัยนำร่องครั้งที่สองและการศึกษาหลัก
ชื่อหัวหน้าโครงการ	วรุณภา ศรีโสภาท
เลขที่โครงการ/รหัส	-
สังกัดหน่วยงาน	Faculty of Health Sciences, University of Southampton, United Kingdom
การรับรอง	ขอรับรองโครงการวิจัยดังกล่าวข้างบนนี้ได้ผ่านการพิจารณาและรับรองจาก คณะกรรมการจริยธรรมเกี่ยวกับการวิจัยในมนุษย์โรงพยาบาลพุทธชินราช พิษณุโลก เมื่อวันที่ 23 เม.ย. 2557

ลงนาม



ประธานคณะกรรมการจริยธรรมเกี่ยวกับการวิจัยในมนุษย์

Ethical approval form

Ethics Committee of the Buddhachinaraj Hospital, Phitsanulok

Project title: PREDICTION OF UPPER LIMB RECOVERY POST-STROKE USING WRIST MOTOR IMPAIRMENTS

Researcher: WAROONNAPA SRISOPARB

Project number: -

Institute: FACULTY OF HEALTH SCIENCES, UNIVERSITY OF SOUTHAMPTON, UNITED KINGDOM

Status: Ethical approval was obtained from the Ethics Committee of the Buddhachinaraj Hospital, Phitsanulok since 27 April 2014

Dr Sirilak Klanarong

Principal of Ethics Committee of the
Buddhachinaraj Hospital

Appendix B Poster for recruitment of healthy participants (pilot study 1)

UNIVERSITY OF
Southampton

Are you a healthy individual with no injury to your dominant arm?

Would you like to participate in research?


We are looking for people with no injury to dominant arm to help us find out what wrist movements predict your arm function.

An instrumented wrist rig

EMG sticky pad

Comfortable air splint

Target display



What is involved?

1. A one hour visit to the Faculty of Health Sciences (Building 45)
2. We will use this wrist rig to measure your wrist movement, strength and control.
3. You will also perform six simple arm tasks in a seated position.

For further details please contact:
Ms Waroonnapa (Nick) Srisoparb
Email: ws2e12@soton.ac.uk Tel: 075-21542316

Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 075-21542316
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[10/12/13] [Version 1]

Appendix C Poster for recruitment of chronic stroke participants (pilot study 1)

UNIVERSITY OF
Southampton

Have you had a stroke?
Is your arm movement affected?

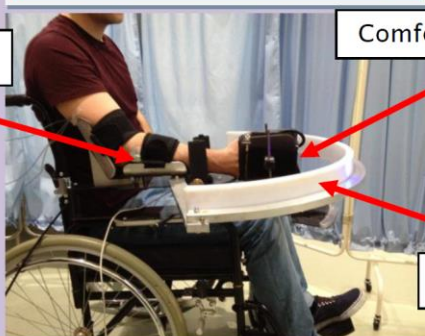
Would you like to participate in research?

We are looking for people to help us find out what wrist movements predict arm recovery following stroke.

An instrumented wrist rig

EMG sticky pad

Comfortable air splint



Target display

What is involved?

1. A one hour visit to the Faculty of Health Sciences (Building 45)
2. We will use this wrist rig to measure your wrist movement, strength and control.
3. You will also perform six simple arm tasks in a seated position.

For further details please contact:

Ms Waroonnapa (Nick) Srisoparb

Email: ws2e12@soton.ac.uk Tel: 075-21542316

Wrist Rig Research
Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

Wrist Rig Research
Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

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Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

Wrist Rig Research
Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

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Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

Wrist Rig Research
Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

Wrist Rig Research
Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

Wrist Rig Research
Nick
ws2e12@soton.ac.uk
Tel: 075-21542316

Appendix D Invitation letter for healthy and chronic stroke participants (pilot study 1)



Date:

Dear Sir/ Madam

Re: Invitation to participate in a research study

I am writing to you on behalf of the Faculty of Health Sciences at the University of Southampton to invite you to take part in a research study that investigates arm recovery after a stroke. We are looking for healthy and chronic stroke participants to help us to evaluate the test procedure that investigates wrist movement pattern and arm function.

The assessment will be carried out at the Faculty of Health Sciences (Building 45) in the University of Southampton. A map is included with this invitation to help you find us. It will involve you making just one visit, which will last for about an hour. Once you have read the enclosed information sheet and decide you would like to take part in this study, please email me or call me at the telephone number found at the end of this letter. I will answer any questions you might have and will also take the opportunity to ask you some general questions about your health status. These questions will help me determine if the assessment is suitable for you. An appointment will then be made for you to come for your one hour visit, at a day and time that are convenient for you.

Many thanks for taking the time to read this invitation letter. I look forward to meeting you if you choose to take part in the study.

Yours sincerely,

Waroonnapa (Nick) Srisoparb
Mphil/PhD student,
Rehabilitation & Health Technologies Research Group
Faculty of Health Sciences,
University of Southampton,
Building 45, Room 0001,
Highfield campus,
SO17 1BJ
United Kingdom

Email: ws2e12@soton.ac.uk
Mobile: 075-21542316

[21/01/14] [Version 2]

Appendix E Participant Information Sheet for healthy participants (pilot study 1)



Participant Information Sheet for healthy participants

Study Title: Prediction of upper limb recovery post-stroke using wrist motor impairments: Pilot study 1

Researcher: Waroonnapa Srisoparb

Ethics number:

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

Introduction

I am a physiotherapist and currently I am pursuing a degree of Doctor of Philosophy at the University of Southampton, United Kingdom. As part of this degree, I am conducting this research study.

I would like to invite you to participate in my research study. Before make your decision, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with your relatives, friends or your GP if you wish.

If something is not clear, or you would like more information, please do not hesitate to contact me. Take time to decide whether or not you wish to take part. Thank you for reading this.

What is the research about?

Muscle weakness, tightness (known as spasticity) and loss of control of movement are common problems among people who have had a stroke. There is a need for better measures of movement problems in order to improve research on the arm function of people who have had a stroke. A better understanding of the underlying reason for improvement in arm activity after a stroke will enable better diagnosis of movement problems and more targeted therapy.

The purpose of this pilot study is to evaluate the test procedure (the wrist rig tests and the arm function test) which will be conducted in a future main study with stroke participants. The result of this pilot study will enable the researcher to make refinements to the protocol before proceeding to collect data in chronic stroke patients.

Why have I been chosen?

You have been chosen to take part in this study as:

- i) you are healthy people who are over the age of 18
- ii) you do not have any neuromusculoskeletal condition that impair movement of your dominant arm and visual deficiencies that are not corrected by contact lenses or glasses.

If you decide to take part you will be one of three participants.

Do I have to take part?

No, you don't, is up to you to decide but your help would be very much appreciated. If you are interested, please inform the researcher by phone or email. The researcher will then contact you to describe the study and go through this information sheet, which you are asked to keep. If you are still interested, you will be asked to sign a consent form to show you have agreed to take part and that you understand what is involved.

You are free to withdraw at any time, without giving a reason. This would not affect the standard of healthcare you receive.

[21/01/14] [Version 2]

What will happen to me if I take part?

You will be involved in an assessment session which will take place at the Faculty of Health Sciences laboratory, University of Southampton. The tests will be conducted by the researcher and the session will last approximately one hour with regular breaks (see figure 1). If you feel too tired to complete the session, the rest break will be provided before continuing with the assessments.

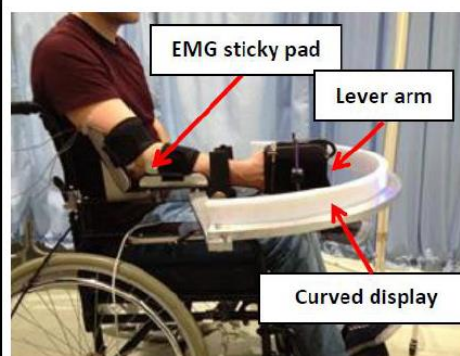
Figure 1 The test schedule.

Interviewing and screening arm test (5 minutes)	Break (5 minutes)	Arm function test (10 minutes)	Break (5 minutes)	The wrist rig test (20 minutes)
-------------------------------------------------	-------------------	--------------------------------	-------------------	---------------------------------

You will be required to wear a loose short sleeved top, or one that can be rolled up to the elbow.

A wrist rig (see figure 2) is designed to measure how the arm moves and how the muscles are working. This comprises of:

- A red light at the tip of the lever arm
- A blue light will appear on the white curved display in front which is located on a standard wheelchair.
- Your forearm and arm will be supported on the arm rest.
- Electromyography (EMG) measurement (the electric signals from the muscles that move your wrist).
- An instrument in the arm rest that measures your wrist angle and an instrument that measures the strength you use to move your wrist.
- A Laptop computer



At the first session, you will be asked to move your arm in different directions. Subsequently, you will perform a series of 6 tasks in a seated position. These tasks include.

- i) hand to table
- ii) hand to box
- iii) lift can
- iv) lift pencil
- v) fold towel
- vi) reach and retrieve a one-pound weight

Following these tasks, you will undergo tests on the wrist rig. To perform the wrist rig tests you will be seated in a standard wheelchair with your arm placed on the rig armrest (as illustrated in the photo). The skin on your forearm will be cleaned with alcohol wipes and sticky gel pads will be placed on your arm. These pads are used for the measurement of your muscle activity. The researcher will again help you to place your arm in the rig in the correct position, and your arm will be secured with velcro straps.

During the testing process you will be first asked to move your wrist towards you and away from you as far as you can. The researcher will then move your wrist



through its full range. There will be a blue light on a white curved display which placed in front of the arm rest. You will then be asked to move your wrist to follow the blue light as they light up in different sequences for a few minutes. Subsequently, you will be asked to push and then pull your hand against a resistance for five seconds. Finally, the assessor will move your wrist to follow a blue light on a curved display while you relax your arm.

A video recording may be taken during the testing process for the purpose of assessment, teaching and presentation of results. This will only happen if you consent to it.

After the whole assessment session, you will be interviewed about your views of the whole experience.

Are there any benefits in my taking part?

There is no direct benefit to you from taking part. However, the information provided by you in this study may help to improve the measurement of movement problems for future patients with stroke.

Are there any risks involved?

There is a very slight risk of reddening of the skin on the hand and arm while it is held in the rig by Velcro straps; care will therefore be taken to ensure that the supports are not fastened too tightly and if you are undergoing tests for longer than 20 minutes the arm will be released and the skin checked for reddening at 20 minute intervals. If you become uncomfortable while in the rig, your arm will be released from the rig until any discomfort has eased

Will my participation be confidential?

All information which is collected about you during the course of the research will be kept strictly confidential. Any information about you on report forms will have your name and address removed so that you cannot be recognised from it. You will be identified by a unique number that connects your data to you. Your personal details will be kept separately from the research records. The data recorded, for the purpose of the research project, will be held on a password protected computer or as paper records kept in a locked filing cabinet in the Faculty of Health Sciences of the University of Southampton.

What happens if I change my mind?

If you wish to withdraw from the study, you may stop the testing at any time without giving any reason. If you agree, I will use any data I have collected from you up until the point of you withdrawing from the study.

What happens if something goes wrong?

If you become uncomfortable or distressed during the session, you will immediately be offered assistance by the researcher. If you have a concern or a complaint about this study you should contact

Dr Martina Prude,
Head of Research Governance, at the researcher Governance Office
University of Southampton,
Building 37, Highfield,
Southampton,
SO17 1BJ:
Tel: +44 (0)23 8059 5058
Email: mad4@soton.ac.uk

If you remain unhappy and wish to complain formally, Dr Martina Prude can provide you with details of the University of Southampton Complaints Procedure.

[21/01/14] [Version 2]



What will happen to the results of the research study?

The results of the study will be compiled in reports and published or presented at scientific conferences. If you participate in this study, you will not be identified in any report, presentation or publication as your name will be removed. Your identity will be protected at all times.

Who is organising and funding the research?

The study is being organised through the University of Southampton and funded by Naresuan University, Thailand.

Who has reviewed the study?

The Faculty of Health Sciences Ethics Committee of the University of Southampton has reviewed this study.

Where can I get more information?

If you would like any further information, please contact:

Waroonnapa (Nick) Srisoparb
Mphil/PhD student,
Faculty of Health Sciences,
University of Southampton,
Building 45, Room 0001,
Highfeild campus,
SO17 1BJ
Tel: +44 (0)23 8059 2568
Mobile phone: +44 (0)75 2154 2316
Email: ws2e12@soton.ac.uk

Dr Ruth Turk
Lecturer in Physiotherapy
Professional Practice in Health Sciences,
Faculty of Health Sciences, Building 67,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 23 8059 8928
Email: r.turk@soton.ac.uk

Prof. Jane Burridge
Professor of Restorative Neuroscience
Head of Rehabilitation and Health Technologies Research Group,
Faculty of Health Sciences, Building 45,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 2380 598 885
Mobile: +44 (0) 7909 523 193
FAX: +44 (0) 2380 595 301
E-mail: jhb1@soton.ac.uk

Thank you for considering taking part in this study. You will be given a copy of the information sheet and a signed consent form to keep.

Appendix F Participant Information Sheet for chronic stroke participants (pilot study 1)



Participant Information Sheet for chronic stroke participants

Study Title: Prediction of upper limb recovery post-stroke using wrist motor impairments: Pilot study 1

Researcher: Waroonnapa Srisoparb

Ethics number:

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

Introduction

I am a physiotherapist and currently, I am pursuing a degree of Doctor of Philosophy at the University of Southampton, United Kingdom. As part of this degree, I am conducting this research study.

I would like to invite you to participate in my research. Before you make your decision, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with your relatives, friends or your GP if you wish.

If something is not clear, or you would like more information, please do not hesitate to contact me. Take time to decide whether or not you wish to take part. Thank you for reading this.

What is the research about?

Muscle weakness, tightness (known as spasticity) and loss of control of movement are common problems among people who have had a stroke. There is a need for better measures of movement problems in order to improve research on the arm function of people who have had a stroke. A better understanding of the underlying reason for improvement in arm activity after a stroke will enable better diagnosis of movement problems and more targeted therapy.

The purpose of this pilot study is to evaluate the test procedure (the wrist rig test and the arm function test) which will be carried out in a future main study with sub-acute stroke participants. The result of this pilot study will enable the researcher to make refinements to the protocol before proceeding to collect data in sub-acute stroke patients.

Why have I been chosen?

You have been chosen to take part in this study as:

- i) You had stroke more than six months ago and you are over the age of 18
- ii) From your stroke you have some movement problems with your affected arm

If you decide to take part you will be one of three participants.

Do I have to take part?

No, you don't, it is up to you to decide but your help would be very much appreciated. If you are interested, please inform the researcher by phone or email. She will then contact you to describe the study and go through this information sheet, which you are asked to keep. If you are still interested, you will be asked to sign a consent form to show you have agreed to take part and that you understand what is involved.

You are free to withdraw at any time, without giving a reason. This would not affect the standard of care you receive.

[21/01/14] [Version 2]

What will happen to me if I take part?

You will be involved in an assessment session which will take place at the Faculty of Health Sciences laboratory, University of Southampton. The tests will be conducted by the researcher and the session will last approximately one hour with regular breaks (see figure 1). If you feel too tired to complete the session, the rest break will be provided before continuing with the assessments.

Figure 1 The test schedule.

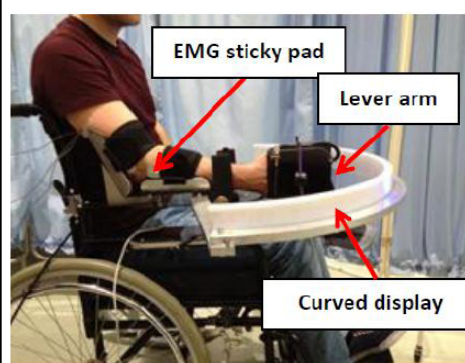
Interviewing and screening arm test (5 minutes)	Break (5 minutes)	Arm function test (10 minutes)	Break (5 minutes)	The wrist rig test (20 minutes)
-------------------------------------------------	-------------------	--------------------------------	-------------------	---------------------------------

The researcher can assist you with any personal needs during that time but you may also like to be accompanied by a carer.

You will be required to wear a loose short sleeved top, or one that can be rolled up to the elbow.

A wrist rig (see figure 2) is designed to measure how the arm moves and how the muscles are working. This comprises of:

- A red light at the tip of the lever arm
- A blue light will appear on the white curved display in front which is located on a standard wheelchair.
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- Electromyography (EMG) measurement (the electric signals from the muscles that move your wrist).
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- i) hand to table
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- vi) reach and retrieve a one-pound weight

Following these tasks, you will undergo tests on the wrist rig. To perform the wrist rig tests you will be seated in a standard wheelchair with your arm placed on the rig armrest (as illustrated in the photo). The skin on your forearm will be cleaned with alcohol wipes and sticky gel pads will be placed on your arm. These pads are used for the measurement of your muscle activity. The researcher will again help you to place your arm in the rig in the correct position, and your arm will be secured with velcro straps.



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A video recording may be taken during the testing process for the purpose of assessment, teaching and presentation of results. This will only happen if you consent to it.

After the whole assessment session, you will be interviewed about your views of the whole experience.

Are there any benefits in my taking part?

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Are there any risks involved?

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Will my participation be confidential?

All information which is collected about you during the course of the research will be kept strictly confidential. Any information about you on report forms will have your name and address removed so that you cannot be recognised from it. You will be identified by a unique number that connects your data to you. Your personal details will be kept separately from the research records. The data recorded, for the purpose of the research project, will be held on a password protected computer or as paper records kept in a locked filing cabinet in the Faculty of Health Sciences of the University of Southampton.

What happens if I change my mind?

If you wish to withdraw from the study, you may stop the testing at any time without giving any reason. If you agree, I will use any data I have collected from you up until the point of you withdrawing from the study.

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If you remain unhappy and wish to complain formally, Dr Martina Prude can provide you with details of the University of Southampton Complaints Procedure.

What will happen to the results of the research study?

The results of the study will be compiled in reports and published or presented at scientific conferences. If you participate in this study, you will not be identified in any report, presentation or publication as your name will be removed. Your identity will be protected at all times.

Who is organising and funding the research?

The study is being organised through the University of Southampton and funded by Naresuan University, Thailand.

Who has reviewed the study?

The Faculty of Health Sciences Ethics Committee of the University of Southampton has reviewed this study.

Where can I get more information?

If you would like any further information, please contact:

Waroonnapa (Nick) Srisoparb
Mphil/PhD student,
Faculty of Health Sciences,
University of Southampton,
Building 45, Room 0001,
Highfield campus,
SO17 1BJ
Tel: +44 (0)23 8059 2568
Mobile phone: +44 (0)75 2154 2316
Email: ws2e12@soton.ac.uk

Dr Ruth Turk
Lecturer in Physiotherapy
Professional Practice in Health Sciences,
Faculty of Health Sciences, Building 67,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 23 8059 8928
Email: r.turk@soton.ac.uk

Prof. Jane Burridge
Professor of Restorative Neuroscience
Head of Rehabilitation and Health Technologies Research Group,
Faculty of Health Sciences, Building 45,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 2380 598 885
Mobile: +44 (0) 7909 523 193
FAX: +44 (0) 2380 595 301
E-mail: jhb1@soton.ac.uk

Thank you for considering taking part in this study. You will be given a copy of the information sheet and a signed consent form to keep.

[21/01/14] [Version 2]

Appendix G Poster for recruitment of sub-acute stroke participants (pilot study 2)

UNIVERSITY OF
Southampton

Have you had a stroke?
Is your arm movement affected?

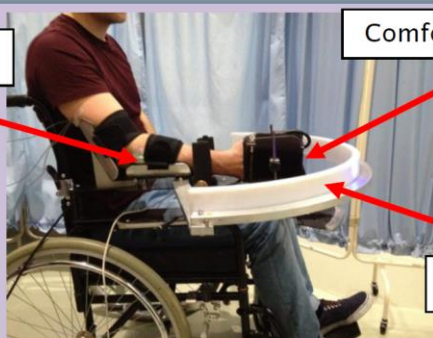
Would you like to participate in research?

We are looking for people to help us find out what wrist movements predict arm recovery following stroke.

An instrumented wrist rig

EMG sticky pad

Comfortable air splint



Target display

What is involved?

1. A single visit to the Department of Physiotherapy, Buddhachinaraj Hospital or your house.
2. We will use this wrist rig to measure your wrist movement, strength and control.
3. You will also perform six simple arm tasks in a seated position.

For further details please contact:

Ms Waroonnapa (Nick) Srisoparb

Email: ws2e12@soton.ac.uk Tel: 089-2260665

Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665
--------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------

Appendix H Invitation letter for sub-acute stroke participants (pilot study 2)



Date:

Dear Sir/ Madam

Re: Invitation to participate in a research study

I am a Thai Physiotherapy lecturer and currently, I am doing a degree of Doctor of Philosophy at the University of Southampton, United Kingdom. I would like to invite you to take part in a research study that investigates the recovery of the arm after stroke. I am looking for the people who just have had a stroke for less than eight weeks to help us to evaluate the test procedure that investigates wrist movement pattern and arm function.

The assessment will be conducted at the Department of Physiotherapy, Buddhachinaraj Hospital, Phitsanulok, or at your house, whichever is more convenient for you. You will be required to take part in a single one-hour assessment. However, if you are willing to participate in a related future study, you will be asked to take part in up to three further hourly assessments.

Once you have read the enclosed information sheet and decide you would like to take part in this study, please email me or call me at the telephone number found at the end of this letter. I will answer any questions that you may have and will also take the opportunity to ask you some general questions about your health status. These questions will help me determine if the assessment is suitable for you. An appointment will then be made for you to attend an assessment session on a day and time that is convenient for you.

Many thanks for taking the time to read this invitation letter. I look forward for meeting you if you choose to take part in the study.

Yours sincerely,

Waroonnapa (Nick) Srisoparb
Faculty of Allied Health Sciences,
Naresuan University,
Phitsanuloke,
65000
Thailand

Email: ws2e12@soton.ac.uk
Mobile: 0872260665

Invitation letter pilot study 2 [03/02/14] [Version 1]

Appendix I Participant Information Sheet for sub-acute stroke participants (pilot study 2)



Participant Information Sheet for sub-acute stroke participants in the pilot study 2

Study Title: Prediction of upper limb recovery post-stroke using wrist motor impairments: Pilot study 2 and Main study

Researcher: Waroonnapa Srisoparb

Ethics number:

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

Introduction

I am a Thai Physiotherapy lecturer and currently, I am doing a degree of Doctor of Philosophy at the University of Southampton, United Kingdom. As part of this degree, I am conducting this research study.

I would like to invite you to participate in my research study. Before you make your decision, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with your relatives, friends or your GP if you wish.

If something is not clear, or you would like more information, please do not hesitate to contact me. Take time to decide whether or not you wish to take part. Thank you for reading this.

What is the research about?

Muscle weakness, tightness (known as spasticity) and loss of control of movement are common problems among people who have had a stroke. There is a need for better measures of movement problems in order to improve research on the arm function of people who have had a stroke. A better understanding of the underlying reason for improvement in arm activity after a stroke will enable better diagnosis of movement problems and more targeted therapy.

The purpose of this pilot study is to evaluate the procedure of assessing wrist movements in a mechanical rig and an arm function test. It will involve a single assessment and the results will enable the researcher to make refinements to the test procedure before proceeding to collect data in a future related study which tracks stroke patients for six months.

Why have I been chosen?

You have been chosen to take part in this study as:

- i) you had a stroke within the last eight weeks and you are over the age of 18.
- ii) From your stroke you have some movement problems with your affected arm

If you decide to take part you will be one of 6 participants.

Do I have to take part?

No, you don't, is up to you to decide but your help would be very much appreciated. If you are interested, please inform the Physiotherapist who is in-charge of you or by returning the reply slip in the pre-paid envelope. The researcher will then contact you and will describe the study and go through this information sheet, which you are asked to keep. If you are still interested, you will be asked to sign a consent form to show you have agreed to take part and that you understand what is involved.

You are free to withdraw at any time, without giving a reason. This would not affect the standard of care you receive.

What will happen to me if I take part?

You will be involved in a single assessment session which will take place at the Department of Physiotherapy, Buddhachinaraj Hospital, Phitsanulok, Thailand or your house, whichever is more convenient for you. The tests will be conducted by the researcher and the session will last approximately one hour with regular breaks (see figure 1). If you feel too tired to complete the session, the rest break will be provided before continuing with the assessments.

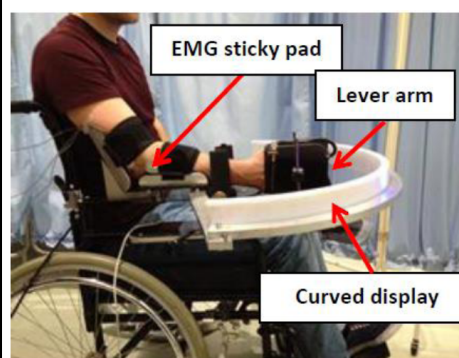
Figure 1 The test schedule

Interviewing and screening arm test (5 minutes)	Break (5 minutes)	Arm function test (10 minutes)	Break (5 minutes)	The wrist rig test (20 minutes)
-------------------------------------------------	-------------------	--------------------------------	-------------------	---------------------------------

The researcher can assist you with any personal needs during that time but you may also like to be accompanied by a carer. You will be required to wear a loose short sleeved top, or one that can be rolled up to the elbow.

A wrist rig (see figure 2) is designed to measure how the arm moves and how the muscles are working. This comprises of:

- A red light at the tip of the lever arm
- A blue light will appear on the white curved display in front which is located on a standard wheelchair.
- Your forearm and arm will be supported on the arm rest.
- Electromyography (EMG) measurement (the electric signals from the muscles that move your wrist).
- An instrument in the arm rest that measures your wrist angle and an instrument that measures the strength you use to move your wrist.
- A Laptop computer



At the first session, you will be asked to move your arm in different directions. Subsequently, you will perform a series of 6 tasks in a seated position. These tasks include.

- i) hand to table
- ii) hand to box
- iii) lift can
- iv) lift pencil
- v) fold towel
- vi) reach and retrieve a one-pound weight

Following these tasks, you will undergo tests on the wrist rig. To perform the wrist rig tests you will be seated in a standard wheelchair with your arm placed on the rig armrest (as illustrated in the photo). The skin on your forearm will be cleaned with alcohol wipes and sticky gel pads will be placed on your arm. These pads are used for the measurement of your muscle activity. The researcher will again help you to place your arm in the rig in the correct position, and your arm will be secured with velcro straps.



During the testing process you will be first asked to move your wrist towards you and away from you as far as you can. The researcher will then move your wrist through its full range. There will be a blue light on a white curved display which placed in front of the arm rest. You will then be asked to move your wrist to follow the blue light as they light up in different sequences for a few minutes. Subsequently, you will be asked to push and then pull your hand against a resistance for five seconds. Finally, the assessor will move your wrist to follow a blue light on the curved display while you relax your arm.

A video recording may be taken during the testing process for the purpose of assessment, teaching and presentation of results. This will only happen if you consent to it.

After the whole assessment session, you will be interviewed about your views of the whole experience.

You will be required to take part in a single one-hour assessment. However, if you are willing to participate in a related future study, you will be asked to take part in up to three further hourly assessments.

Are there any benefits in my taking part?

There is no direct benefit to you from taking part. However, the information provided by you in this study may help to improve the measurement of movement problems for future patients with stroke.

Are there any risks involved?

There is a very slight risk of reddening of the skin on the hand and arm while it is held in the rig by Velcro straps; care will therefore be taken to ensure that the supports are not fastened too tightly and if you are undergoing tests for longer than 20 minutes the arm will be released and the skin checked for reddening at 20 minute intervals. If you become uncomfortable while in the rig, your arm will be released from the rig until any discomfort has eased

Will my participation be confidential?

All information which is collected about you during the course of the research will be kept strictly confidential. Any information about you on report forms will have your name and address removed so that you cannot be recognised from it. You will be identified by a unique number that connects your data to you. Your personal details will be kept separately from the research records. The data recorded, for the purpose of the research project, will be held on a password protected computer or as paper records kept in a locked filing cabinet in the Department of Physiotherapy, Buddhachinaraj Hospital, Thailand.

What happens if I change my mind?

If you wish to withdraw from the study, you may stop the testing at any time without giving any reason. If you agree, I will use any data I have collected from you up until the point of you withdrawing from the study.

What happens if something goes wrong?

If you become uncomfortable or distressed during the session, you will immediately be offered assistance there and then by the researcher. If you have a concern or a complaint about this study you should contact

Dr Martina Prude,
Head of Research Governance, at the researcher Governance Office
University of Southampton,
Building 37, Highfield,
Southampton,



SO17 1BJ;
Tel: +44 (0)23 8059 5058
Email: mad4@soton.ac.uk

What will happen to the results of the research study?

The results of the study will be compiled in reports and published or presented at scientific conferences. If you participate in this study, you will not be identified in any report, presentation or publication as your name will be removed. Your identity will be protected at all times.

Who is organising and funding the research?

The study is being organised through the University of Southampton and funded by Naresuan University, Thailand.

Who has reviewed the study?

The Faculty of Health Sciences Ethics Committee of the University of Southampton and the Institutional Review Board of Buddhachinaraj Hospital Ethics Committee have reviewed this study.

Where can I get more information?

If you would like any further information, please contact:

Waroonnapa (Nick) Srisoparb
Faculty of Allied Health Sciences,
Naresuan University,
Phitsanuloke,
65000
Thailand
Mobile: +66 (0) 89 226 0665
Email: ws2e12@soton.ac.uk

Dr Ruth Turk
Lecturer in Physiotherapy
Professional Practice in Health Sciences,
Faculty of Health Sciences, Building 67,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 23 8059 8928
Email: r.turk@soton.ac.uk

Professor Jane Burrridge
Professor of Restorative Neuroscience
Head of Rehabilitation and Health Technologies Research Group,
Faculty of Health Sciences, Building 45,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 2380 598 885
Mobile: +44 (0) 7909 523 193
FAX: +44 (0) 2380 595 301
E-mail: jhb1@soton.ac.uk

Thank you for considering taking part in this study. You will be given a copy of the information sheet and a signed consent form to keep.

Appendix J Poster for recruitment of sub-acute stroke participants (longitudinal study)

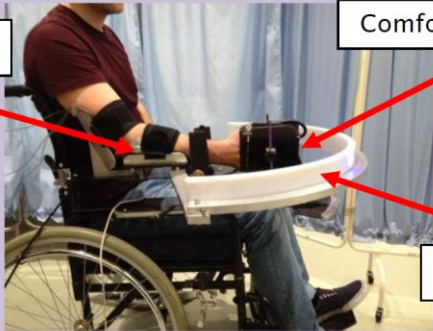
UNIVERSITY OF
Southampton

**Have you had a stroke?
Is your arm movement affected?**

Would you like to participate in research?

We are looking for people to help us find out what wrist movements predict arm recovery following stroke.

An instrumented wrist rig



What is involved?

1. Four one-hour visits to the Department of Physiotherapy, Buddhachinaraj Hospital or your house.
2. We will use this wrist rig to measure your wrist movement, strength and control.
3. You will also perform six simple arm tasks in a seated position.

**For further details please contact:
Ms Waroonnapa (Nick) Srisoparb
Email: ws2e12@soton.ac.uk Tel: 089-2260665**

Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665	Wrist Rig Research Nick ws2e12@soton.ac.uk Tel: 089-2260665
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Appendix K Invitation letter for sub-acute stroke participants (longitudinal study)



Date:

Dear Sir/ Madam

Re: Invitation to participate in a research study

I am a Thai Physiotherapy lecturer and currently, I am doing a degree of Doctor of Philosophy at the University of Southampton, United Kingdom. I would like to invite you to take part in a research study that investigates the recovery of the arm after stroke. I am looking for the people who have recently had a stroke (less than eight weeks) to help us to evaluate wrist movement patterns and arm function.

The research assessments will be conducted at the Department of Physiotherapy, Buddhachinaraj Hospital, Phitsanulok, or at your house, whichever is more convenient for you. You will be required to make up to four visits, each lasting one hour.

Once you have read the enclosed information sheet and decide you would like to take part in this study, please email me or call me at the telephone number found at the end of this letter. I will answer any questions that you may have and will also take the opportunity to ask you some general questions about your health status. These questions will help me determine if the assessment is suitable for you. An appointment will then be made for you to attend an assessment session on a day and time that is convenient for you.

Many thanks for taking the time to read this invitation letter. I look forward for meeting you if you choose to take part in the study.

Yours sincerely,

Waroonnapa (Nick) Srisoparb
Faculty of Allied Health Sciences,
Naresuan University,
Phitsanuloke,
65000
Thailand

Email: ws2e12@soton.ac.uk
Mobile: 0872260665

Appendix L Participant Information Sheet for sub-acute stroke participants (longitudinal study)



Participant Information Sheet for sub-acute stroke participants in the main study

Study Title: Prediction of upper limb recovery post-stroke using wrist motor impairments: Pilot study 2 and Main study

Researcher: Waroonnapa Srisoparb

Ethics number:

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

Introduction

I am a Thai Physiotherapy lecturer and currently, I am doing a degree of Doctor of Philosophy at the University of Southampton, United Kingdom. As part of this degree, I am conducting this research study.

I would like to invite you to participate in my research study. Before you make your decision, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with your relatives, friends or your doctor if you wish.

If something is not clear, or you would like more information, please do not hesitate to contact me. Take time to decide whether or not you wish to take part. Thank you for reading this.

What is the research about?

Muscle weakness, tightness (known as spasticity) and loss of control of movement are common problems among people who have had a stroke. There is a need for better measures of movement problems in order to improve research on the arm function of people who have had a stroke. A better understanding of the underlying reason for improvement in arm activity after a stroke will enable better diagnosis of movement problems and more targeted therapy.

The purpose of this study is to measure the movement problems of the arm of people who have suffered a stroke and to understand how these movement problems are related to an individual's ability to perform activities such as reach and grasp. This involves some wrist movement tests in a mechanical rig and an arm function test.

Why have I been chosen?

You have been chosen to take part in this study as:

- i) you had a stroke within the last eight weeks and you are over the age of 18.
- ii) From your stroke you have some movement problems with your affected arm

If you decide to take part you will be one of 40 participants.

Do I have to take part?

No, you don't, is up to you to decide but your help would be very much appreciated. If you are interested, please inform the Physiotherapist who is in-charge of you or by returning the reply slip in the pre-paid envelope. The researcher will then contact you and will describe the study and go through this information sheet, which you are asked to keep. If you are still interested, you will be asked to sign a consent form to show you have agreed to take part and that you understand what is involved.

You are free to withdraw at any time, without giving a reason. This would not affect the standard of care you receive.

PIS Main Study [03/02/14] [Version 1]

What will happen to me if I take part?

You will be involved in up to four assessment sessions (at two, four, eight and 26 weeks after your stroke). They will take place at the Department of Physiotherapy, Buddhachinaraj Hospital, Phitsanulok, Thailand or your house, whichever is more convenient for you. The tests will be conducted by the researcher and the sessions will last approximately one hour with regular breaks (see figure 1). If you feel too tired to complete the session, the rest break will be provided before continuing with the assessments.

Figure 1 The test schedule

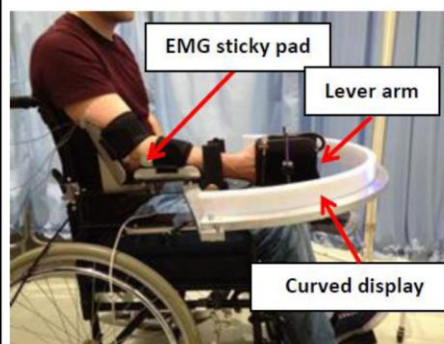
Interviewing and screening arm test (5 minutes)	Break (5 minutes)	Arm function test (10 minutes)	Break (5 minutes)	The wrist rig test (20 minutes)
-------------------------------------------------	-------------------	--------------------------------	-------------------	---------------------------------

The researcher can assist you with any personal needs during that time but you may also like to be accompanied by a carer.

You will be required to wear a loose short sleeved top, or one that can be rolled up to the elbow.

A wrist rig (see figure 2) is designed to measure how the arm moves and how the muscles are working. This comprises of:

- A red light at the tip of the lever arm
- A blue light will appear on the white curved display in front which is located on a standard wheelchair.
- Your forearm and arm will be supported on the arm rest.
- Electromyography (EMG) measurement (the electric signals from the muscles that move your wrist).
- An instrument in the arm rest that measures your wrist angle and an instrument that measures the strength you use to move your wrist.
- A Laptop computer



At the first session, you will be asked to move your arm in different directions. Subsequently, you will perform a series of 6 tasks in a seated position. These tasks include.

- i) hand to table
- ii) hand to box
- iii) lift can
- iv) lift pencil
- v) fold towel
- vi) reach and retrieve a one-pound weight

Following these tasks, you will undergo tests on the wrist rig. To perform the wrist rig tests you will be seated in a standard wheelchair with your arm placed on the rig armrest (as illustrated in the photo). The skin on your forearm will be cleaned with alcohol wipes and sticky gel pads will be placed on your arm. These pads are used for the measurement of your muscle activity. The researcher will again help you to



place your arm in the rig in the correct position, and your arm will be secured with velcro straps.

During the testing process you will be first asked to move your wrist towards you and away from you as far as you can. The researcher will then move your wrist through its full range. There will be a blue light on a white curved display which placed in front of the arm rest. You will then be asked to move your wrist to follow the blue light as they light up in different sequences for a few minutes. Subsequently, you will be asked to push and then pull your hand against a resistance for five seconds. Finally, the assessor will move your wrist to follow a blue light on the curved display while you relax your arm.

A video recording may be taken during the testing process for the purpose of assessment, teaching and presentation of results. This will only happen if you consent to it.

Are there any benefits in my taking part?

There is no direct benefit to you from taking part. However, the information provided by you in this study may help to improve the measurement of movement problems for future patients with stroke.

Are there any risks involved?

There is a very slight risk of reddening of the skin on the hand and arm while it is held in the rig by Velcro straps; care will therefore be taken to ensure that the supports are not fastened too tightly and if you are undergoing tests for longer than 20 minutes the arm will be released and the skin checked for reddening at 20 minute intervals. If you become uncomfortable while in the rig, your arm will be released from the rig until any discomfort has eased

Will my participation be confidential?

All information which is collected about you during the course of the research will be kept strictly confidential. Any information about you on report forms will have your name and address removed so that you cannot be recognised from it. You will be identified by a unique number that connects your data to you. Your personal details will be kept separately from the research records. The data recorded, for the purpose of the research project, will be held on a password protected computer or as paper records kept in a locked filing cabinet in the Department of Physiotherapy, Buddhachinaraj Hospital, Thailand.

What happens if I change my mind?

If you wish to withdraw from the study, you may stop the testing at any time without giving any reason. If you agree, I will use any data I have collected from you up until the point of you withdrawing from the study.

What happens if something goes wrong?

If you become uncomfortable or distressed during the session, you will immediately be offered assistance there and then by the researcher. If you have a concern or a complaint about this study you should contact

Dr Martina Prude,
Head of Research Governance, at the researcher Governance Office
University of Southampton,
Building 37, Highfield,
Southampton,
SO17 1BJ:
Tel: +44 (0)23 8059 5058
Email: mad4@soton.ac.uk



What will happen to the results of the research study?

The results of the study will be compiled in reports and published or presented at scientific conferences. If you participate in this study, you will not be identified in any report, presentation or publication as your name will be removed. Your identity will be protected at all times.

Who is organising and funding the research?

The study is being organised through the University of Southampton and funded by Naresuan University, Thailand.

Who has reviewed the study?

The Faculty of Health Sciences Ethics Committee of the University of Southampton and the Institutional Review Board of Buddhachinaraj Hospital Ethics Committee have reviewed this study.

Where can I get more information?

If you would like any further information, please contact:

Waroonnapa (Nick) Srisoparb
Faculty of Allied Health Sciences,
Naresuan University,
Phitsanuloke,
65000
Thailand
Mobile: +66 (0) 89 226 0665
Email: ws2e12@soton.ac.uk

Dr Ruth Turk
Lecturer in Physiotherapy
Professional Practice in Health Sciences,
Faculty of Health Sciences, Building 67,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 23 8059 8928
Email: r.turk@soton.ac.uk

Professor Jane Burridge
Professor of Restorative Neuroscience
Head of Rehabilitation and Health Technologies Research Group,
Faculty of Health Sciences, Building 45,
University of Southampton,
Southampton, England,
SO17 1BJ
Tel: +44 (0) 2380 598 885
Mobile: +44 (0) 7909 523 193
FAX: +44 (0) 2380 595 301
E-mail: jhb1@soton.ac.uk

Thank you for considering taking part in this study. You will be given a copy of the information sheet and a signed consent form to keep.

Appendix M Short form of the Fugl-Meyer Motor scale (S-FM-UE)



Short Form of the Fugl-Meyer Motor Scale

Date:...../...../..... Patient ID:.....

Assessor:.....

Items	none	partial	full
Shoulder flexion 90°-180°	0	1	2
Grasp, adduct thumb	0	1	2
Elbow 90° pronation/ supination	0	1	2
Elbow 90° wrist flexion/ extension	0	1	2
Elbow extension	0	1	2
Shoulder elevation	0	1	2
Total (max 12)			

(Hsieh et al. 2007; Hsueh et al. 2008)

Appendix N Consent Form



CONSENT FORM (Version 1)

Study title: Prediction of upper limb recovery post-stroke using wrist motor impairments: pilot study 2 and main study

Researcher name: Waroonnapa Srisoparb

Study reference:

Ethics reference:

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (03/02/14/ version 1 of participant information sheet) and have had the opportunity to ask questions about the study.

☐

I agree to take part in this research project and agree for my data to be used for the purpose of this study

☐

I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected

☐

I am happy to be contacted regarding other unspecified research projects. I therefore consent to the University retaining my personal details on a database, kept separately from the research data detailed above. The 'validity' of my consent is conditional upon the University complying with the Data Protection Act and I understand that I can request my details be removed from this database at any time.

☐

Data Protection

I understand that information collected about me during my participation in this study will be stored on a password protected computer and that this information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Name of participant (print name).....

Signature of participant.....

Date.....

[03/02/14] [Version 1]



Consent Form – Images

Study title: Prediction of upper limb recovery post-stroke using wrist motor impairments: pilot study 2 and main study

Researcher name: Waroonnapa Srisoparb

Study reference:

Ethics reference:

1 I agree to photography or video recording during the intervention

Please
initial
box

2 Photographs of me can be used in printed material such as academic papers

3 Photos or videos of me may be used in presentations

4 Photos or videos of me can be used on websites such as the university website

Name of Participant

Signature

Date

Name of Researcher

Signature

Date

[03/02/14] [Version 1]

Appendix O Confounding factors record



Assessment form of research title Prediction of upper limb recovery post-stroke using wrist motor impairments

Date:...../...../..... Patient ID:.....

Confounding factor

Items	Characteristic		
1. Age			
2. Gender	<input type="checkbox"/> Male	<input type="checkbox"/> Female	
3. Hemiplegic side	<input type="checkbox"/> Right	<input type="checkbox"/> Left	
4. Type of stroke	<input type="checkbox"/> Ischemic	<input type="checkbox"/> Haemorrhagic	
5. Wrist joint proprioception	<input type="checkbox"/> 2-normal	<input type="checkbox"/> 1-impaired	<input type="checkbox"/> 0-absent
6. mRS			

Appendix P Modified Rankin Scale (mRS)



MODIFIED RANKIN SCALE (MRS)

Date:...../...../..... Patient ID:..... Therapist ID:

Score	Description
0	No symptoms at all
1	No significant disability despite symptoms; able to carry out all usual duties and activities
2	Slight disability; unable to carry out all previous activities, but able to look after own affairs without assistance
3	Moderate disability; requiring some help, but able to walk without assistance
4	Moderately severe disability; unable to walk without assistance and unable to attend to own bodily needs without assistance
5	Severe disability; bedridden, incontinent and requiring constant nursing care and attention
Total	

(van Swieten et al. 1988)

Appendix Q Upper limb treatment recording form



Upper limb treatment recording form

Date:...../...../..... Patient ID:.....

Tick ✓ in the box if that exercise programme is administered by the therapist or caregiver.

Programme	0 to 2 wks	2 to 4 wks	4 to 8 wks	8 to 12 wks	Estimated total time			
					0 to 2 wks	2 to 4 wks	4 to 8 wks	8 to 12 wks
1. Passive movement exercises								
2. Active movement exercises								
3. Strengthening exercises								
4. Massage								
5. Functional training								
6. Facilitation technique								
7. Inhibitory technique								
8. Proprioceptive stimulation								
9. Electrical stimulation								
Prostheses/Orthoses								
Other								

Appendix R Edinburgh handedness inventory-short form



Edinburgh Handedness Inventory–Short form

Date:...../...../..... Patient ID:..... Therapist ID:

Please indicate your preferences in the use of hands in the following activities or objects:

Always right Usually right Both equally Usually left Always left

Writing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Throwing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Toothbrush	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Spoon	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

(Veale 2014)

Appendix S Streamlined Wolf motor Function Test form (sub-acute stroke version)



Streamlined Wolf Motor Function Test (Sub-acute stroke version)

Date:...../...../..... Patient ID:..... Assessment: 1/ 2/ 3/ 4/ 5/ 6

	Task	Time (seconds)	Functional ability scale	Remarks
1	Hand to table (front)			
2	Hand to box (front)			
3	Lift can			
4	Lift pencil			
5	Fold towel			
6	Reach and retrieve			
Mean time			Mean FAS	

Score	Mean FAS
0	Does not attempt
1	Does not participate functionally-attempt to make use of upper extremity (UE)
2	Does, but requires assistance of the UE not being tested for minor readjustments or change of position; or require more than 2 attempts to complete; or accomplishes very slowly
3	Does, but movement is influenced to some degree by synergy or is performed slowly or with effort
4	Does; movement close to normal but slightly slower; may lack precision, fine coordination or fluidity
5	Movement appears normal

(Bogard et al. 2009)

Appendix T Wrist rig participant record form



Wrist rig participant record form

Date:...../...../..... Patient ID:..... Assessment: 1/ 2/ 3/ 4/ 5/ 6

Test	Files records/ comments/ problems					
1. AROM 3 times						
2. PROM 3 times						
3. MVC at 20° 3 times	Ext:			Flex:		
4. Stretch response 3.5Hz, +/-20°						
5. Active tracking						
Sinusoidal 0.5Hz, +/-20°						
Random step 5° to 40°						
6. Force/angle test 5°/s full PROM						

Appendix U Interview schedule for pilot studies



Interview schedule for pilot studies

Date:...../...../..... Patient ID:..... Therapist ID:

Pilot study 1 (Healthy participants and Chronic stroke participants)

1. What do you think about the whole assessment?
2. Do you feel tired after the whole assessment session?
3. What do you think about the wrist rig test?
 - a. Do you feel comfortable when you are doing the test?
 - b. Is it easy to move against resistance that I have set?
 - c. Is it easy to move your wrist within the range that I have set?
 - d. Do you feel that the test is too long?
 - e. Do you feel pain when you are on the wrist rig?
 - f. Do you think the wrist rig is suitable to be used for stroke patient?
4. What do you think about the Streamlined Wolf Motor Function Test (S-WMFT)?
 - a. Is that easy to perform these activities S-WMFT?
 - b. Do you feel that the test is too long?
5. If you have the opportunity, would you mind being tested again?
6. Is there anything else you would like to suggest for us to improve the whole assessment?

Pilot study 2

1. What do you think about the whole assessment?
2. Do you feel tired after the whole assessment session?
3. What do you think about the wrist rig test?
 - a. Do you feel comfortable when you are doing the test?
 - b. Is it easy to move against resistance that I have set?
 - c. Is it easy to move your wrist within the range that I have set?
 - d. Do you feel that the test is too long?
 - e. Do you feel pain when you are on the wrist rig?
 - f. Do you think the wrist rig is suitable to be used for stroke patient?



4. What do you think about the Streamlined Wolf Motor Function Test (S-WMFT)?
 - a. Is that easy to perform these activities S-WMFT?
 - b. Do you feel that the test is too long?
5. If you have the opportunity, would you mind being tested again?
6. Where do you prefer to be tested (your house or hospital)
7. Is there anything else you would like to suggest for us to improve the whole assessment?

